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EDITORIAL PAPER

IGU-YECG SPECIAL ISSUE: GEOSPATIALITY AND SUSTAINABLE DEVELOPMENT GOALS

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ABSTRACT. The rapid human development and the conflicts between society, economy and environment has greatly hindered the implementation of sustainable development strategy. The '*2030 Agenda for Sustainable Development*' and the Sustainable Development Goals (SDGs) provides a universal framework for addressing the issues identified in previous development agendas and achieving policy goals in social, economic and environmental spheres. However, the governments and decision-makers across the world have been facing challenges related to monitoring and assessing the progress of SDGs. The use of geospatial science and spatial data architectures can address these challenges and support holistic monitoring and evaluation of SDGs. This editorial paper discusses the role of geospatial science in implementation of SDGs by drawing on the scholarly works published in the special issue titled 'Geospatiality and Sustainable Development Goals'. The issue provided a platform for research publications by young and early career geographers from across the world. Several papers in the issue were drawn from different IGU conference sessions organised by the IGU-Task Force for Young and Early Career Geographers (IGU-YECG) since from its establishment (Beijing, 2016) to the upcoming 34th IGC at Istanbul (2021). By bringing the debates on SDGs to the forefront explicitly, this editorial paper reinstates interest in the topic.

KEY WORDS: Geospatiality; Sustainable Development Goals; COVID-19; Urbanisation; International Geographical Union

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INTRODUCTION

The rapid human development and the contradiction between society, economy and environment has greatly hindered the implementation of sustainable development strategy (Zhao and Wu 2019). In order to draw more attention on sustainable development from different actors, the United Nations has adopted the 17 Sustainable Development Goals (SDGs), 169 sub-goals and 232 targets at the United Nations Summit on Sustainable Development in 2015. Unlike the previous development agendas such as the Millennium Development Goals (MDGs), where the emphasis was on economic growth, the SDGs are a universal framework that contains many potentially diverging policy goals in the economic, social, and environmental sphere, while some goals are thought to be mutually supportive (Kroll et al. 2019). The SDGs also allows malleability between programs of environment and development; places from local to global; institutions of government, civil society and industry (Robert et al. 2005). Many experts and researchers have been making great efforts to monitor, assess and realise SDGs. For example, while some researchers analysed the application of SDGs to ecology and environment (Salleh 2016; Yenneti et al. 2016), others applied SDGs to humanities and education (Chowdhury and Koya 2017; Sterling 2014). Yet there are many difficulties. There is a lack of awareness, understanding and uptake of geospatial information and spatial data architectures at policy and decision-making levels (Scott and Rajabifard 2017). The sheer volume of geospatial data, the different understanding of the SDG indicators, the lack of policy and guidance, the gaps in geospatial information can be further impediments to achieve the SDGs. Further, there are relatively limited studies that attempt to more holistically capture the varieties of geospatial factors and contexts behind the articulation of SDGs. There is a need to assess the trade-offs and synergies to meet the SDGs and fill the gaps.

In order to develop a vision for ensuring sustainable development, a discussion of the SDGs needs careful examination through new concepts, approaches and solutions to the problems. In particular, it is crucial to integrate and connect geospatial information with the global development agendas in a more holistic and sustainable manner to monitor, measure and achieve the 17 SDGs, their 169 targets and the 2030 Agenda for Sustainable Development. Geospatial information has attracted widespread attention as a means to build a universal measurement and monitoring framework that can be applied across the world (Choi et al. 2016).

This special issue brings together integrated interdisciplinary and international studies on SDGs, monitoring and evaluation of SDGs, the use of different existing and emerging geospatial technologies in assessing challenges in implementation of SDGs, the social and gender dimensions in SDG research and other development-related themes. The use of geospatial programmes and data can help in analysing the social, economic and environmental benefits and costs of implementing different SDGs and inform scientific community, policy, industry and civil society (Moomen et al. 2019). The analysis, modelling and mapping of issues in implementation of SDGs can provide an integrative framework for global cooperation, collaboration and evidence-based decision-making (Scott and Rajabifard 2017).

The issue provided a platform for research publications by young and early career geographers from across the world. Several papers in this issue were drawn from different International Geographical Union (IGU) conference sessions organised by the IGU-Task Force for Young and Early Career Geographers (IGU-YECG) since from its establishment (Beijing, 2016) to the upcoming 34th IGC at Istanbul (2021). There is a cutting-edge research by young and early career scholars which deserves to be recognised and popularised. The special issue will enhance the understandings and conceptualisations of the interrelationship between geospatiality and SDGs. In particular, the integration of new geographies of theory, new conceptual vectors, innovative geospatial techniques and methodologies, the role of institutions, macro and micro level actors, policy options and effects, and governance and planning can be of significant value addition to the emerging literature on SDGs. The papers have addressed SDGs at the local, regional, and global scales, in various geographical contexts and across multiple dimensions (economic, social, political, developmental, and environmental). Interestingly, the intersectionality of COVID-19 pandemic has been contextualised with SDGs in some of the papers, which gave a greater nuanced approach to the special issue. The papers have adopted a relational perspective and showcased the conduits to address theoretical, methodological, and empirical issues in implementation of the SDGs.

SDGs and COVID-19 Pandemic

In the paper by *da Silva et al.,* the authors have assessed that the efficient and effective investment to meet Good Health and Well Being (SDG 3) and Clean Water and Sanitation (SDG 6) can be directly associated with the ability to successfully deal with the infectious diseases. Using the case study of Brazilian cities, a model is established for analysing the impact of compliance to SDGs in the fight against COVID-19. Likewise, B*hattacharjee and Sattar* revealed that COVID-19 had differential impacts on different wards of Mumbai city which was associated with socio-economic inequalities prevailing in the city. Efforts are required to meet the targets of SDGs in order to minimise urban vulnerability.

Sustainable Urbanisation and Quality of Life

Cabrera-Barona and Cisneros have explained the effective implementation of forests (SDG 15) and water resources (SDG 6) which has a significant implication on achieving quality of life in Metropolitan District of Quito. The authors assert that better strategies are required to ensure that the participation of local governments in policy implementation is more meaningful. Similarly, *Aditya and Ningam* have measured the greenness of an Indonesian city by using the presence and distribution of urban tree canopy. Urban trees are essential to meet SDG 11: Resilient and Sustainable Cities, SDG 13: Climate Action and SDG 15: Life on Land. The residents of Indonesian city have poor access to urban greenery as the urban tree canopy is less than the UN thresholds. Marginal green cover can exert severe environmental impacts such as urban heat island (UHI), air pollution, and surface water run-off. There is a rapid expansion of urban built up and decline of agricultural land and vegetation in Fateh Jang, Attock, Pakistan as analysed by Tariq at al. using Land Use Land Cover (LULC) analysis that could be helpful in urban planning and design.

Kudryatvaseva et al. evaluated the population externalities in 114 cities of Russia across three dimensions viz., economic, ecological and social. The authors demonstrated that efficient city size in terms of population, environment management and changes in city area are crucial for achieving SDG 11 in Russian cities. While relating to SDG 11, *Raman et al.* have assessed urban traffic congestion and its impacts on the stakeholders in the context of Azadpur Mandi-Asia's largest vegetable and fruit market. The authors have concluded that there is huge congestion by vehicles from surrounding states of Delhi, lack of proper parking spaces and air pollution which makes the targets of SDG 11 unachievable in present circumstances.

Sustainable Consumption

Herron et al. explored the potential of green waste as an avenue for additional revenue generation for the City of Greater Geelong. The authors have used GIS technology and modelling software of Global Methane Initiative to undertake a series of simulations and determined the viability of anaerobic digester for the City of Greater Geelong. The authors proposed an innovative economic model to value the organic waste in the city and achieve Goal 12: Ensure sustainable consumption and production pattern. The mapping of groundwater potential zones by *Dwivedi et al.* is beneficial for sustainable groundwater management and planning and can contribute to SDG 6. The study used GIS and remote sensing and the integration of Analytical Hierarchy Process (AHP) technique to identify ground water potential zones in the Betul-Chhindwara region of Madhya Pradesh. Besides, agroforestry zoning is an important tool to monitor forest areas (SDG 15). In the paper on Mexico-Guatemala transborder region, D*aniel and Aristides* have applied spatial analysis and modelling to map homogeneous units for environmental planning.

Social Dimensions of Sustainable Development

Analysing the electoral participation of women in context of Patna, Bharti and Ghosh highlighted upon the gender and social dimensions of SDG 5. Increase in the temporal pattern of women's participation in elections is evident from the study; however, the growth rate of the women voting percentage is less than that of men. This shows that women in the study area are being politically empowered. *Rajput and Arora* have measured and mapped food insecurity in Rajasthan in the context of SDG 2: End Hunger and Achieve Food Security. *Eremchenko et al.* assessed the least resource base in terms of minimum area and energy flow required to maintain long-term sustainable development of an isolated society.

CONCLUSION

The Special Issue highlights that it is important to render a multidimensional character to the debates on SDGs as the global cities and communities pose several challenges due to the existence of varied problems such as high population density, poverty, climate change, pollution and infectious diseases. Additionally, it calls for localisation and co-creation of the SDGs; closer collaboration between local communities, civil society, governments and industry can be a good candidate for the effectiveness of SDGs. This should be complemented with better conceptual and empirical analysis of the implementation of SDGs across the biophysical, socioeconomic and institutional factors.

To conclude, despite the long term interest in investigating sustainability at different spatial levels, empirical studies on the geospatiality and SDGs are only emerging. By bringing the debates on SDGs to the forefront explicitly, the special issue has reinstated interest in the topic and provided a scholarly framework for policy on geospatial capabilities.

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RESEARCH PAPER

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SUSTAINABLE DEVELOPMENT GOALS AGAINST COVID-19: THE PERFORMANCE OF BRAZILIAN CITIES IN SDGS 3 AND 6 AND THEIR REFLECTION ON THE PANDEMIC

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ABSTRACT. The aim of this article is to understand the relationship between two of the Sustainable Development Goals (UN Agenda 2030) – Good health and well-being (SDG 3) and Clean water and sanitation (SDG 6) – and the statistics of the COVID-19 pandemic (number of cases and deaths) in Brazilian cities. To analyze this relationship, we used secondary data from public organizations on the SDG panorama by city and conducted a moderated regression analysis. The sample was composed of 649 cities with a population exceeding 50 thousand inhabitants. The results show that the higher were the indicators used to measure SDGs, the lower was the number of cases and deaths from the disease. We have also proved that cities' population density and their distance from the pandemic epicenter moderate this relationship, since a higher level of these moderation variables increases the impact of a lower level of SDGs 3 and 6 coverage in society on the number of cases and deaths from COVID-19. Thus, the efficient and effective investment to reach SDGs 3 and 6 is directly associated with cities' ability to successfully deal with infectious diseases and the resulting number of deaths. As for its contribution, this research innovates by establishing a model for analyzing the impact of compliance with SDGs on cities' performance in their fight against COVID-19, which may also suit other nations.

KEY WORDS: Environmental Development; Coronavirus; Pandemic Outbreak; Sustainability

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INTRODUCTION

COVID-19 pandemic and its effects on achieving SDGs

The world is facing one of the most serious moments in its history with the advance of SARS-CoV-2, a virus that triggers a severe acute respiratory syndrome called COVID-19, which has killed more than 2,700,000 people worldwide (Johns Hopkins University [JHU][1] 2020; Jurcik et al. 2020). The impact of this disease goes beyond the health sphere, also triggering social, economic, cultural and environmental problems (Chakraborty and Maity 2020; Shakil et al. 2020; Zambrano-Monserrate, Ruano and Sanchez-Alcalde 2020; Sarkar, Debnath and Reang 2020). Therefore, its effects pose a serious threat to the development prospects of nations (Khetrapal and Bhatia 2020; Leal Filho et al. 2020). One of the major challenges for countries, especially the developing ones, is to comply with the Sustainable Development Goals (SDGs) since their financial, political and technological resources have been directed to contain the pandemic (Khetrapal and Bhatia 2020).

The 17 SDGs were established by the United Nations Agenda 2030 plan of action on September 25, 2015, and became effective in January 2016. All developed and developing countries must promote and implement these

[1] *Johns Hopkins University [JHU] (2020). COVID-19 Dashboard by the Center for Systems Science and Engineering (CSSE). Available at: https://www.arcgis.com/apps/opsdashboard/index.html#/bda7594740fd40299423467b48e9ecf6 [Accessed 25 Set. 2020]*
[2] *United Nations [UN] (2015). Transforming our world: the 2030 Agenda for sustainable development. Available at: https://sustainabledevelopment.un.org/post2015/transformingourworld [Accessed 7 Set. 2020].*

global goals as mediators for building practical tools to respond to systemic and universal problems, among them water management and sanitation, as well as global health care (United Nations [UN][2] 2015; Mordeson and Mathew 2020; Delanka-Pedige et al. 2020).

Many of these objectives are interconnected, which has led to an increased impact of the COVID-19 pandemic on all of them (Huan, Liang and Zhang 2020; Zhao et al. 2020). However, some studies (Ahmed et al. 2020; Khetrapal and Bhatia 2020) have called attention to two specific problems associated with the disease: the first detections of SARS-CoV-2 in untreated residual waters, and the effects of the disease on the health and well-being of populations around the world. These are indications that non-compliance with SDG 3 (health and well-being) and SDG 6 (clean water and sanitation) affects cities' performance in responding to a pandemic such as COVID-19. In addition, few studies (Khetrapal and Bhatia 2020; Mordeson and Mathew 2020; Leal Filho et al. 2020; Iwuoha and Jude-Iwuoha 2020) took into account the association between SDGs and COVID-19, although they did not intend to develop models that associate SDG results with COVID-19 statistics (cases and deaths from the disease). It is important to point out that the achievement of these sustainable objectives is reached through the adoption of indicators and monitoring tools, which are often used in literature (e.g. Bobylev et al. 2018; Kristjánsdóttir, Ólafsdóttir and Ragnarsdótti, 2018), since they allow to simplify, aggregate and clarify the information available to policymakers. In addition, the indicators are understood as means and not ends to achieve sustainable development, so the cross-analysis of the indexes can provide more accurate results (MacDonald et al. 2018).

The pandemic duration is uncertain, and nobody can estimate its full effects yet; therefore, the achievement of goals for each SDG within the given period (up to 2030, at most) becomes more and more difficult (Khetrapal and Bhatia 2020). Hence, we draw attention to developing countries, since some studies (Ahmed et al. 2020) show that COVID-19 affects them more negatively. One of these countries, Brazil, has unique environmental, social, and economic characteristics, such as high social inequality, deficiencies in public health, high and constant air and water temperatures, low rates of basic sanitation and high population density among the states (Von Braun, Zamagni and Sorondo 2020; Hart and Halden 2020). Therefore, these social, political, economic and environmental gaps between cities, states and regions can worsen the pandemic effects (Rourke et al. 2020; Khetrapal and Bhatia 2020) as well as make it impossible to meet these sustainable goals, especially SDGs 3 and 6.

In addition, on 03/18/2021, Brazil was the second country in the number of cases, and second – in the number of deaths from COVID-19 (JHU 2020), and this virus has spread to several regions in the country, from the North (the Amazon) to the South, close to Argentina and Uruguay (Candido et al. 2020). Hence, this study aims to understand the relationship between these two Sustainable Development Goals – Good health and well-being (SDG 3), and Clean water and sanitation (SDG 6) – and the distribution of COVID-19 cases and deaths in Brazilian cities.

SDG 3 (Good health and well-being) and COVID-19

SDG 3 aims at the well-being of individuals and the collective health of all communities (UN 2015). This objective promotes restructuring of the health system, thus strengthening the proposal of universal coverage (Seidman 2017). Therefore, this SDG is associated with the current pandemic the most as the first effects of non-compliance with it will directly affect the health system (Leal Filho et al. 2020).

COVID-19 continues to harm public health and its effects may be worse in tropical and subtropical countries like Brazil, which fights a battle against endemics such as dengue, malaria and yellow fever (Zeng et al. 2018). In addition, most developing countries suffer from the ineffectiveness of the health system due to the lack of funding, equipment, qualified personnel and poor hospitals' infrastructure, which mainly affects the most vulnerable communities from the social and economic standpoint (Leal Filho et al. 2020; Von Braun, Zamagni, and Sorondo 2020).

Previous studies (Kruk et al. 2018; Lucas et al. 2019) assessed the impact of achieving SDGs on countries' mortality rates, showing that countries with better SDG indices also demonstrate better cost-benefit ratios in the health system. Wang et al. (2020) associated population density with cases and deaths from COVID-19, and Câmara, Pinto, Silva and Gerhard (2020) showed that the distance from the epicenter is related to the growth of the virus proliferation curve. Therefore, considering the current scenario – a global health crisis caused by the COVID-19 pandemic – we have developed the following hypotheses:

H_1 – Cities that do not comply with SDG 3 report a higher number of COVID-19 cases;

H_2 – Cities that do not comply with SDG 3 report a higher number of deaths from COVID-19;

H_3 – Population density moderates the relationship between SDG 3 and the number of COVID-19 cases;

H_4 – Population density moderates the relationship between SDG 3 and the number of deaths from COVID-19;

H_5 – The distance between cities and the epicenter of the pandemic moderates the relationship between SDG 3 and the number of COVID-19 cases.

SDG 6 (Clean water and sanitation) and COVID-19

SDG 6 deals with sustainable water management and the quality of sewage services. Water is a critical component for life and human development, thus, it is vital in the battle against this pandemic (UN 2020)[1].

There is a consensus that the main transmission route of COVID-19 is close contact with infected people by either handshake, saliva droplets, sneeze, cough or vomit (Dehning et al. 2020). Therefore, the hygiene of the environment and body, especially hands, is essential to avoid COVID-19 transmission (Azoulay and Jones 2020). However, basic sanitation conditions in several regions of developing countries are still very precarious, which brings risks of secondary transmission. Another problem associated with the lack or discontinuity of clean water supply is that people end up resorting to alternative solutions for access to water, that is, access to sources such as lakes, ponds and rivers contaminated with other biological and chemical pathogens. These solutions are not the most appropriate as people may be infected by SARS-CoV-2 (Rimoldi et al. 2020) in addition to becoming susceptible to other transmission routes, such as fecal-oral.

Fecal-oral transmission of a disease concerns any form of contagion where the disease's etiologic agent is expelled through the host's feces or urine and is transmitted to a potential host either by direct ingestion, aerosols of contaminated water or by fomites associated with the action of biological vectors (Ahmadiara 2020). Up to now, there is no scientific evidence of fecal-oral transmission of

COVID-19, but it cannot be ruled out since this has occurred with other viruses of the coronavirus family. Several studies have found the presence of the SARS-CoV-2 virus in the feces and urine of symptomatic and non-symptomatic people throughout the world (W. Ahmed et al. 2020; Kitajima et al. 2020).

Hence, cities with worse conditions of sanitary sewage and water distribution can facilitate virus proliferation, and SDG 6 sets these conditions (Azoulay and Jones 2020; Kitajima et al. 2020). Furthermore, population density and distance from the epicenter can be decisive in this relationship (Câmara et al. 2020; Wang et al. 2020). A city with a high number of individuals requires an efficient water supply and sanitary sewage for everyone (Delanka-Pedige et al. 2020). Likewise, the closer to the epicenter, the greater is the risk that a certain natural resource is contaminated due to virus proliferation. Therefore, we propose additional hypotheses:

H_6 – Cities that do not comply with SDG 6 report a higher number of COVID-19 cases;

H_7 – Cities that do not comply with SDG 6 report a higher number of deaths from COVID-19;

H_8 – Population density moderates the relationship between SDG 6 and the number of COVID-19 cases;

H_9 – Population density moderates the relationship between SDG 6 and the number of deaths from COVID-19;

H_{10} – The distance between cities and the epicenter of the pandemic moderates the relationship between SDG 6 and the number of COVID-19 cases.

METHODOLOGY

To achieve the research objective, we carried out a quantitative study based on secondary data in 649 Brazilian cities with more

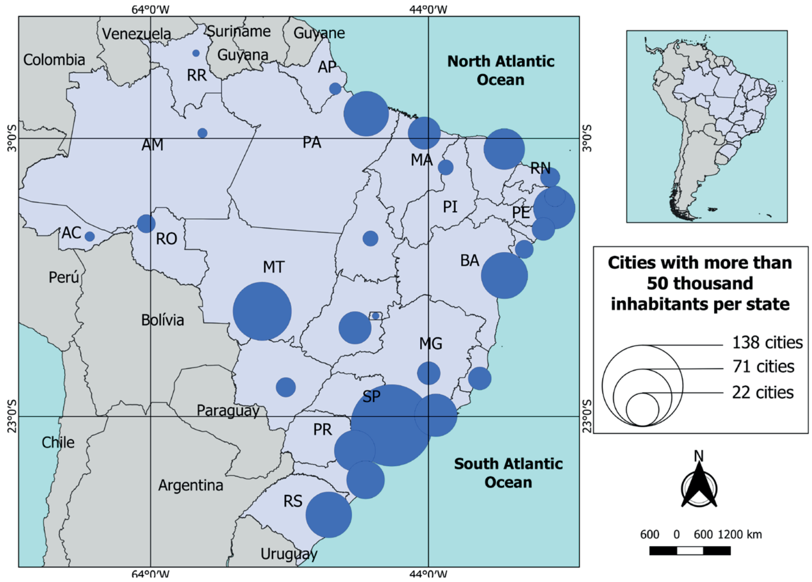

Fig. 1. Number of Brazilian cities with population over 50 thousand inhabitants, per State. AC = Acre; AL = Alagoas; AP = Amapá; AM = Amazonas; BA = Bahia; CE = Ceará; DF = Distrito Federal; ES = Espírito Santo; GO = Goiás; MA = Maranhão; MT = Mato Grosso; MS = Mato Grosso do Sul; MG = Minas Gerais; PA = Pará; PB = Paraíba; PR = Paraná; PE = Pernambuco; PI = Piauí; RJ = Rio de Janeiro; RN = Rio Grande do Norte; RS = Rio Grande do Sul; RO = Rondônia; RR = Roraima; SC = Santa Catarina; SP = São Paulo; SE = Sergipe; TO = Tocantins.
Note. Made with software Qgis version 3.4.13.

Table 1. Description of the variables analyzed for each SDG and the organizations that provided them

Objective	Organization	Data collected from the cities
SDG 3	Informatics Department of Unified Health System (DATASUS)	Number of neonatal deaths Number of child deaths (up to 5 years old) Number of deaths Maternal deaths during pregnancy or up to 42 days after giving birth Number of live births of women aged 15 to 19 years old Number of new HIV cases Number of malaria cases Number of hepatitis B cases Number of deaths by suicide Number of deaths by traffic accidents Vaccination coverage Abandonment of vaccination
SDG 6	National Information System on Sanitation (SNIS) and Trata Brasil Institute	Level of coverage of the urban and rural population by water supply Level of coverage of the urban population by piped water Level of coverage the of urban and rural population by sewage collection The volume of treated sewage in relation to the volume of water consumed, controlled by the collection rates

[1] *Instituto Brasileiro de Geografia e Estatística [IBGE]. (2015). Pesquisa Nacional por Amostra de Domicílios (PNAD). Available at: https://www.ibge.gov.br/estatisticas/sociais/populacao/9127-pesquisa-nacional-por-amostra-de-domicilios.html?=&t=o-que-e [Accessed 15 Set. 2020].*
[2] *Governo do Estado de São Paulo (SP) (2019). 1º Relatório de Acompanhamento dos Objetivos de Desenvolvimento Sustentável do Estado de São Paulo. São Paulo, Brasil. Available at: http://www.seade.gov.br/wpcontent/uploads/2019/07/SDGsp.pdf [Accessed 20 Set. 2020].*

than 50 thousand inhabitants (Fig. 1) according to the last census conducted by the Brazilian Institute of Geography and Statistics (IBGE)[1] in 2010. We used this population limit and this sample size (n = 649) because databases did not have enough information for cities with a population below 50 thousand inhabitants.

We defined the criterion for selecting the variables according to the State of São Paulo monitoring report on SDGs (SP 2019)[2], based on the goals established by Agenda 2030 for each objective (UN 2015). Thus, we divided the data analysis into two stages. First, we measured an index for each SDG from the collected information. In SDG 3, where the variables are represented in gross values, the indices were placed in the order from worse to better performance of the cities in the respective ODS variable. Subsequently, the sample was divided into percentiles, that is, it was placed in each class interval 1% of the series elements. Regarding the time frame, the period 2010-2018 was considered for the analysis considered.

As for SDG 6, we adopted the methodology developed by Trata Brasil Institute (2020)[1], which considers the total coverage level for water supply when the service rates reach 100%, while for sewage collection it considers total coverage as 98% of service. To calculate the level of water and sewage coverage, we used the following equations, established by SNIS (2018)[2].

Where:

$$IA = \frac{POPwater}{POP} \tag{1}$$

IA = Total water service rate or urban water service rate;
POPwater = Total population served with water or urban population served with water;
POP = Total population or urban population.

Where:

$$IE = \frac{POPsewage}{POP} \tag{2}$$

IE = Total sewage service rate or urban sewage service rate;
POPsewage = Total population served with sewage or urban population served with sewage;
POP = Total population or urban population.

Where:

$$IEAC = \frac{VE}{(Vac - Vae)} \tag{3}$$

IEAC = Treated sewage rate by water consumed;
Ve = Volume of treated sewage;
Vac = Volume of water consumed;
Vae = Volume of water exported.

Thus, once we measured the indices, we adopted the weighted mean for the final composition of SDG 6, where the indices in equations 1, 2 and 3 added up to 10%, 20% and 40% of the grade, respectively (Trata Brasil 2020). Finally, we calculated the dependent variables (DV) from the relationship between the COVID-19 statistics (number of cases and deaths) and the city's total population. These dependent variables were considered one at a time because the number of cases of the disease is not reflected in the same proportion as the number of deaths. Furthermore, the data referring to the COVID-19 statistics and the city's total population were extracted from DATASUS (2020c)[3] and IBGE (2020)[4], respectively.

For the second stage of the research, in which the relationships proposed by the hypotheses was investigated, we used the techniques of multivariate data analysis from moderation processes (Model 1) with the aid of PROCESS (Hayes 2013)[5] – Statistical Package for the Social Sciences (SPSS) software, version 24.0. In addition, we tested the proposed moderators by using a bootstrapping test with 10,000 samples.

We carried out preliminary data analyses to check the normality and presence of multicollinearity among the variables. As the calculations of the number of cases and deaths over the total population showed high asymmetry and kurtosis, we made logarithmic changes in these variables. Next, to check the presence of multicollinearity, we conducted Pearson's correlation analysis to identify the level of association among the variables (Tabachnick and Fidell 2001)[6]. Finally, in order to identify outliers, we used the multivariate detection through the Mahalanobis measure, excluding the cities of Viçosa-MG, Guanambi-BA and Palmas-PR for the statistical analyses with *the* variable «deaths from COVID-19», where, at the time, there were no records of

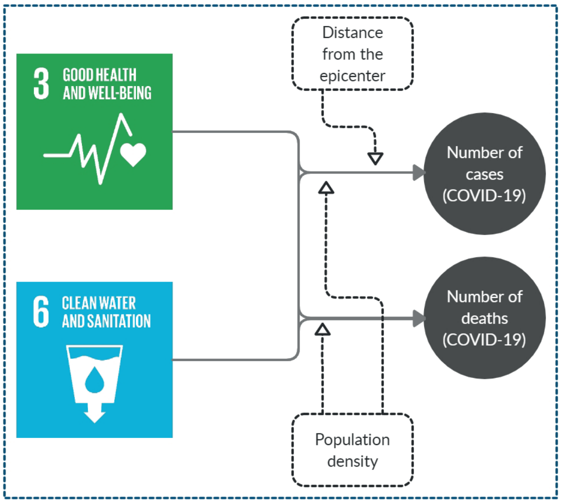

Fig. 2. Proposed conceptual model of the research hypotheses

[1] *Instituto Trata Brasil (2020). Ranking do saneamento. São Paulo, Brasil. Available at: http://tratabrasil.org.br/images/estudos/itb/ranking_2020/Relatorio_Ranking_Trata_Brasil_2020_Julho_.pdf [Accessed 3 Set. 2020]*
[2] *Sistema Nacional de Informações sobre Saneamento [SNIS]. (2018). SNIS: série histórica. Available at: http://app4.mdr.gov.br/serieHistorica/# [Accessed 16 Set. 2020].*
[3] *Sistema de Informática do Sistema Único de Saúde [DATASUS]. (2020c). Painel Coronavírus. Available at: https://covid.saude.gov.br/ [Accessed 14 Set. 2020].*
[4] *Instituto Brasileiro de Geografia e Estatística [IBGE]. (2020). IBGE Cidades. Available at: https://cidades.ibge.gov.br/ [Accessed 8 Set. 2020].*
[5] *Hayes, A. F. (2013). Model templates for SPSS and SAS. Behavior Research Methods, Instruments, & Computers, 36, 717-731. ISBN 978-1-60918-230-4*
[6] *Tabachnick, B. G. and Fidell, L. S. Using multivariate statistics (4th ed.) Needham Heights, MA.: Allyn and Bacon.*
[7] *Hayes, A. F. (2017). Introduction to mediation, moderation, and conditional process analysis: A regression-based approach. New York: Guilford.*

deaths from the disease. Thus, at the end of this stage, the sample had 646 valid observations. We found no outliers for the variable «COVID-19 cases».

Furthermore, we standardized all the variables in order to compare scales with different metrics, since such a procedure does not lead to distortions in variables' interactions (Hayes 2017)[7]. Figure 2 presents the proposed theoretical model based on the hypotheses.

RESULTS

Descriptive statistics and the correlation matrix of all study variables showed that the numbers of cases and deaths from COVID-19 were positively related to the levels of non-compliance with SDGs 3 and 6 (Table 2). However, as these correlation coefficients were not extremely high, there was no multicollinearity among the variables (Tabachnick and Fidell 2001). The correlation matrix provides a significant initial analysis of the association of variables. From this, more robust analysis models were designed to verify these associations.

As for the hypotheses testing, the results of the moderation analysis of the effect of a city's population distance and its density on the relationship between SDG and the COVID-19 levels over the population indicate a certain relationship (Table 3). For the relationship between SDG and COVID-19, the results show a significant negative direct effect of SDG 3 (β = -5.30; p <0.000) and SDG 6 (β = -5.04; p <0.000) variables on the number of cases. Therefore, hypotheses H_1 and H_6 were confirmed.

Regarding the effects of the first moderation, we noticed that population density regulates the relationship between SDGs and COVID-19 cases, showing a statistically significant negative effect of SDG 3 (β = -2.35; p <0. 05) and SDG 6 (β = -3.44; p <0.000) on the disease cases. Thus, we can infer that the impact of these goals on the number of COVID-19 cases gets higher with increasing population density in the city (Table 3).

Likewise, the combined effect of cities' distance with that of SDG 3 (β = -1.99; p <0.05) and SDG 6 (β = -3.40; p <0.000) was negatively significant, showing that the impact of SDGs on the COVID-19 cases is weaker for cities that are further away from the pandemic's initial dissemination zones. In addition, the graphical representation of moderation, in Table 3, shows that distance was a natural socio-geographical obstacle for the disease spread despite the low levels of SDG. Therefore, hypotheses H_3, H_5, H_8 and H_{10} were accepted.

Table 2. Correlation of variables, mean and standard deviation for variables 1 to 6 for Brazilian cities

Variables	Mean	S.D.	1	2	3	4	5	6
1. Cases/Population	.013	.009	1.00					
2.Deaths/Population	.0003	.000	.549***	1.00				
3. SDG 3	50.16	21.2	-.158***	-.301***	1.00			
4. SDG 6	.5309	.299	-.187***	-.192***	-.197***	1.00		
5. Distance	235.6	229	.065*	-.232***	.085**	-.086**	1.00	
6. Density	652.6	1567	-.003	.312***	-.370***	-.155***	-.284***	1.00

Note. * p<0.1; **p<0.05; ***p<0.01

Table 3. Moderation Analysis for the number of COVID-19 cases in the population

COVID-19 cases/population							
Structural path	β	SE	R^2	Structural path	β	SE	R^2
(F = 10.1191; 3; 642; p<0.000)				(F = 14.0284; 3; 642; p<0.000)			
Constant	0.048 (1.161)			Constant	-0.031 (-0.782)		
SDG 3	-0.224 (-5.30***)	0.042		SDG 6	-0.201 (-5.04***)	0.040	
Density	0.036 (0.868)	0.042		Density	-0.104 (-2.63***)	0.399	
SDG 3x Density	-0.095 (-2.35**)	0.040	.045	SDG 6 x Density	-0.138 (-3.44***)	0.040	0.061
(F = 9.231; 3; 642; p<0.000)				(F = 13.4605; 3; 642; p<0.000)			
Constant	0.027 (0.689)			Constant	-0.005 (0.136)		
SDG 3	-0.193 (-4.83***)	0.040		SDG 6	-0.167 (-4.43***)	0.038	
Distance	-0.057 (-1.392)	0.041		Distance	-0.096 (-2.51***)	0.038	
SDG 3 x Distance	-0.075 (-1.99**)	0.037	0.041	SDG 6 x Distance	-0.129 (-3.40***)	0.038	0.059

Note. ** Significant at 5%; *** Significant at 1%.

Table 4. Moderation Analysis for the number of deaths in the population

COVID-19 deaths/population							
Structural path	β	SE	R^2	Structural path	β	SE	R^2
(F = 27.7611; 3; 642; p<0.000)				(F = 39.2535; 3; 642; p<0.000)			
Constant	0.035 (0.966)			Constant	-0.002 (-0.069)		
SDG 3	-0.206 (-5.43***)	0.038		SDG 6	-0.248 (-7.03***)	0.05	
Density	-0.176 (-4.66***)	0.037		Density	-0.337 (-9.56***)	0.035	
SDG 3 x Density	-0.023 (-0.652)	0.036	0.114	SDG 6 x Density	-0.095 (-2.70***)	0.035	0.155

** Significant at 5%; *** Significant at 1%.

Table 4 presents the relationship between the SDG variables and the number of deaths from COVID-19. Similar to the previous theoretical model, the interrelationship of the variables had comparable values, with all SDG 3 (β = -5.43; p <0.000) and SDG 6 (β = -7.03; p <0.000) variables demonstrating a significant negative relationship with the number of deaths from the disease, thus confirming H_2 and H_7. However, there was a significant improvement in the model resulting from the independent variables, which indicated that the SDGs level better explains the number of deaths caused by the disease than its way of dissemination.

From the analysis of the combined effects, the density was a moderator only in the relationship between SDG 6 and the number of deaths (β = -2.70; p <0.000). Such an association reveals that the higher population density of a location increases the impact of a lower level of SDG 6 coverage on the number of deaths by COVID-19. Therefore, from these results, only hypothesis H_9 was confirmed. Finally, Table 5 summarizes the main results of the theoretical-empirical model of the study.

DISCUSSION

Confirmation of the hypotheses allows us to infer that the achievement of these SDGs improves the performance of communities throughout the world in the face of a critical health scenario. Hence, an efficient and effective investment in SDGs 3 and 6 is directly associated with the ability of cities, regions or countries to successfully deal with infectious diseases and the resulting death numbers (Khetrapal and Bhatia 2020). To do that, these sustainable goals should not play a secondary role in the current scenario and the post-pandemic future.

Regarding SDG 6, Brazil lacks a greater coverage of water supply (currently it is 83.6%) to reach the goal of universal and equitable access to clean water, thus reducing the risk of COVID-19 contagion (SNIS 2018; UN 2020). In addition, there is inequality in access to water when comparing the cities since 149 of them have a service in the range of 60% to 80%, and in 147 cities, this rate is below 40% (SNIS 2018).

This difference among regions can be explained by the socio-spatial segmentation and segregation that has historically marked Brazil and is linked to historical, economic, political, cultural and social aspects (Rezende and Heller 2002[1]; Nahas et al. 2019). In addition, service rates are worse for the sewerage system, whose average in 2018 was 53.2%, with 249 cities with a service range of 20% to 40%, while 324 had rates below 20% (SNIS 2018).

Furthermore, several studies (W. Ahmed et al. 2020; Kitajima et al. 2020) show that the poor sanitary and management structure for water distribution leaves cities exposed to the spread of COVID-19. These factors, which are linked to a higher concentration of inhabitants per square kilometer and the reluctance to adopt social distancing policies, have a direct effect on the virus proliferation (Iwaya et al. 2020; Wang et al. 2020). This moderation gets stronger for the SDG levels and the number of deaths from COVID-19 since the closer to the epicenter, the higher is the risk of contamination of water resources due to virus proliferation. In addition, the greater is the population in need of water supply and sanitation, the lower are the rates of compliance with SDGs and the greater are the health risks (Câmara et al. 2020; Wang et al. 2020). Therefore, the literature confirms the hypotheses that refer to SDG 6.

Finally, regarding the performance of Brazilian cities in health management (SDG 3), child mortality has decreased over the period 1990-2015 (initial milestone of Agenda 2030) (França et al. 2017). In addition, in that same period, there was a sharp reduction in the number of cases of communicable diseases, maternal deaths, cardiovascular diseases and chronic respiratory diseases; however, the number of cases of noncommunicable diseases rose across the country (Malta et al. 2017). Furthermore, recent preliminary data from the Ministry of Health (September 2020) indicate a drop in vaccination coverage, which in 2019 reached 72.31% and currently is at the level of 49.78% (DATASUS 2020a)[2]. The results may still change since states could report the data until the end of September, but this information preview is disturbing and shows a potential scenario of post-pandemic impacts with an increase in infections of unvaccinated people. In most vaccination campaigns in Brazil, the intended target coverage is between 90% and 95% (DATASUS 2020b)[3]. Therefore, from the hypotheses proposed and from previous studies we can infer (Leal Filho et al. 2020; Khetrapal and Bhatia 2020; Iwuoha and Jude-Iwuoha 2020) a relationship between SDG 3 indicators and the COVID-19 statistics, knowing that this disease worsens an already fragile health system.

Table 5. Hypothesis tests for the Theoretical Model

H	Structural Paths	B	SE	P	Result
H1	SDG 3 → Cases by COVID-19	-0.224	0.04	0.000***	Accepted
H2	SDG 3 → Deaths by COVID-19	-0.206	0.03	0.000***	Accepted
H3	(SDG 3 x Density) → Cases by COVID-19	-0.095	0.04	0.018**	Accepted
H4	(SDG 3 x Density) → Deaths by COVID-19	-0.023	0.03	0.514	Rejected
H5	(SDG 3 x Distance) → Cases by COVID-19	-1.99	0.03	0.046**	Accepted
H6	SDG 6 → Cases by COVID-19	-0.201	0.04	0.000***	Accepted
H7	SDG 6 → Deaths by COVID-19	-0.248	0.05	0.000***	Accepted
H8	(SDG 6 x Density) → Cases by COVID-19	-0.138	0.04	0.000***	Accepted
H9	(SDG 6 x Density) → Deaths by COVID-19	-0.095	0.03	0.007***	Accepted
H10	(SDG 6 x Distance) → Cases by COVID-19	-3.40	0.03	0.000***	Accepted

** Significant at 5%; *** Significant at 1%.

[1] *Rezende, S. C., and Heller, L. (2002). O saneamento no Brasil: políticas e interfaces [Sanitation in Brazil: Policies and Interfaces]. Belo Horizonte: Editora da UFMG*

[2] *Sistema de Informática do Sistema Único de Saúde [DATASUS]. (2020a). Informações de saúde (TABNET). Available at: http://www2.datasus.gov.br/DATASUS/index.php?area=02 [Accessed 14 Set. 2020].*

[3] *Sistema de Informática do Sistema Único de Saúde [DATASUS]. (2020b). Cobertura vacinal (TABNET). Available at: http://tabnet.datasus.gov.br/tabdata/LivroIDB/2edrev/f13.pdf [Accessed 14 Set. 2020].*

CONCLUSION

The results show that the investment and dedication to meet the goals established in SDGs 3 and 6 affects cities' performance regarding the COVID-19 statistics since cities that have a better performance in the indicators of these objectives have fewer cases and deaths from COVID-19. Likewise, the population density of the cities and their distance from the pandemic epicenter moderate this relationship.

The pandemic can cause an overload in the health system due to the increase in cases of coronavirus increasing the number of deaths from other diseases not related to COVID-19. Well-being and mental health may also be affected by social isolation. In addition, water is an essential component in combating the transmission of COVID-19 as it is necessary for cleaning the environments and cleaning the body and its uneven management will possibly aggravate the pandemic scenario. Therefore, coping with the COVID-19 pandemic cannot be separated from the goals and indicators outlined in the SDGs since achieving the two objectives analyzed in this research, SDGs 3 and 6, will strengthen the health system, water and sewage management.

As for the contribution of the research, it innovates by establishing a model that can suit other nations for assessing the impact of complying with SDGs on the performance of cities in the battle against COVID-19. The UN report is incisive, showing that world progress so far is below expectations and, with the pandemic, a setback is still expected. Therefore, it is essential to be cautious at this critical moment, bearing in mind that decisions that do not rely on scientific knowledge compromise progress in complying with SDGs and affect the health statistics, especially in developing countries. Finally, in order to contribute to the control of these goals, we emphasize the urgent need for studies addressing the following issues: (1) monitoring compliance of the SDG indicators not addressed in this research and their relationship with COVID-19; (2) evaluation of public policies adopted for achieving these goals; and (3) involvement of the private sector in the search for sustainable growth.

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RESEARCH PAPER

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PANDEMIC AND URBAN SUSTAINABILITY: ANALYZING THE COVID-19 SCENARIO IN MUMBAI, INDIA

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ABSTRACT. The present study analyses the case of urban sustainability in Mumbai in the context of the COVID-19 pandemic and aims to identify the relationship between the existing sustainability issues and the spread of the pandemic across the administrative wards of the Municipal Corporation of Greater Mumbai. It also tries to delve into the reasons behind the observed relationships to establish the patterns created by the COVID-19 pandemic in Mumbai by the end of August 2020. The study relies on secondary sources of data, that include reports published by government agencies, news articles, journals and websites. The study comprises a large amount of quantitative data that were analyzed using ArcGIS 10.4.1 and SPSS 23. The qualitative data collected through an extensive literature review was used alongside the quantitative data to support the study. The findings reveal that the COVID-19 pandemic had a varied impact across the wards of Mumbai, which was found to be associated with the unequal socio-economic conditions that prevail across the city. This inequality has contributed to Mumbai's reduced resilience, for building which the Sustainable Development Goals (SDGs) have to be achieved.

KEY WORDS: COVID-19, Density, Pandemic, Poverty, Sustainability, Urban

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INTRODUCTION

The need for sustainable development in cities has been recognized in the Sustainable Development Goals (SDGs) formulated by the United Nations, where SDG 11 is dedicated to making cities and communities sustainable[1]. Large population and diverse activities in urban areas have resulted in the emergence of several socio-economic and environmental challenges rendering a multi-dimensional character to the sustainability debate (Kwivani 2010). Furthermore, sustainable development in the cities of the Global South poses several challenges due to the existence of various problems such as high population density, urban informality, poverty, housing crisis and growing unemployment. Therefore, sustainable development in the cities of the Global South would require accomplishing certain other SDGs in conjunction with Goal 11. These goals include Goal 1 (No Poverty), Goal 2 (Zero Hunger), Goal 3 (Good Health and Well-Being), Goal 8 (Decent Work and Economic Growth) and Goal 17 (Partnerships)'[2]. On top of all the existing challenges, the emergence of the COVID-19 pandemic has crippled the urban areas raising more concerns about the future of sustainability. Black et al., (2020) note that, «In dense, internationally connected cities, risk of transfer of infectious disease is exacerbated through rapid population flows, and lack of quality public space». By bringing the issue of urban vulnerability to the forefront, the pandemic has reinstated interest in the subject (Sharifi et al. 2020). It has also provided an opportunity to examine how pandemics affect urban areas and what can be done to increase the urban resilience to pandemics (Sharifi et al. 2020). With 90% of the reported cases, the urban areas across the world have emerged as ground zero of the pandemic[3&4]. This has not been an exception for India, where the progress of the pandemic has made it evident that the urban areas of the country are bearing the brunt of the crisis. According to Jha, «With an ever-larger shift of populations to urban areas in conjunction with a shift of a very large percentage of national economies to large urban centers, the concentration of a succession of epidemics and pandemics in cities has become stronger»[5].

The city of Mumbai is one of the worst affected areas by the COVID-19 pandemic. It is one of the most densely populated cities of India and the density in its ghettos of the urban poor is strikingly high, for instance, in Mumbai's 'Dharavi', which is one of the most densely populated slum areas of the world, the population density is 277,136/km^2 (Golechha 2020). Unlike the affluent sections of the

[1] United Nations, n.d.
[2] Sustainable Development Goals | Partnerships platform, n.d.
[3] Guterres, n.d.
[4] Praharaj and Vaidya, n.d.
[5] Jha 2020

society, the urban poor are facing far greater challenges under the lockdown. 'People living in urban slums are exposed to greater risks than those residing in wealthy neighborhoods'[1] (Neiderud 2015), especially in times of a pandemic. Prevalence of co-morbid conditions, malnutrition and insufficient diets weakens the immune system, which alongside factors such as lack of clean drinking water and improper sanitation facilities make people susceptible to disease transmission and deaths (Toole and Waldman 1990). Paul et al. (2020) note that high population density and a large concentration of the population in slums with high household density and low per-capita income drive the spread of infectious diseases, as people living under such circumstances are compelled to violate social distancing norms for their basic needs. In the slums of Mumbai, maintaining social distancing for stopping the spread of the virus is a luxury, which the slum dwellers cannot afford for the sake of their survival. Along with this, homelessness is another major challenge confronting Mumbai. The COVID-19 pandemic has posed a severe challenge to this less recognized section of Mumbai's population as well. The present study aims at examining the scenario emerging from the pandemic in the Indian city of Mumbai from the perspective of urban sustainability. The paper attempts to explore the relationship existing between the spatial distribution of the pandemic, urban density and urban poverty in the city.

MATERIALS AND METHODS

The Study area

The study area chosen for the study is the coastal city of Mumbai located in the western part of India, in the state of Maharashtra. Mumbai is administered by the Municipal Corporation of Greater Mumbai (MCGM). Greater Mumbai is a city spread over two districts, Mumbai City District and Mumbai Suburban District. It is divided by the MCGM into 24 administrative wards, of which 9 are in Mumbai City District and 15 are in Mumbai Suburban District[2] (Fig. 1). The wards located in the Mumbai City District are A Ward (Colaba), B Ward (Sandhurst Road), C Ward (Marine Lines), D Ward (Grant Road), E Ward (Byculla), F/S Ward (Parel), F/N Ward (Matunga), G/N Ward (Dadar/Plaza) and G/S Ward (Elphinstone)[2]. The wards located in the Mumbai Suburban District are H/W Ward (Bandra), H/E Ward (Khar/Santacruz), K/E Ward (Andheri East), K/W Ward (Andheri West), P/S Ward (Goregaon), P/N Ward (Malad), R/S Ward (Kandivali), R/C Ward (Borivali), R/N Ward (Dahisar), L Ward (Kurla), M/E Ward (Chembur), M/W Ward (Chembur West), N Ward (Ghatkopar), S Ward (Bhandup) and T Ward (Mulund)[2].

Data collection and processing

To meet the objectives of the research, two major sets of data were used in this study. The first set of data is on the scenario of the COVID-19 pandemic in Mumbai, which is collected from the key updates and trends published by the Municipal Corporation of Greater Mumbai, dated 30th of August 2020[3]. This set comprises the ward-wise data on COVID-19 positive cases, active cases, cases discharged and cases resulting in deaths as well as containment zones and sealed buildings in Mumbai. The second set comprises demographic data on gross population density, slum population and homeless population in the wards of Mumbai as per the estimates of the Census of 2011. The ward-wise data on gross population density and slum population were collected from the District Disaster Management Plans of Mumbai City District and Mumbai Suburban District[3]&[4]; whereas the ward-wise data on homeless population was derived from the FAQ document of the Public Health Department of the MCGM[5]. In addition to this, data from other sources such as journals, websites and news articles were also used to support the study.

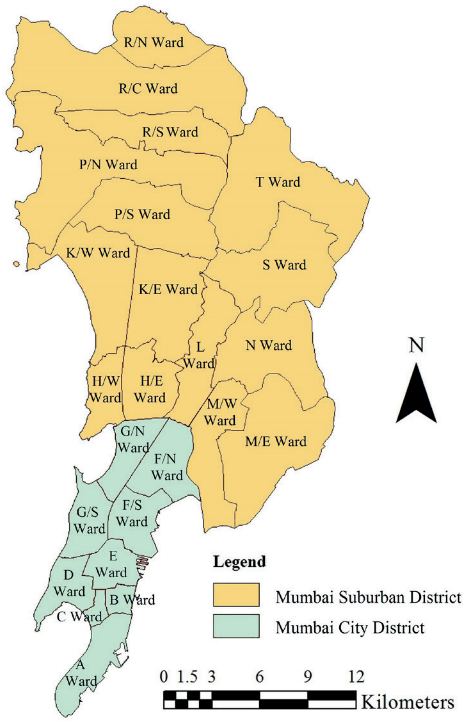

Fig. 1. Wards and Districts comprising Mumbai

[1] *Choudhry and Avinandan 2020*
[2] *District Census Handbook: Mumbai Suburban District, 2011*
[3] *MCGM 2020b*
[4] *MCGM 2019a*
[5] *MCGM 2020a*

The collected data were processed and analyzed using ArcGIS 10.4.1 and SPSS 23. Using ArcGIS 10.4.1, the ward-wise distribution of the total number of positive COVID-19 cases, number of active cases, patients discharged, patient deaths, containment zones and sealed buildings as well as population density, slum and homeless population in Mumbai were mapped to reveal the emerging spatial patterns. Thereafter, the correlation between these variables was analyzed in SPSS 23 to analyse the existence of any significant associations. In addition to these, the map showing the wards and districts of Mumbai was also prepared in ArcGIS 10.4.1.

RESULTS AND DISCUSSION

The COVID-19 scenario of Mumbai

The COVID-19 pandemic has affected Mumbai tremendously. With Dharavi emerging as a COVID-19 hotspot in April[1], Mumbai's fate in terms of the pandemic seemed extremely gloomy. However, since then Dharavi went a long way, going from being a hub of SARS-CoV-2 infections to becoming a success story. In the wake of the growing number of cases in Mumbai, the success of Dharavi in controlling the spread of the SARS-CoV-2 virus has altered the dynamics of the pandemic in the city. In this study, the COVID-19 situation that emerged in Mumbai at the end of August 2020 was considered. Analyzing the ward-wise distribution of the positive COVID-19 cases in Mumbai revealed the existence of significant differences throughout the city (Fig. 2). Some wards such as P/N, K/W, K/E and G/N were marked by a high number of COVID-19 positive cases, ranging from 7670 to 8727, while the wards H/W, C, B and A had a very low number of positive cases, ranging from 1247 to 2052. There were also wards such as S and N, which witnessed only a moderate number of COVID-19 positive cases.

Variation among the wards of Mumbai also exists in terms of the number of active cases, people discharged and cases resulting in deaths (Fig. 3). The highest number of active cases was recorded in the R/C ward (1641), followed by the R/S (1327) and K/W (1229) wards, whereas the lowest number of active cases was recorded in the B ward (129), followed by the C (241) and L (462) wards. The highest number of cases discharged was recorded in the P/N ward (7530), followed by the K/E (7413) and G/N (7102) wards, whereas the lowest number of cases discharged was recorded in the B ward (1039), followed by the C (1768) and R/N (3104) wards. With regards to the number of COVID-19 related deaths, the highest number of deaths was recorded in the K/E ward (540), followed by the G/N (506) and S (474) wards, whereas the lowest number of deaths was recorded in the A ward (72), followed by the B (93) and C (106) wards.

As a result of the growing number of cases, the municipal authorities have identified containment zones in each of these wards (Fig. 4). Containment zones refer to areas where positive cases of COVID-19 were detected and to protect everyone inside and outside from further spread of the virus, the surrounding zone covering these areas were sealed[2]. The restrictions on movement and interactions were the most severe in the containment zones with only basic supplies and services allowed inside[3]. The highest number of containment zones was in the L ward (54), followed by the R/N (53) and S (52) wards, whereas the lowest number of containment zones was in the B ward (2), followed by the H/W, G/S (6 each) and M/W (8) wards.

Along with containment zones, individual buildings were also sealed. Since apartment living is highly prevalent in

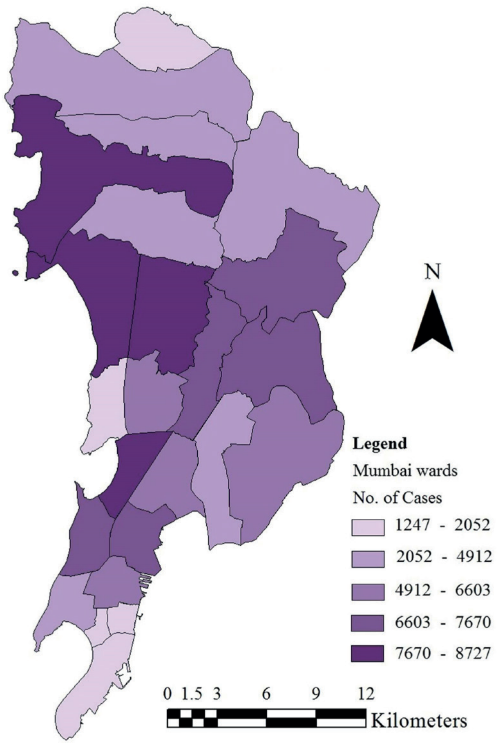

Fig. 2. Ward-wise distribution of the total number of COVID-19 cases in Mumbai
(Source: Computed based on data from MCGM's «Stop Coronavirus – With Right Information & Simple Measures: Key Updates & Trends» 2020)

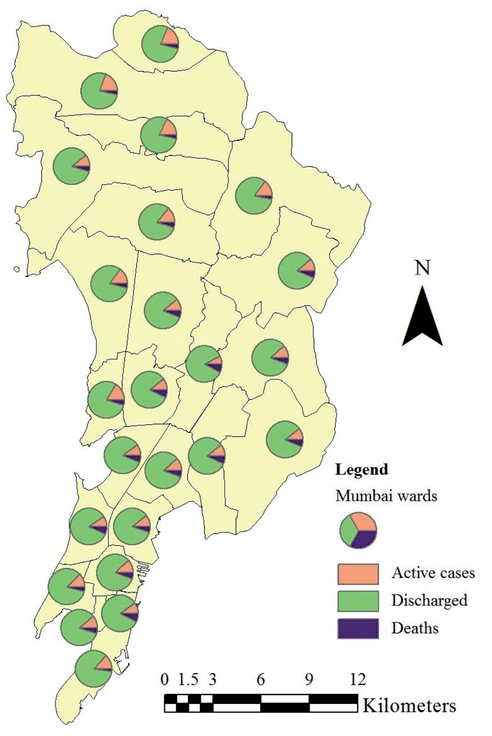

Fig. 3. Ward-wise distribution of the number of active cases, cases discharged and cases resulting in deaths in Mumbai
(Source: Computed based on data from MCGM's «Stop Coronavirus – With Right Information & Simple Measures: Key Updates & Trends» 2020)

[1] *The Hindu 2020*
[2] *MCGM 2020b*
[3] *The Indian Express 2020*

Mumbai, the civic authorities of the city have resorted to sealing buildings upon detection of positive COVID-19 cases in them. The distribution of the sealed buildings varied across the wards of the city (Fig. 5). The highest number of sealed buildings in Mumbai was in the R/C ward (981), followed by the R/S (551) and K/W (458) wards, whereas the lowest number of sealed buildings was in the E ward (37), followed by the A (56) and C (60) wards.

Linking the COVID-19 spread in Mumbai to urban density and poverty

High population density has been linked to the spread of the SARS-CoV-2 virus in India[1] (Bhadra et al. 2020). Adlakha and Sallis have however pointed towards the protective health benefits of urban density such as active lifestyle, more walkability and lower risk of chronic health diseases due to lesser use of transport, thereby refuting the notion that urban density is necessarily unhealthy[2]. The development of slums and shantytowns are a product of the rapid growth of urban centres with poor urban planning and lack of capacity to meet the needs of the growing population (Reyes et al. 2012). McFarlane notes that «The problem is not with high population density per se, but with the imbalance between good quality urban provisions – including housing, services and infrastructure – and the population density of an area»[3]. Living in impoverished slums and on streets exposes the urban poor to health issues and immunity-related challenges. People residing in the poorer neighborhoods are likely to have pre-existing health problems, as in the case of Mumbai, where in several of its slum communities tuberculosis has been found to be prevalent in large proportions[3].

Before identifying the links between the COVID-19 spread in Mumbai to the population density and poverty in the city, it is important to understand the existing state of the population density and poverty in different wards. It is a well-known fact that Mumbai is a densely populated city. As per the Census of 2011, the total population of Mumbai is 12,442,373 people[4]. The most densely populated ward of Mumbai is the C ward with a gross density of 869 pp ha, whereas the least densely populated ward is the T ward with a gross density of 75 pp ha (Fig. 6).

The fact that the COVID-19 pandemic has affected the urban poor the most has come to be recognized worldwide[3] (Tampe 2020). Unequal cities bear marks of poverty on the one hand and prosperity on the other, as in the case of Mumbai, where rags and riches reside side by side. The high concentration of slums by the side of skyscrapers bears testimony to the city's unequal character. Except for the C ward, all other wards of the city have slums. Out of 24 wards, 9 wards have more than 50% of the population living in slums. The highest share of the slums population (72.3%) is found in the S ward (Fig. 7).

Along with the slum dwellers, there is also a large number of homeless people. As per the MCGM, there are 35,408 homeless people living in Mumbai, of which the highest numbers are found in the C ward (4685) and the lowest numbers are found in the M/E ward (356) (Fig. 8). It is worth mentioning that such official statistics on the homeless population are not very reliable because the official enumeration takes place during day hours when it is most difficult to track down the homeless as they are busy earning their livelihood away from their place of stay (Sattar 2014). Nonetheless, it at least provides some idea on the current situation regarding homelessness.

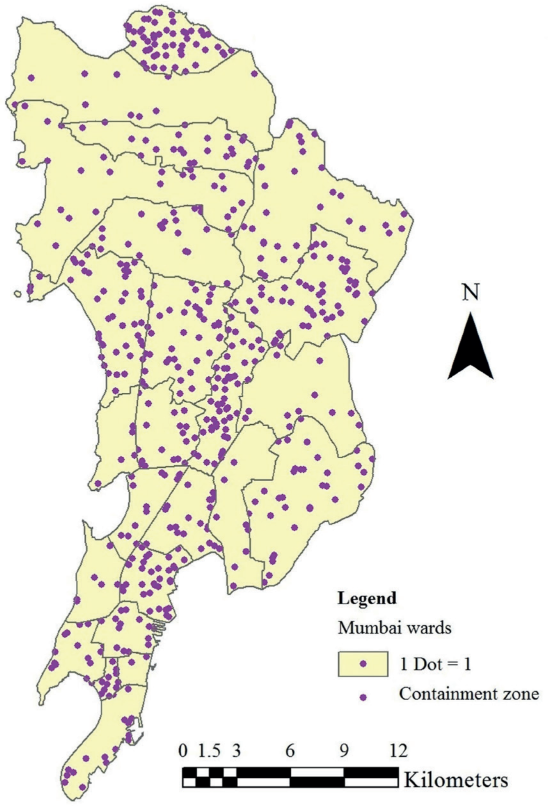

Fig. 4.Ward-wise distribution of containment zones in Mumbai
(Source: Computed based on data from MCGM's «Stop Coronavirus – With Right Information & Simple Measures: Key Updates & Trends» 2020)

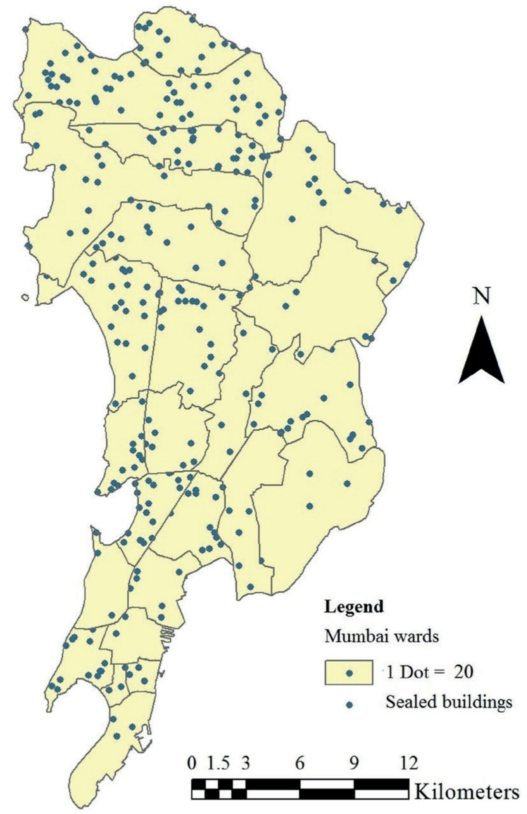

Fig. 5. Ward-wise distribution of sealed buildings in Mumbai
(Source: Computed based on data from MCGM's «Stop Coronavirus – With Right Information & Simple Measures: Key Updates & Trends» 2020)

[1] *Baggchi 2020*
[2] *Adlakha and Sallis 2020*
[3] *McFarlane 2020*
[4] *District Census Handbook: Mumbai Suburban District 2011*

To identify the relationship between the current state of the COVID-19 pandemic in Mumbai and urban density and poverty in the city, the correlation between relevant variables was analyzed (Table 1). From the analysis, a number of associations were observed. At a significance level of 0.05, a slightly strong positive correlation of 0.408 was found between the number of containment zones and slum population (%), whereas a slightly strong negative correlation of -0.409 was observed between the number of containment zones and homeless population. The positive correlation between the number of containment zones and slum population can be explained by the fact that as the slum population of Mumbai became highly affected by COVID-19, most containment zones came to be set up in and around these areas. Apart from living in congested conditions, the slum dwellers are also required to use public/community toilets and collect water from community water collection points, which puts them at greater risk of infection. The number of such public/community toilets is highly insufficient, as there is 1 toilet seat for every 75 to 100 people[1].

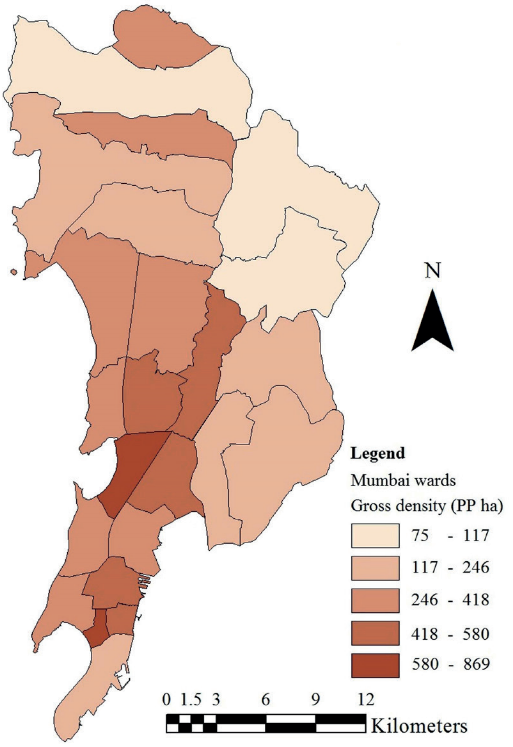

Fig. 6. Ward-wise distribution of gross population density in Mumbai
(Source: Computed based on data from MCGM's «Draft Disaster Management Plan for Mumbai City District» 2019; «Draft Disaster Management Plan for Mumbai Suburban District» 2019)

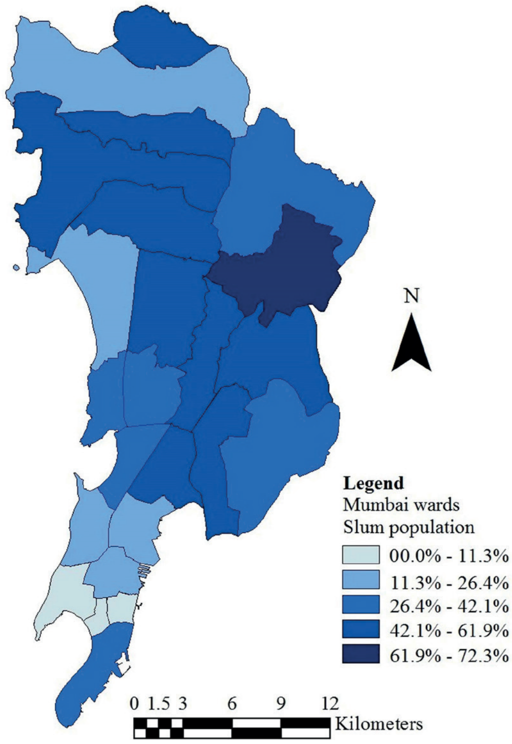

Fig. 7. Ward-wise distribution of slum population in Mumbai
(Source: Computed based on data from MCGM's «Draft Disaster Management Plan for Mumbai City District» 2019; «Draft Disaster Management Plan for Mumbai Suburban District» 2019)

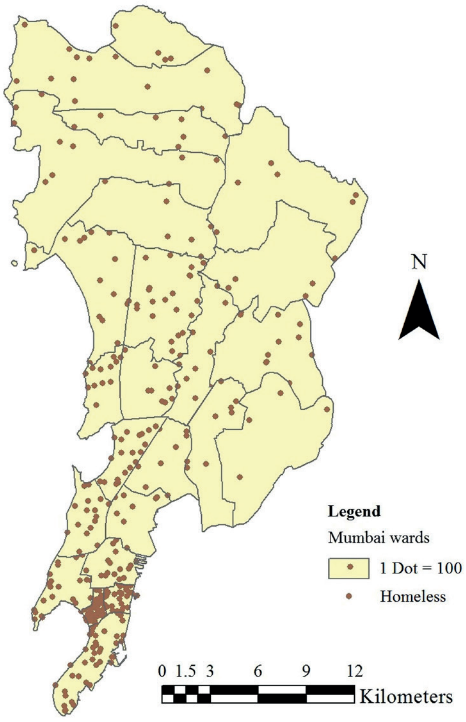

Fig. 8. Ward-wise distribution of homeless population in Mumbai
(Source: Computed based on data from «FAQ document of the Public Health Department of the MCGM», n.d.)

[1] *Karelia 2019*

Table 1. Correlation Matrix

		Containment Zones	Sealed Buildings	Total Cases	Cases Discharged	Deaths	Active cases	Gross population density	Slum population (%)	Homeless population
Containment Zones	Pearson Correlation	1	-0.005	0.346	0.347	0.34	0.201	-0.195	0.408*	-.409*
	Sig. (2-tailed)		0.982	0.098	0.097	0.104	0.346	0.361	0.048	0.047
	N	24	24	24	24	24	24	24	24	24
Sealed Buildings	Pearson Correlation	-0.005	1	0.591**	0.547**	0.119	0.888**	-0.312	0.028	-0.202
	Sig. (2-tailed)	0.982		0.002	0.006	0.579	0	0.138	0.897	0.343
	N	24	24	24	24	24	24	24	24	24
Total Cases	Pearson Correlation	0.346	0.591**	1	0.998**	0.743**	0.796**	-0.296	0.299	-0.404
	Sig. (2-tailed)	0.098	0.002		0	0	0	0.16	0.156	0.05
	N	24	24	24	24	24	24	24	24	24
Cases Discharged	Pearson Correlation	0.347	0.547**	0.998**	1	0.757**	0.759**	-0.278	0.296	-0.389
	Sig. (2-tailed)	0.097	0.006	0		0	0	0.189	0.16	0.061
	N	24	24	24	24	24	24	24	24	24
Deaths	Pearson Correlation	0.34	0.119	0.743**	0.757**	1	0.27	0.029	0.39	-0.404*
	Sig. (2-tailed)	0.104	0.579	0	0		0.202	0.894	0.06	0.05
	N	24	24	24	24	24	24	24	24	24
Active	Pearson Correlation	0.201	0.888**	0.796**	0.759**	0.27	1	-0.451*	0.165	-0.361
	Sig. (2-tailed)	0.346	0	0	0	0.202		0.027	0.442	0.083
	N	24	24	24	24	24	24	24	24	24
Gross population density	Pearson Correlation	-0.195	-0.312	-0.296	-0.278	0.029	-0.451*	1	-0.417*	.471*
	Sig. (2-tailed)	0.361	0.138	0.16	0.189	0.894	0.027		0.042	0.02
	N	24	24	24	24	24	24	24	24	24
Slum population (%)	Pearson Correlation	0.408*	0.028	0.299	0.296	0.39	0.165	-0.417*	1	-0.610**
	Sig. (2-tailed)	0.048	0.897	0.156	0.16	0.06	0.442	0.042		0.002
	N	24	24	24	24	24	24	24	24	24
Homeless population	Pearson Correlation	-0.409*	-0.202	-0.404	-0.389	-0.404*	-0.361	0.471*	-0.610**	1
	Sig. (2-tailed)	0.047	0.343	0.05	0.061	0.05	0.083	0.02	0.002	
	N	24	24	24	24	24	24	24	24	24

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).

(Source: Computed based on data from MCGM's «Stop Coronavirus – With Right Information & Simple Measures: Key Updates & Trends», 2020; MCGM's «Draft Disaster Management Plan for Mumbai City District», 2019; «Draft Disaster Management Plan for Mumbai Suburban District», 2019; and «FAQ document of the Public Health Department of the MCGM», n.d.)

Even though Dharavi has flattened the COVID-19 curve in mid-June, four of the most densely populated pockets of slums inside Dharavi, i.e. the Matunga Labour Camp, Kumbharwada, Kala Killa and Koliwada are still on MCGM's watch list[1]. To understand the negative correlation between the number of containment zones and homeless population, it is first necessary to keep in mind that the data on homeless population used in the study is in conjunction with the Census of India's definition of houseless households. It includes only those households, which do not live in buildings or census houses and rather reside in the open or near roads, places of worship, railway platforms, etc[2]. Such houseless households are highly scattered across the city and are also mobile, leading to

[1] *Eshanpriya 2020*
[2] *Census of India 2011*

their negative correlation to the spread of the containment zones. At the significance level of 0.05, a slightly strong negative correlation of -0.404 was observed between the homeless population and COVID-19 related deaths. The extent to which the homeless people, being the most neglected section of the society, are getting tested for COVID-19 is still an open question. Along with this, many of the homeless are found to shift from one locality to another, which makes it difficult to track and trace their health status along with their spatial distribution. Similarly, a slightly strong negative correlation of -0.451 is observed between the number of active cases and gross population density at the same significance level. This reinforces the fact that density per se is not necessarily the sole determining factor for the growing number of active cases. There are a number of other factors such as the immunity of people, their health conditions and prevalence of other ailments along with the extent of adherence to the social distancing guidelines that in conjunction with density contribute towards the growing number of COVID-19 cases. Fang and Wahba have rightly pointed out in this regard that densely populated urban areas may have door-to-door delivery services and access to high-speed internet, enabling the residents to avail all the necessary services without requiring them to step out of their homes[1]. Under such circumstances maintaining physical/social distance can be more convenient than otherwise. Besides these, certain other patterns were also revealed by the analysis, which are not discussed here as they are not relevant to the subject matter of the article.

CONCLUSIONS

The above analysis revealed that at the end of August 2020, the highest number of positive COVID-19 cases was recorded in P/N, K/W, K/E and G/N wards of Mumbai. The highest numbers of active cases, cases discharged and cases resulting in deaths were recorded in the R/C, P/N and K/E wards. The highest number of containment zones was in the L ward and the highest number of sealed buildings was in the R/C ward. In terms of population density, Mumbai is known to be a densely populated city and among its wards, C has the highest density. In addition to this, inequality is rampant across Mumbai. The slum population can be found in all the wards of the city except the C ward. The highest percentage of slums population is found in the S ward. There is also a large number of homeless people living in the city. All the wards of Mumbai have homeless population and the highest number of homeless corresponds to the C ward. The correlation analysis between the COVID-19 data, population density and poverty in Mumbai revealed a more detailed picture. A slightly strong positive correlation was observed between the number of containment zones and slums population, whereas a slightly strong negative correlation was observed between the containment zones and homeless population. A moderately strong negative correlation was observed between the homeless population and COVID-19 related deaths. Also, a slightly strong negative correlation was observed between the number of active cases and gross population density. These results summarize the conditions that emerged in Mumbai at the end of August 2020. Thus, the battle against the COVID-19 pandemic in Mumbai has been a mixed tale of success and failure. With the COVID-19 situation changing fast, it is difficult to say what will happen in the coming future. Nonetheless, the pandemic has exposed the deep-seated inequality ingrained in the urban structure of Mumbai. The prevalence of poverty, unsanitary conditions in the slums and lack of adequate housing have culminated in Mumbai's lack of resilience to pandemics and epidemics. Hence, with the amplification of the urban vulnerability during the pandemic, the need for revisiting and implementing the SDGs has become highly necessary[2] (Filho et al. 2020). On the positive side, the outbreak of the pandemic has stirred up the authorities and civic bodies to take necessary measures for addressing the difficulties and drawbacks that plagued the residents of Mumbai. It was realized that the successful implementation of the SDGs can save the city from such disasters. SDG 11, which aims at making cities and communities sustainable, can serve as a key in this regard. Achieving the very first target of SDG 11, i.e. 'ensuring access for all to adequate, safe and affordable housing and basic services along with upgrading of the slums', can contribute significantly to resolving the sustainability crisis in Mumbai. Along with it, ending poverty (as specified in SDG 1), making provisions for clean water and sanitation (as specified in SDG 6) and promoting decent work and economic growth (as specified in SDG 8)[3], can enable Mumbai to gain resilience and become more sustainable.[1,2]

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RESEARCH PAPER

SUSTAINABLE DEVELOPMENT: UNDERSTANDING THE LEAST RESOURCE BASE

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ABSTRACT. In the paper, the least resource base required to ensure isolated human habitat sustainability over a historically long period of time is discussed. Territory and energy are proposed as such basic resources. The analysis of isolated societies of Tasmania, the Chatham Islands, and North Sentinel Island concludes that habitat can exist long and sustainably in a local area of at least 30 square kilometres in a mode of inherent safety, without the use of artificial technologies. This conclusion demonstrates the possibility of sustainable development of human civilization as a sum of local communities in the context of the isolationism paradigm, an alternative to globalism's currently dominant concept. The significance of identifying the least resource base of sustainable development of isolated communities in the context of the establishment of scientific bases and settlements in remote areas of the globe, on the Moon and other planets of the solar system, and developing strategies to combat pandemics such as COVID-19, is highlighted.

KEY WORDS: Sustainable Development, isolationism, resource base, habitats

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INTRODUCTION

Sustainable development is the 'Holy Grail', fundamental worldview paradigm of modern civilization and one of the five most important priorities of the UN. This versatile and holistic term could be defined as «development that meets the needs of the present without compromising the ability of future generations to meet their own needs» (World Commission 1987), or «development that promotes prosperity and economic opportunity, greater social well-being, and protection of the environment» (UN.org 2017).

The vital importance of sustainability for societies, cities and humankind in general is obvious and hardly requires any elaboration. However, until now sustainable development has been more a declaration of intentions rather than established policy (Braun, Whatmore 2010). The entire history of civilization, especially modern history, looks more like a chain of severe crises rather than sustainable growth. The most recent significant global crisis is a pandemic caused by the COVID-19 virus (WHO.int 2019), which has spread throughout the world since the end of 2019. This has led to many thousands of deaths (Gisanddata.maps.arcgis.com 2020) and huge financial losses, it devastated world economy and severely impacted global sustainable development; this crisis is far from being overcome at the time of preparing this article.

There are numerous technological, political, etc. obstacles to sustainable development, but lack of understanding of the nature of biological and social processes should be considered as the most serious one. There are no satisfactory models and even comprehensive definitions of the key biological, social, or environmental concepts, systems and processes, including the definition of life itself (Pross 2011; Chodasewicz 2014). There are no theoretical models that would allow to identify possible threats and risks to sustainable development, forecast them and quantify risk factors in advance, although we live in a risk society (Beck 1992). There is no methodology to predict new types of challenges except the extrapolation of crises of the past, which inevitably leads to biased forecasting and planning. The contradiction between the obvious existence of threats and risks to sustainable development, on the one hand, and the impossibility of their scientific description, on the other hand, becomes a major factor of insufficient decision making. Demarcation of the boundaries between science and common sense (Gieryn 1999) is still an issue, which is ought to be resolved. These problems are well recognized, there are attempts to describe and categorize a wide range of possible risks and threats facing humanity, some of them are thought-provoking (Wells 2009), but inevitably speculative. The existing definitions of the term «sustainable development» are also vague, controversial and leave a lot of room for interpretation.

Inconsistency of sustainable development concept compels us to consider its premises, defaults and prerequisites, which are usually not mentioned in the definitions, but are integral and inherent parts of the whole paradigm. One of the most fundamental defaults is the concept of globalism, that could be described as a «network of connections that span multi-continental distances» (Nye 2002). Sustainable development is usually coterminous with globalism, assuming that the response to global and, therefore, universal challenges to sustainability should be universal and global as well. The intrinsic relations between the concepts of globalism and sustainable development are manifested many times – for example, from the perspective of forecasting environmental aspects of global sustainable development (Krapivin, Varotsos 2007).

Globalism as a representation of global interconnectivity and transboundary processes of commons (Middleton, Ito 2020) requires a unification of economics and cultures throughout the world. An alternative approach for ensuring sustainable development is isolationism. Possibly, effective governance should flexibly combine both approaches. Indeed, globalism implies progress of the civilization by the means of free exchange of products and sharing of the best practices for the benefit of all humankind. Instead, isolationism is focused on defending civilization through the proliferation of cultural models and, especially, preventing the spread of local crises to the rest of the world. (Heinonen et al. 2017). The vital importance of the isolation is clearly demonstrated by the fact that the global response to the severe COVID-19 crisis (Filetti 2020) and other epidemic threats (Brown, Labonté et al. 2011) leads to temporal fragmentation of the world with severe limitation of world trade and free movement of people as an ultimate remedy. In general, this isolation could be extremely long.

Therefore, it seems necessary to study the question of what is the least resource base for maintaining the sustainable development of human culture for a historically long time without the risk of its degradation. Solving this problem is important in both academic and applied aspects. Also, this research agenda matches with the Sustainable Development Goal #11 «Sustainable Cities and Communities» (sustainabledevelopment.un.org 2015).

From an academic point of view, the answer to this question will allow us to assess the lower limit for the autonomy of the human community in terms of various basic resources that are necessary to support its existence for a historically long time with the natural, risk-free processes. This data could also be valuable for designing isolated scientific bases and habitats, forecasting measures to eliminate the consequences of natural and man-made disasters, planning scientific exploration of other planets, etc.

Of particular importance in this regard is the question of the resistance of isolated settlements to factors that we cannot estimate even roughly, such as their ability to resist the combined impact of biological and societal processes: emergences of new infectious diseases, vulnerability to genetic degeneration in closed populations, sustaining cultural models, etc.

A special aspect and area of application of the results of the study is the design of habitable bases in remote areas of the Earth (in the Arctic and Antarctic, on the ocean floor, in mountainous areas), in space, on other planets, etc. Currently, the possibility and feasibility of creating long-term habitable scientific stations on the Moon and on Mars – and, potentially, on other bodies of the Solar system – is widely discussed (Cohen 2015); there is even futuristic concept design of floatable space stations for deploying in Venus atmosphere (Linaraki, Oungrinis 2013). Such stations will have to ensure the life of the teams for a long time and in conditions of complete isolation from the overseas bases. They should be resilient to a wide spectrum of external impacts, including physical ones (meteorites, radiation, etc.). Moreover, such stations may be isolated from the Earth due to numerous technical factors. There are studies of resilience aspects of long-term manned space missions (Schwendner et al. 2017; Oluwafemi et al. 2018). Nevertheless, it is necessary to consider the possibility of assuring sustainability of distant habitats in case of long-term isolation.

MATERIALS AND METHODS

Today, sustainable development is often understood in the context of technological development. Technology is thought of as an implicit background of society. This approach, however, is methodically controversial since the time horizon of technological development of mankind is quite small and its benefits are questionable to say the least. It is difficult to conclude about the long-term consequences of technological development. In this scope is reasonable to study the concept of sustainable development in the broadest possible context regardless of the technological perfection of the investigated cultures. Therefore, comparative indicators are required.

The main objective of the study is to empirically assess the lower threshold of the resource base used by an isolated community, which is sufficient to ensure its long-term sustainable development. The context of the study includes an attempt to determine which of the two possible alternatives for sustainable development – globalization or fragmentation – is the most effective strategy of ensuring the security and sustainable development of humanity in the scope of unpredictable threats, risks and challenges, as well as forecasts of the long-term consequences of the humankind development within the current technological and urban paradigm. One of the conditions for setting this task is to verify that sustainable development on a limited resource base is possible and to roughly estimate the «quantum» of the least resource base.

There are many obstacles to solving this task. The term «resource base» needs to be clarified and defined. It should be acknowledged that there is currently no comprehensive, exhaustive and scientifically substantiated list of resources required for sustainable development. It is not easy to determine the size of this resource base in the scope of trade relations with other societies. Non-intrusive study of other cultures, especially those radically different from the world's dominant ones, also poses a major challenge. Finally, any study of sustainable development requires confirmation on a significant time horizon, which exceeds that of modern science. Under these conditions, it becomes necessary to involve additional retrospective material, which becomes extremely problematic in case of isolation of the community under research.

In addition, a fully theoretical, model-based approach to solving the problem of estimation of the least possible resource base for sustainable development seems unachievable at the current level of science due to a lack of understanding of the nature of biological, social and even geographical entities and structures – especially considering the whole variety of interactions between them. (Girard 2020). Current models are hypothetical and controversial to say the least. There is no clear vision of biological and environmental factors of risks, as it was clearly unveiled by the COVID-19 and other virus pandemics and their long-term consequences for humankind.

In this situation, it seems reasonable to propose a conservative approach based on a combination of non-intrusion empirical, observational, forensic and comparative methods to roughly estimate a few vital parameters required for long-term sustainable development of existed human societies in real Earth conditions, and subsequently improve this estimate recursively.

The proposed methodology is based on the concept of inherent, or 'passive', safety as an approach for supporting sustainability only with natural resources, without any potentially vulnerable technological systems; systems should return to normal state only by the means of natural laws, without any intentional actions that involve application of external power or forces. This vision of the inherent safety concept became very popular in the modern nuclear industry as a response to the Chernobyl and Fukushima nuclear incidents. Reliance of system must be «placed on natural laws, properties of materials and internally stored energy» (www-pub.iaea.org 1991).

The use of this heterogeneous methodology requires vast interdisciplinary approach and aggregation of volumes of data that describe different aspects of human societies in a situation of complete isolation by studying in situ societies that survived isolation for a very long time.

This task is also a great challenge since it is necessary to find a culture, regardless of its technological maturity, that was sufficiently isolated socially and geospatially for long (from a historical point of view) time, but at the same time that has been sufficiently studied to prove that it is or it was isolated. Of course, both requirements contradict each other. In addition, this study can only be carried out based on modern, approved and verified data, since the reliability of historical information about isolated cultures, especially ancient ones, raises reasonable doubts.

Moreover, at present isolation is a relic, as all societies are increasingly and even definitively involved into the world governing infrastructure and interconnected as networked localities (Ito 1999) with each other by world trade, unification of the economics, migration, information exchange, adopting universal social standards and other factors.

Another challenge is identifying a set of vital measurable parameters relevant to sustainability issues. Such parameters can hardly be considered due to the difficulties of accurately measuring them in closed, isolated communities. At the same time, the assessment of community resilience to biological, medical, and genetic threats is of particular interest and is of paramount importance, since until now our understanding of the dangers of epidemics and how to counter them is formed ad hoc, based on available empirical data (Bardosh et al. 2017).

As a mandatory condition, it should be specified that a sustainable society that exists in a limited area should not use any non-renewable resources and/or materials, such as crude oil, coal, metals, etc. Also, trade, migration, etc. should be excluded.

Under these conditions, it seems reasonable to try to determine the general physical and geospatial factors that limit the effect of other factors, which could be measured empirically and using remote sensing methods. These factors should be a part of a framework and encapsulate the effect of all other factors that affect the functioning and sustainability of societies. Others factors, like cultural ones, related to maintaining a balance between natural resources and human practices (Rappaport 1984) require further research, but also deserve proper attention and relevance, especially in the context of isolated human settlements.

Therefore, it makes sense to choose two factors – one geospatial and one physical. The geospatial factor can be the area of the habitat that supplies natural resources for its existence. For the physical factor is reasonable to choose the mean amount of energy that is dissipated in this area and provides society with renewable resources. From a methodological point of view, it is possible to obtain the values of these two parameters. It is possible to determine the area, for example, using remote sensing data. The amount of energy dissipated within a given area, in the absence of significant thermal energy flows, is completely determined by the integral flow of solar energy, which depends on latitude and the season and varies slightly from year to year. The use of non-renewable energy sources in this study is excluded since it contradicts the considered paradigm of sustainable development. Nevertheless, when the analysis focuses on the human settlements on the Moon/Mars and other celestial bodies, some changes must be taken into account. Many studies related to the human exploration of space foresee the use of nuclear power to supply the necessary level of energy to the human settlements and guarantee a long period of the permanence on the celestial body. The use of such kind of energy source does not necessarily contradict with the concept of development in space. Furthermore, some energy sources which can be considered not acceptable for sustainable development on Earth may emerge as adequate for the sustainable development in space. For example, on Mars, the use of carbon dioxide, which is available in the atmosphere of the red planet and causes pollution on Earth, is essential for the production of oxygen, necessary for the life of the humans and for the process of «terraforming», which will provide Mars of an «earth-like» environment.

The list of isolated cultures that currently exist or have existed on a limited land base in the recent, well-documented past, is very short. According to some rough estimations, there are nearly 100 isolated indigenous societies in the world today (BBC.co.uk 2008). Half of them, circa 50 tribes, are situated in lowland South America (Walker, Hill 2015) and include 28 isolated settlements with a total population of about 1700 in the Amazon basin in four Brazilian states, which were unveiled by the means of remote sensing data (Kesler, Walker 2015). At least two Indian officially scheduled tribes (Tribal.nic.in 2018), Jarawas and Sentinelese, both on Andaman archipelago, remain a high degree of isolation up to now.

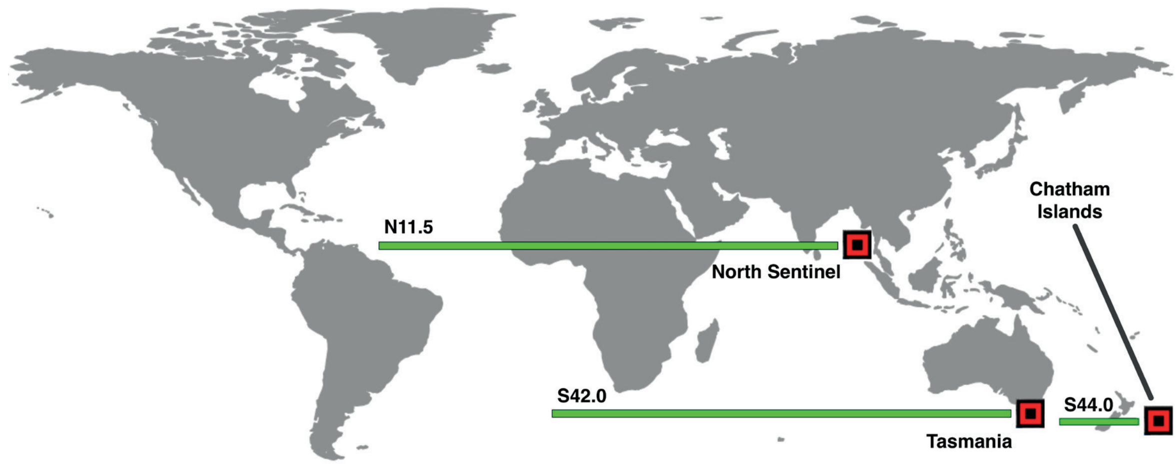

Fig. 1. Location of Tasmania, Chatham Islands and North Sentinel and their latitudes

Several presumably isolated tribes have survived in the west part of Papua New Guinea Island (Regnskog.no).

The assessment of the resource base of isolated societies living on the continental territory is extremely difficult because it is impossible to clearly identify its boundaries. In these circumstances, it makes sense to select communities existed on island territories, the area of which is easy to determine.

The study of the islands and its ecology in a non-intrusive way is currently being carried out using remote sensing methods, mainly by the space-based sensors. Currently, there is a significant and constantly growing library of data on the islands with different spatial, spectral and temporal resolutions. At present, the highest spatial resolution is provided by Maxar satellites (USA) – about 0.3 m (Maxar.com). The energy resolution of hyper-spectral imaging can reach 100 angstrom and above, imaging with a spatial resolution of half a meter can be carried out with a frequency of up to twelve images per day (Planet.com). Active radar sounding with a resolution of about 1 meter is also possible. However, these data do not allow us to sustainably observe traces of traditional culture development or, for example, to assess the population of an island.

As research objects for our purposes we have chosen the cultures that existed in not-so-distant past on the island of Tasmania (Australia), the Chatham Islands archipelago (New Zealand) and currently exist on the North Sentinel Island (India) (Fig. 1). This allows to better account for the scale factor as the areas of the respective island territories differ by about two orders of magnitude (Fig. 2).

Tasmania Island

Tasmania Island (in fact, it is an archipelago of more than three hundred islands) is located to the south of Australia mainland (S42, E147) and is separated by the 200 km wide Bass Strait. Area of Tasmania is approximately 65 thousand sq. km, it is 26th largest island in the world. There are mountains (the highest point is 1617 m), rivers, and lakes. There are no active volcanos on Tasmania today.

Tasmania has a cool temperate climate with four distinctly separated seasons, which significantly varies across the island. The lowest recorded temperature was -14.2C, the highest temperature was +42.2C. Nevertheless, the temperature in the coastal regions rarely drops below freezing, and daily temperature variations are also quite small. There are indicators that Tasmania's climate during last 1000 years has changed repeatedly with the minimum (characterized by the average temperature of 2C lower than at present) circa 1050AD (Saunders et al. 2013). Significant biodiversity of the island is supported by the mountain region in the West and high variability in precipitation patterns. There is extremely diverse vegetation, some plants are unique. The island is well-known as a home for many endemic mammals, some of which are partly extinct by now.

The island was populated by Australian aboriginal people around 40 thousand years ago via a natural bridge, that connected Australia and Tasmania at that time. Later, once the sea level rose, the bridge was destroyed, and the local population was completely isolated from the continent for approximately 8,000 years, until the period of European exploration, British colonization and penetration of modern western culture at the turn of the 18th and 19th centuries, which broke the isolation and destroyed the unique culture of the local aboriginal society that sustained all that time. The population of Tasmania island during isolation epoch is roughly estimated at the level of 3,000 – 5,000 with the mean value of 4,000. There were 9 tribes on the island, which consisted of 50 to 85 different 'bands'; each band occupied territory 500-800 square kilometers and each tribe occupied territory 2,500-8,000 square kilometers (Jones 1974).

Chatham Islands archipelago

Small and dense, the Chatham Islands archipelago is located in the southern part of Pacific, 800 km to the East from Northern Island of New Zealand (S44, W176). The archipelago consists of dozen islands including two relatively big and populated. The total area is near 1,000 square kilometers. The last signs of volcanic activity on the islands date back to the Cretaceous period. The highest point of the main island is about 300 m; there are streams and many big lakes.

The Chatham Islands are characterized by an oceanic, cool and windy climate with small temperature variations and frequent rainfall. The record high temperature was 23.8C, the daily mean temperature is 11.5C. Snowfall is extremely rare but was registered in 2015. Regardless of harsh conditions, the ecosystem of the archipelago is quite diverse – there are dozens of endemic plants, many endemic birds (partly extinct). Chatham Rise acts as a source of food for fish and marine mammals.

The Chatham Islands is well known as a location of sustained aboriginal Moriori tribe that developed a unique culture based on the fundamental idea of pacifism and

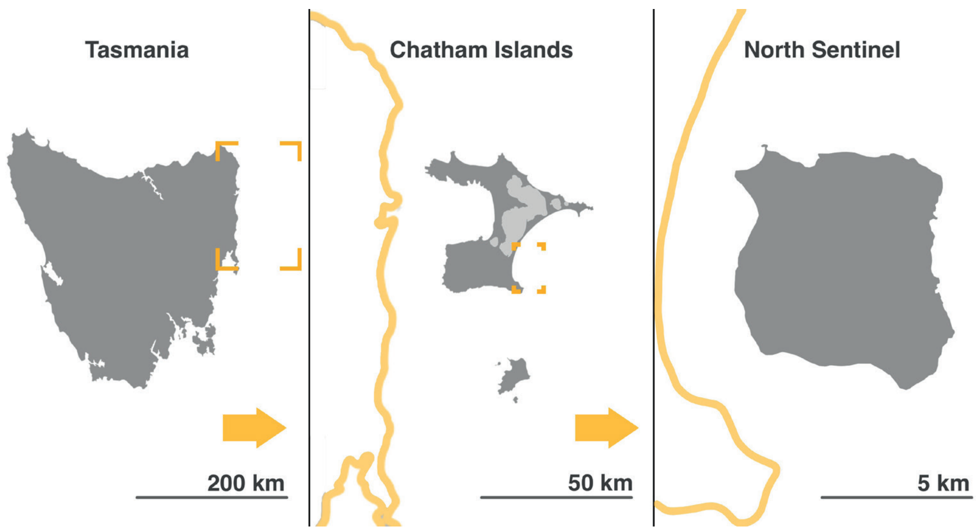

Fig. 2. Comparing of areas (left to right): Tasmania, Chatham Islands and North Sentinel

rejection of violence; in the 19th century, Moriori culture was destroyed as a result of the genocide (Brett 2015). The origin of Moriori remains debatable. According to some studies, ancestral Moriori were Polynesians and arrived to the Chatham Islands between 1200 and 1500 AD. Therefore, Moriori culture existed in isolation for more than 300 years and sustained at least for dozens of generations. Isolation was enhanced by the remoteness of the archipelago and the severity of conditions atypical for the area of settlement of Polynesians. The population of Moriori people on the Chatham Islands during their isolation is estimated as 2,000 people (Blank 2007).

North Sentinel Island

One of the rare and most impressive examples of a tiny local culture, which at the beginning of the 21st century is still isolated from the outer world and has survived successfully, is a culture of North Sentinel Island in the Andaman archipelago (Bay of Bengal, Indian Ocean). The area of this small, square-shaped island, bordered by a coral reef, is less than 50 sq. km, length of the coastline is less than 30 km. North Sentinel Island is clearly visible on satellite images (Fig. 3 a, b), provided by Proba satellite (Esa.int 2005), and EO-1 satellite (NASA). The island is located in a tropical region, N11.5, E92.2, and is completely covered by dense wet evergreen forest. There are no lakes, no rivers, no mountains (the elevation of the two highest points – Northern Hill and Southern Hill is both roughly estimated at 122 m) and no signs of volcanic or thermal activities on the island. Distance to the closest island in the Andaman archipelago is quite small – North Sentinel Island is located less than 30 km to the west from the southern part of South Andaman. Despite the tiny size of the island, it is inhabited (Venkateswar 1999). The local population, called 'Sentinelese', is still largely unknown (ncst.nic.in 2017). Cultures of the aboriginal people of the Andaman Islands are isolated, according to some estimations, for around 60 thousand years (Jobling 2012), although a few unsuccessful documented contact attempts, and even military expedition to the island in 1880, were made (Hamilton 2018). The population of North Sentinel Island is unknown too; there are estimations of the current population ranging from 100 to 150 (and even up to 500), which periodically decreases down to 50. Nevertheless, society has developed its own sustainable and unique culture. At least core concept of that culture – hostility to aliens – is inherited and sustained for a long time. At the same time, Sentinelese society shows the ability for innovations (Hamilton 2018).

North Sentinel Island is vulnerable to a wide spectrum of natural threats – for example, forest fires. Island was severely impacted by the 2004 «Christmas» tsunami. Lifting of the tectonic plate by 1-2 meters has changed the coastline, subsequently increasing the area of the island, dried coral reef around the island and vanished the shallow lagoons. Due to the limited population and dependence on the environment, island inhabitants are critically vulnerable to various biogenic risks such as diseases, infections, genetic degradation risks, etc. However, the long-term sustainable existence of the population indicates that these risks can be overcome for a community that exists on a resource base of the North Sentinel Island.

RESULTS

The data in the form of population/area and specific population density/area graphs for the three selected examples are shown in Fig. 4 (a, b).

Surprisingly, the data indicates that the smaller area (in case of the Chatham Islands and especially North Sentinel Island) supports the stable existence of a much more

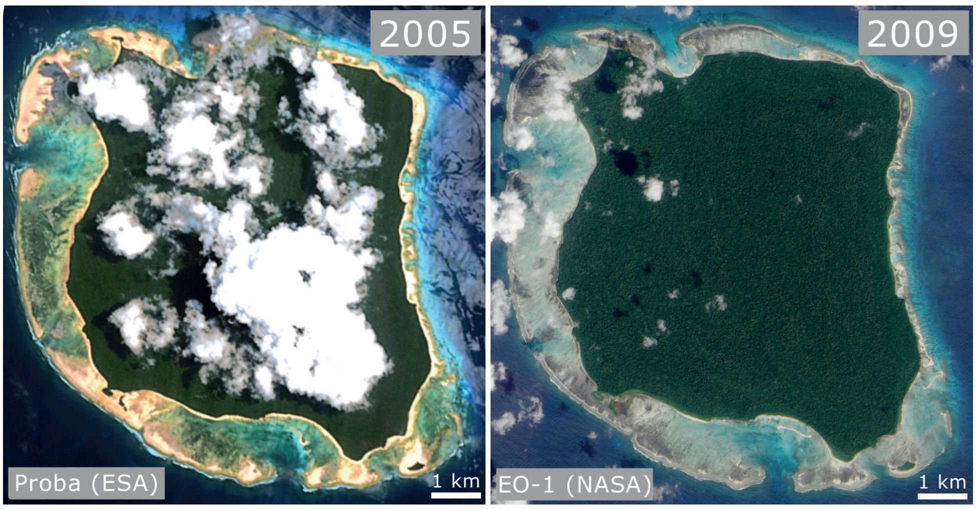

Fig. 3. (a, b). (Left to right) Satellite images of North Sentinel Island: a) Made on April, 23, 2005 by Proba satellite (ESA) after the 2004 «Christmas» tsunami; made on December, 31, 2009 by EO-1 satellite (NASA)

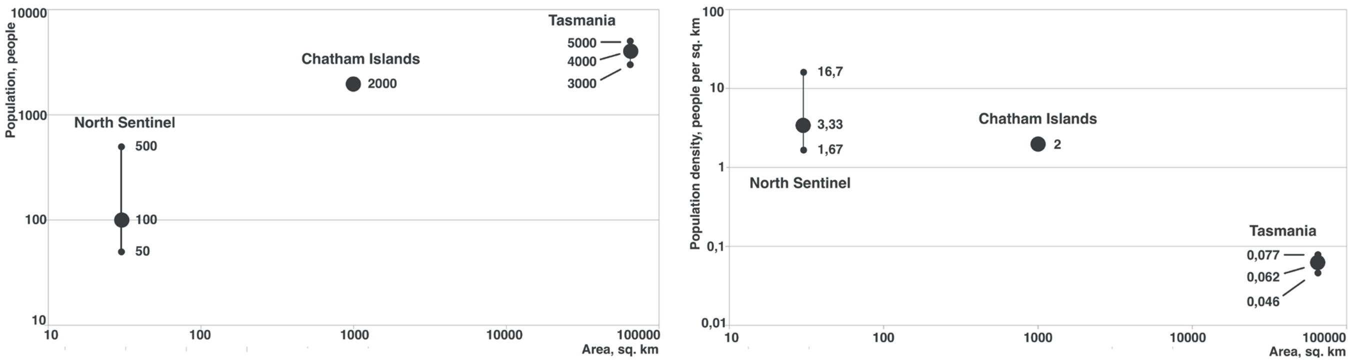

Fig. 4. (a, b). Population/area (a, left) and population density/area (b, right) graphs for isolated sustained societies in Tasmania, the Chatham Islands and North Sentinel Island. Both axes on both figures are logarithmic

densely populated society. This may be due to errors in population estimates or their interpretation. However, it is more likely that this effect is related to the availability of marine resources, which are particularly effective in ensuring the sustainable existence of societies; their relative importance increases as the size of the island decreases causing a relative increase in the length of a coastline section per unit area. When taking into account the water area necessary for the sustainable existence of communities, it can be assumed that it is approximately equal to the share of the world's oceans that falls on the area of the washed island multiplied roughly by a factor of three.

Therefore, we could assume that a resource base with a land area of about 30 square kilometres and a water area of about 90 square kilometres, located in tropics, at 11 degrees latitude, could provide sustainable reproduction of renewable resources, sufficient to ensure the long-term existence of the human community on a historical timescale.

By knowing the average density of solar energy per unit surface area and time, and assuming that this parameter is constant, we can determine the amount of energy needed to maintain biodiversity and ensure sustainable development of society in an isolated area at 11 degrees latitude. According to current measurements, the solar constant – or, more accurately, total solar irradiance (TSI) – is 1361W/m2 and varies over time by less than 1 percent (Kopp et al. 2005). Assuming Earth's albedo is around 0.3 (Rosenbaum et al. 2018), the energy flow of 120 GW is enough for assuring long-term sustainable development of a closed society (Table 1). The population of society in this case could be estimated as 100 people (Fig. 5).

DISCUSSION

Assessment of the least resource base for sustainable development of isolated communities is complicated by the methodological and technical difficulties that were already mentioned above briefly.

From the methodological point of view, it is necessary to consider the applicability of the idea of a «resource base» and its suitability in the context of the research. The idea that the biosphere can be separated into fragments to support independent evolution of several isolated communities is only an assumption. It is quite obvious that this idea is an implementation of a broader methodological concept of «close-range interaction», or the dominance of local factors over global ones. This vision is widely accepted, for example, in epidemiology. Nevertheless, the prevalence of the local specific factors over the global non-specific ones is discussable and should be critically considered.

Another methodological problem is the identification of the pivotal factors of the sustainability of a social system. In this study, space (area) and energy are proposed as essential ones. This assumption fits well with the current worldview, but it also needs to be verified, critically analysed and possibly refined. In any case, both factors are framework only and the future research should investigate such factors as the spectrum of electromagnetic radiation, magnetic field, mineral composition, etc.

Technical difficulties include the need to use a retrospective approach and, therefore, to use the assumption of stability of measured parameters over long time horizons. The stability of territories in space seems to be quite obvious. At the same time, the long-term stability of the solar energy flow is a conclusion that follows from

Table 1. Least resource base required for sustainable development of isolated society

Parameter	Value	Units
Total Area	120	Square kilometers
Land Area	30	Square kilometers
Water Area	90	Square kilometers
Energy Flow	120	GW
Population	100	People
Population Density	3.3	People per square kilometer

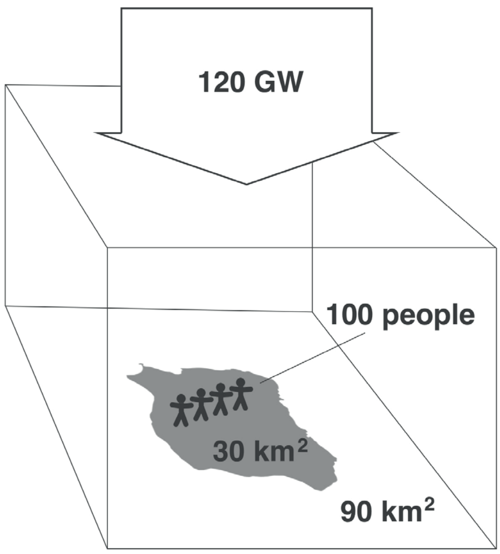

Fig. 5. Visual representation of least framework parameters required for sustainable development of an isolated society

the assumption that the sun is an absolutely black body. In this case, its luminosity, in accordance with the law of Stefan-Boltzmann, depends on the temperature and surface.

Despite the satisfactory accuracy of the proposed estimates of the area and energy density required to maintain sustainable community development in a limited area, this system is not closed. It is submerged in the environment of the ocean and atmosphere, from which it receives a significant and possibly vital part of the resources. Therefore, in further studies of this kind, it is necessary to quantify these factors.

Comparing the universalism-isolationism as two scenarios for sustainable development of humankind is also a challenge. The concept of globalism undoubtedly dominates today, but the vulnerability of global society, primarily to biological and social threats, is evident. This vulnerability was demonstrated by the 2020 COVID-19 pandemic. On the other hand, it is not quite clear whether the sum of isolated societies will be a more successful and more resilient alternative to universalism.

Presumably, the most striking example of the importance of the proposed approach is the deployment of isolated settlements in an unfavourable environment, primarily on other planets. Under these circumstances, providing the minimum territory and energy required for sustainable development of a society becomes the most important and universal factor. The most actively discussed option for such settlements are settlements on the Moon and Mars. In this case, it is possible to consider the settlement on Moon/Mars as an insulated system and the «area – energy density» parameters can be a good starting point for the analysis of the sustainable development. In conditions of physical isolation from the Earth and radically different environment, ensuring the minimum resources necessary for the sustainable development of a settlement when transport links with the Earth are terminated is seen as a critical task. Another aspect of the study of the smallest resource base for sustainable development is the theoretical aspect. The study of management experience and practical approaches to ensuring sustainable development, practiced in ultra-compact communities, is an important source of knowledge about the nature of the biological and social factors.

It must be taken into account that this assessment is a part of a much broader interpretation of the meaning of the «sustainable development» concept than the currently dominant one. The validity of such an interpretation needs to be critically considered. Nevertheless, the intensifying signs of growing instability of the human community in the context of epidemic threats like COVID-19, caused by globalization, and the constant need for a regime of isolation to prevent such threats indicate that an expanded interpretation of the term «sustainable development» is feasible.

CONCLUSIONS

The work assessed the least resource base in terms of minimum area and energy flow required to maintain long-term sustainable development of an isolated society. For this purpose, the available empirical material on three cultures was analysed: the Tasmanian and Chatham Islands aboriginal tribes, which existed in isolation until the beginning of 19th century, and the North Sentinel Island society, which exists in complete isolation today and is one of the last cultures of that kind in our era of dominant globalization. The analysis showed that an island area of 30 square kilometres, receiving 120 GW of solar energy, is sufficient for sustainable development of an isolated community with an estimated population of 100 people for at least many centuries. At the same time, an isolated community in these circumstances turns out to be capable of technological development, ensuring sustainable maintenance of basic cultural attitudes and reliable protection from various threats and risks of natural origin – from natural disasters to epidemic and somatic diseases and genetic degradation – within the concept of inherent safety. Therefore, a sufficient level of resilience could be achieved on the relatively modest resource base. This assessment is crude, preliminary and purely empirical. However, it already allows to assess the minimum requirements for maintaining a long (for many generations) existence of a community in complete isolation when there is no contact with human civilization, for example, in the case of settlement on another planet. In addition, this assessment raises the question of the feasibility of searching for theoretically possible alternatives to globalism due to the revealed vulnerability of the global community to threats and risks spreading across the planet, especially biological threats. ■

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RESEARCH PAPER

MEASURING AND MAPPING THE STATE OF FOOD INSECURITY IN RAJASTHAN, INDIA

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ABSTRACT. Food insecurity is a global issue that persists at various scales and intensity. It is linked to irregularity or uncertainty of food, water and fuel and can develop under the influence of multiple factors. Food availability, accessibility, consumption and stability are the four broad dimensions of food security. This paper analyses the relationship between these four dimensions and food insecurity for 33 districts in Rajasthan, India, using the data collected from the published documents, periodicals and websites of the government or other authentic sources. To analyse the link between these four dimensions, several indicators were taken into consideration. The collected data was used to rank the districts based on their level of food insecurity. Thus, the results include categorization of the districts into four zones based on the values of the variables. The results are presented through maps, which show the spatial distribution of food insecurity. It can be concluded, that the districts of Banswara, Dungarpur, Udaipur, Bharatpur, Rajsamand, Dhaulpur and Jalore have a very high level of food insecurity.

KEY WORDS: Food Insecurity, Food Unavailability, Food inaccessibility, Inadequate consumption, instability of food

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INTRODUCTION

Food security is on the global agenda of all the nations, which focuses on achieving the target of zero hunger and providing all people with sufficient and nutritious food. Ensuring the necessary quantity and quality of food has become a big challenge especially in developing and underdeveloped countries. Food provides a human body with energy and helps to maintain the immune system, while its unavailability can cause malnourishment and hunger. In extreme cases, food insecurity can also lead to deaths due to famine and droughts. This paper analyses the concept and measurement of food insecurity as well as spatial variation of food insecurity in Rajasthan, India. Rajasthan, being mostly a semi-arid region, needs to be dealt with special priority and caution. The spatial variation of food insecurity includes differences in the severity of the problem and proportion of population effected (Ilaboya et.al 2012), which should result in the policies that are based on the geospatial variation of the phenomenon. The SDG 2 states, that ending hunger, achieving food security and improved nutrition and promotion of sustainable agriculture is one of the major goals for the world to attain, especially in the developing countries.

Concept of Food Insecurity: a wider perspective

The food security is not just about non-availability of food, it is also linked to its non-accessibility and unaffordability, which are also affected by the uncertainty factor. Therefore, for understanding the concept of food insecurity, the related concepts of food unavailability, inaccessibility, unaffordability and instability should also be considered. Regarding the first three important parameters, FAO's The State of Food security (2001) provides the following definition of food security:

«Food security [is] a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life».

Nord, Andrew and Carlson (Nord et. al 2005) have defined food insecurity as disruption of food intake or eating patterns because of lack of money and other resources. The US Department of Agriculture (USDA) in 2019 defined food insecurity as a lack of consistent access to adequate food for an active, healthy life.

Based on these definitions, it can be observed that there are various aspects linked to food security:

1. Physical, Social and Economic Access
2. Sufficient, safe and nutritious food
3. Dietary needs and food preferences
4. Active and healthy life

The multidimensional and multifaceted concepts associated with food security make it very complicated and even more challenging to accomplish the goal of zero hunger. The concept of Food Security has four dimensions (Fig. 1):

Food availability focuses upon the supply side i.e., the food grown or imported and exported from a region. This means that it characterizes the available food stock and net trade of food commodities in a region.

Food accessibility covers more than just the availability or existence of food. It indicates both physical and economic opportunity of a consumer to obtain or

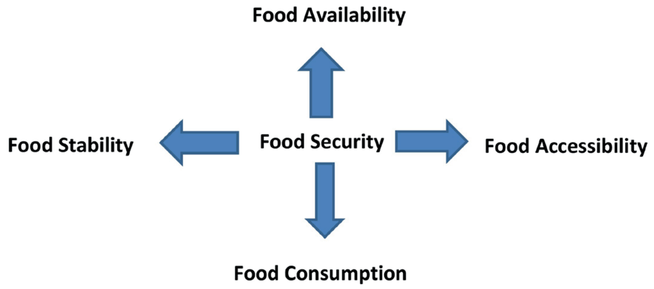

Fig. 1. Dimensions of Food Security

to buy food and characterizes the means by which it reaches people as the mere existence of commodities cannot ensure that the food produce will eventually be consumed or not.

Food utilization again extends the concepts of availability and accessibility. The human body will remain healthy only when it is able to consume a sufficient amount of nutrients. Therefore, the biological utilization of nutritious food is definitely a major dimension of food security.

Food stability is yet another important dimension. The human body needs nutritive food on a regular basis, but due to sudden disasters like flood, famine, etc, the regular supply of food could be interrupted. Food instability can also occur due to various economic factors, which include price or income fluctuations. As a result, food security will not be achieved if at any given point in time the consumer is unable to have access or is unable to consume sufficient amount of food. Therefore, food insecurity can be defined as failure to ensure any of the four dimensions outlined above.

Food Insecurity = f $(FA+FA+FC+FS)^{-1}$

Types of Food Insecurity

Food and Agricultural Organization identifies three types of food insecurity:

1. Chronic Food Insecurity: Chronic food insecurity exists when an individual is constantly deprived of nutritious food. This can be due to poverty, lack of assets, insurance or loss of property etc. It is a situation that persists for a long period of time and can be improved by providing people with education, regular income and insurance rather than by short-term solutions.
2. Transitory Food Insecurity: Transitory food insecurity is a short-term or sudden situation of food deprivation. This can occur due to crop failure, prices or family income fluctuations, political unrest etc. This type of insecurity can be managed by short-term price corrections or policies.
3. Seasonal food insecurity: This is the third type of food insecurity which, can have an annual reflection but is seasonal in nature. It can be related to seasonal unemployment or non-availability of food. It is predictable and cyclic and can be managed by storing food or finding alternative employment opportunities.

Human health, food security and environmental sustainability are linked by complex and multidirectional patterns and present interrelated challenges in the current context. While the world currently produces enough food to feed everyone, over a billion people do not have access to adequate food. As of 2010, a total of 925 million people suffered from chronic hunger: 578 million in the Asia Pacific region, 239 million in Sub-Saharan Africa, 53 million in Latin America, 37 million in North and North East Africa, and just a little over 19 million in the developed countries (Shah 2013). About 870 million people are estimated to have been undernourished (in terms of dietary energy supply) in the period 2010–2012. This represents 12.5 percent of the global population or one in eight people. The vast majority, 852 million, live in developing countries, where the share of people undernourishment is now estimated at 14.9 percent of the population (FAO 2012). The food insecurity, on the other hand, occurs when there is lack of availability of sufficient, safe and nutritious food.

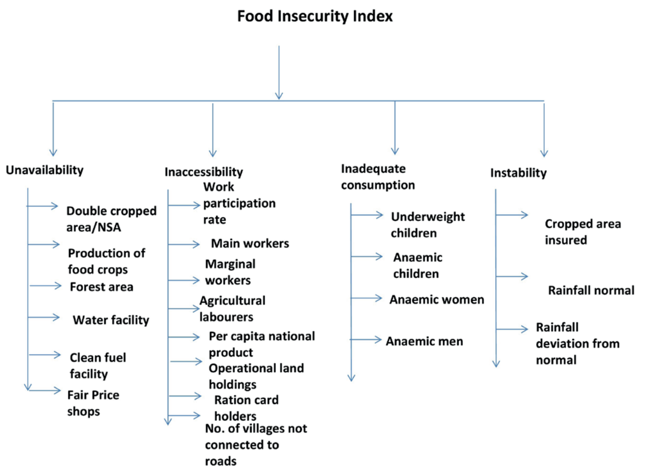

Fig. 2. Food Insecurity Index

Food insecurity is defined by the United States Department of Agriculture (USDA) as a situation of "limited or uncertain availability of nutritionally adequate and safe foods or limited or uncertain ability to acquire acceptable foods in socially acceptable ways" (Bickel et.al 2013). This definition not only focuses upon the aspects of nutrition i.e., related to food consumption but also on the social acceptability of the food. This includes the availability of indigenous food produced and consumed in that region, especially in rural areas. In urban areas, new forms of food that become socially acceptable also need to be available on the market.

According to an estimate by United Nations, in India, 195 million people are undernourished, which accounts for nearly one quarter of the global population with undernourishment, and 4 out of 10 children are undernourished or stunting (https://in.one.un.org/un-priority-areas-in-india/nutrition-and-food-security/). Based on several studies it was highlighted that the states of Bihar, Jharkhand, Rajasthan, Chattisgarh, Madhya Pradesh, Uttaranchal and Odisha are marked by severe food insecurity. The small size of the agricultural landholdings, low area of agricultural land per capita and prevalence of traditional forms of agriculture affect the availability of sufficient food.

Study Area

Rajasthan is the largest state of India in terms of area and seventh largest state in terms of population. It is located in the north-western part of the country, at latitude 27.391277 and longitude 73.432617. Rajasthan has seven divisions and thirty-three districts. There are four major physiographic regions, namely (i) the western desert with barren hills, rocky plains and sandy plains; (ii) the Aravalli hills running south-west to north-east; (iii) the eastern plains with rich alluvial soils; and (iv) the south-eastern plateau. The state is drained mainly by three rivers: Mahi, Chambal and Banas.

The climate varies from hot and dry in the west to humid in the eastern part of the state. In summer the temperature varies between 32° to 45°C whereas in winter it ranges from 4° to 28°C. Nearly 90 percent of the rainfall occurs in monsoon months, the average annual rainfall ranges between 200-400 mm getting as low as 150 mm in extremely dry zones. One other peculiar characteristics of the climate in Rajasthan is the frequent occurrence of droughts. Drought occurs almost once every three years (Bansil 2007) and sometimes the frequency is even higher. Scanty, low and irregular rainfall contributes to the proliferation of droughts. The scale of famine due to failure of monsoon and consequent water stress causes severe hardship to humans and livestock. The districts of Barmer, Jaisalmer, Jalore, Jodhpur and Sirohi experience it once every three years. Ajmer, Bikaner, Bundi, Dungarpur, Sriganganagar, Nagaur, Hanumangarh and Churu experience drought once every four years.

According to the Census of India: Administrative Atlas, 2001; Bhalla (2011) the state can be divided into four major physiographic divisions, namely, the Western Sandy plains, Aravalli and hilly regions, Eastern plain and Hadoti plateau. The 33 districts of Rajasthan belong to one of these regions. The Western Sandy desert can be further divided into the Sandy arid and semi-arid plains. The micro-regions of Marusthali and Dune free tracts are part of the Sandy plain. The semi-arid plain consists of 4 micro-regions: the Luni basin, Shekhawati region, Nagauri Upland and Ghaggar plain. The Aravalli and hilly range covers Alwar hill, the Central Aravalli range, Mewar rocky range and Abu block region. The Eastern plains comprise of the Chambal basin, Banas basin and Mahi plain. Hadoti plateau includes two micro-regions: the Vindhayan scrap land and Deccan Lava plateau.

The population in the state of Rajasthan is unevenly distributed and agriculture is still the most dominant economic activity. Therefore, the extension of alluvial plains and water availability remain as the underlying factors of population distribution. The urbanization in Rajasthan has always remained below the national average. According to the census of 2011, 76.62 percent of the state's population resides in rural areas. Agriculture and industry, particularly handloom and handicrafts, play a significant role in terms of employment and income in the state.

MATERIAL AND METHODOLOGY

To analyse food insecurity at the district level the Food Insecurity Index has been formulated depending upon the data availability for the year 2018–2019. The data has been acquired from Census of India publications, Statistical Abstract of Rajasthan 2018, Agricultural abstract of Rajasthan 2018. Data has also been acquired from some official government sites, such as www.pmfby.rajasthan.gov.in 2016–2017, food.raj.nic.in, rainfall-water.rajasthan.gov.in etc.

The study is based on robust data that was either taken as it is or was converted into a percentage or ratio. The acquired data was then processed and analysed according to the four dimensions of food insecurity, namely Food unavailability, Food inaccessibility, Food inadequate consumption and Food instability (Fig. 2). The various variables were then ranked according to the value they reflect. The following variables were taken to examine each dimension:

Food unavailability: Double cropped area/net sown area, production of food crops (both cereals and pulses), forest area to reporting area, households with

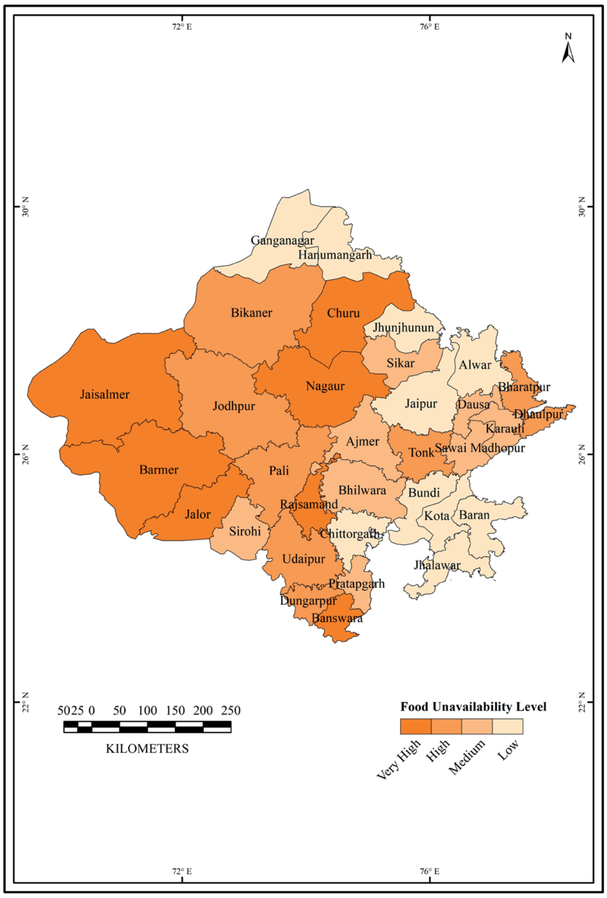

Fig. 3. Food Unavailability

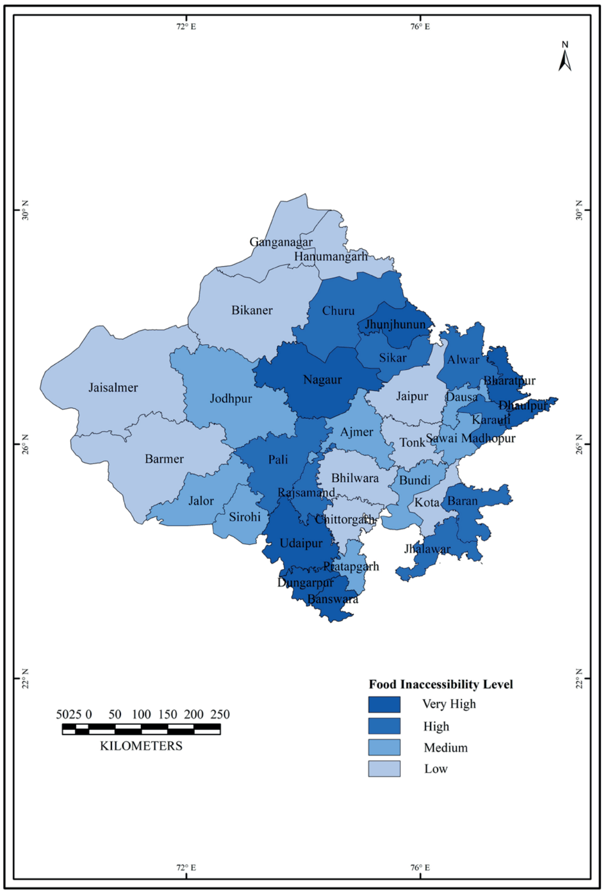

Fig. 4. Food Inaccessibility

improved water facilities, households using clean fuel and population per Fair Price Shop.

Food Inaccessibility: Food inaccessibility was examined based on work participation rate, main working population, marginal working population, number of agricultural labourers, per capita national product, the average size of operational holdings, number of ration card holders and number of villages not connected by roads.

Food inadequate consumption: Food consumption characteristics were also based on the available data i.e., underweight children below 5 years of age, anaemic children below 5 years, anaemic women between 15-49 years of age and anaemic men between 15-49 years of age.

Food instability: There was not much data available on this dimension, so the rainfall data was used as an important indicator as Rajasthan is mostly a semi-arid area and most of the rainfall happens in monsoon. The agriculture is mainly depended upon rainfall and the impacts of rainfall variability are threatening food production systems, leading to losses of livelihood and food insecurity (Murali and Afifi 2013). Crop insurance can be another important indicator as it can provide some security to farmers at the time of crop failure, allowing them to protect against poor harvests and adapt to a changing climate. So, two indicators i.e., total cropped area insured and rainfall normal and deviation from normal (2018) were used in the analysis.

Once the data was collected, the districts were then ranked based on the values of the parameters. Rank 1 was given to the district that was characterised by the highest food unavailability, inaccessibility, inadequate consumption and instability. The highest rank i.e., 33 was given to the district which had the lowest values of food insecurity parameters in each category. Later the ranks were added to find the final scores for each dimension and food insecurity as a whole. Maps are used to depict the geospatial pattern of the food insecurity and its various dimensions.

RESULT

Food insecurity is a multifaceted and multifunctional concept and its complex nature makes it challenging to analyse. The data, which was used to calculate and analyse food insecurity in Rajasthan at the district level, was acquired through numerous authentic published sources. The main limitation was thus associated with the limited availability of relevant and related data. Nevertheless, full care was taken to use the most relevant data.

Food unavailability

This dimension was evaluated by considering 6 factors. The availability of food can be easily characterized by its production and area under cultivation. It can be assumed that the type of food crops grown in the region are mostly the ones that are generally consumed by people and are a part of their staple diet. Besides, one also needs safe drinking water as it constitutes a major part of the human diet and is also needed to cook food. Clean fuel is another important input as its availability also ensures the availability of consumable food items. Forest area is also considered to be important as its resources contribute to the available food as well. In the areas where food crops are not grown in sufficient amounts or some items are not available, Fair Price Shops (FPS) also ensure the availability of food.

Considering all six factors, it was found that the districts of Barmer, Jalore, Churu, Rajsamand, Banswara, Jaisalmer and Nagaur lie in the very high food unavailability zone. Barmer has the lowest double-cropped area and therefore the lowest production of food crops. Most of such areas lie in either southern part of the state or in Mewar region. The districts of Bharatpur, Jodhpur, Tonk, Bikaner, Dhaulpur, Udaipur, Dungarpur and Pali lie in the high food unavailability zone. Bhilwara, Pratapgarh, Sawai Madhopur, Karoli, Sirohi, Ajmer, Sikar and Dausa lie in the moderate food unavailability zone. Alwar, Hanumangarh, Jhunjhunu, Ganganagar, Chittorgarh, Jhalawar, Jaipur, Kota, Bundi and Baran have high food availability. In Baran, the double-cropped area per net sown area is more than 89 percent and Ganganagar has the highest food grain production of all districts. Karoli has nearly 34 percent of its area under forest. Alwar and Kota have high share i.e., more than 96 percent, of households with safe drinking water facilities followed by Hanumangarh, Dausa and Jaipur respectively. Jaislmer, Naugaur, Bansawar have less than 70 percent and districts like Barmer and Bharatpur have around 75 percent of households with safe drinking water facilities. In Kota (66 percent) and Jaipur, more than 54 percent of households have safe clean fuel available for cooking. Bansawar (12.6%), Pratapgarh (13.6%), Karoli (14%) are marked by the lowest share of households with clean fuel available. Analysing the number of people per Fair Price Shop (FPS) it can be seen that Ganganagar has 20,300 people per FPS while Bikaner has around 5030, Churu has 4678 and Jaipur has 3421. The lower is the number of people per FPS, the better is food availability in the district. For example, Baran has 1830 people per FPS, Jaislmer has 1994, Chittorgarh has 2175 (Fig. 3).

Food Inaccessibility

The dimension of food accessibility was measured using eight indicators, namely work participation rate, the proportion of main workers, marginal workers and agricultural labourers, per capita national product, the average size of operational holdings, the number of villages connected by roads and the number of ration card holders. It was attempted to analyse the accessibility from both physical and monetary perspective to highlight the ease of access and affordability of food. Connectivity by roads ensures the physical accessibility of food. Similarly, ration card holders also have access to food items at an affordable cost. The jobs of people also reflect their ability to afford food.

The districts of Bharatpur, Dungarpur, Udaipur, Dhaulpur, Banswara, Nagaur and Jhunjhunu have very high food inaccessibility. The districts of Sikar, Pali, Karoli, Alwar, Baran, Churu, Rajsamand and Jhalawar are characterized by high food inaccessibility. Jodhpur, Ajmer, Sawai Madhopur, Bundi, Dausa, Jalore, Sirohi and Pratapgarh have moderate food accessibility, while Jaisalmer, Kota, Jaipur, Barmer, Tonk, Bikaner, Ganganagar, Bhilwara, Chittorgarh and Hanumangarh have low food inaccessibility. The work participation rate is the highest in Pratapgarh, Chittorgarh, Bansawar. The share of main workers is the highest in Jaipur, Chittorgah and Ajmer i.e., above 80 percent. The share of marginal workers is the highest in Dungarpur district with 66 percent and in Banswara and Udaipur it is around 41 percent. Marginal workers and agricultural labourers are the people with lower guaranteed income. The ratio of agricultural labourers is the highest in Baran (33 percent), Jhalawar (30 percent) and Dungapur (29 percent). The lowest share of agricultural labourers is observed in Jaipur, Jhunjhunu and Sikar, where it does not exceed 9 percent. Per capita national product (at current prices) is high in Jaipur, Alwar, Ganganagar, Kota, while in some districts it is very low i.e., Rs. 50,767 in Dungarpur, Rs. 51,650 in Dhaulpur, Rs., 53,660 in Sawai Madhopur etc (Fig. 4).

Inadequate Consumption of Food

Food insecurity is ultimately related to food consumption and health. If people are not healthy or suffer from deficiency diseases then it is commonly interpreted that they have inadequate consumption of food. To analyse food consumption several indicators were taken into consideration, namely the proportion of underweight children below 5 years of age, anaemic children (0-5 years), anaemic men, and anaemic women. The selection of indicators was based upon the data available.

The districts of Banswara, Udaipur, Dungarpur, Bundi, Pratapgarh, Baran and Sirohi lie in the very high zone of inadequate food consumption. In Kota, Chittorgarh, Jhalawar, Jalore, Rajsamand, Bhilwara, Tonk and Pali inadequate consumption of food is characterized as high. Barmer, Ajmer, Jodhpur, Dhaulpur, Bharatpur, Alwar, Karoli and Bikaner have moderate consumption of food, while Sawai Madhopur, Jaisalmer, Nagaur, Churu, Ganganagar, Jaipur, Jhunjhunu, Dausa, Hanumangarh and Sikar have a low rate of inadequate food consumption. The share of underweight children is high in Pratpgarh, Dungarpur, Udaipur and Banswara where more than 50 percent of children are underweight. Percentage of anaemic children is high in Banswara, Bundi, Udaipur and Jhalawar where it exceeds 75 percent. The highest share of anaemic women is observed in districts of Banswara, Dungarpur, Udaipur and Baran, where it is more than 66 percent of women, while in districts of Banswara and Sirohi it is more than 40 percent. In Kota and Udaipur around 30 percent of men are anaemic (Fig. 5).

Food Instability

Due to lack of relevant data, three main indicators were taken into consideration to analyse food instability, namely the insured cropped area to net sown area, normal rainfall and deviation from normal rainfall for the year 2018. Insurance of crop gives economic assurance to the farmer in case of crop failure. In the short term, crop insurance can help to reduce hunger and in long term, it can increase resilience (https://oneacrefund.org/blog/crop-insurance-can-improve-food-security-africa/). In Rajasthan, which is a semi-arid region with a low number of irrigation facilities, most of the agriculture and, therefore, crop production is depended upon rainfall. Exceedance of the normal rainfall assures economic prosperity in terms of crop production.

The districts of Barmer, Jaisalmer, Banswara, Karoli, Tonk, Jodhpur and Bundi are marked by very high food instability. Dhaulpur, Jalore, Ganganagar, Alwar, Dausa, Udaipur, Bharatpur and Hanumangarh have high food instability. Dungarpur, Pali, Sirohi, Churu, Ajmer, Baran, Nagaur and Bikaner are characterized by moderate food instability. Food stability can be found in districts of Pratapgarh, Bhilwara, Jhunjhunu, Sikar, Jaipur, Sawai Madhopur, Rajsamand, Jhalawar, Kota and Chittorgarh (Fig. 6).

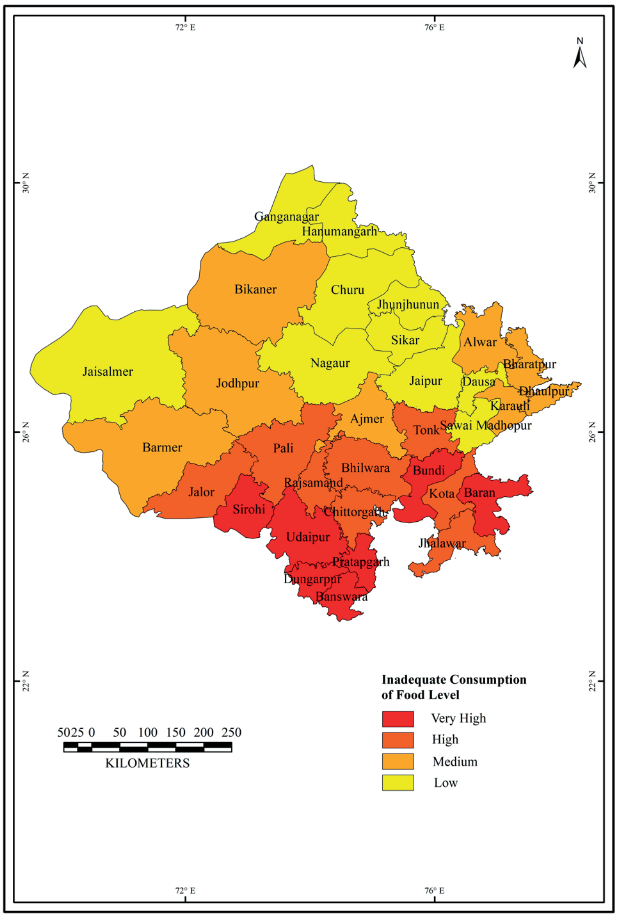

Fig. 5. Inadequate Consumption of Food

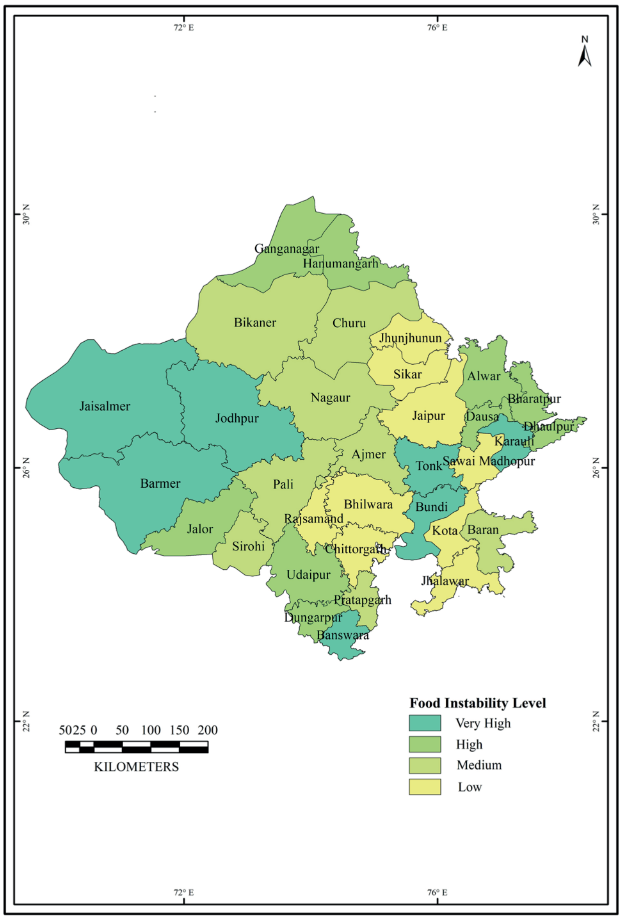

Fig. 6. Food Instability

Dhaulpur has only 12 percent, Bharatpur has 57 percent, Banswara has 80 percent and Dungarpur has 84 percent of its total cropped area insured relative to the net sown area. This parameter reaches as high as 1450 percent in Sirohi, 1140 percent in Chittorgarh, 1120 percent in Kota and around 1100 percent in Pali. Rainfall in Rajasthan varies between 201 mm in Sirohi and 868 mm in Sikar. Pali, Banswara and Jalore also received more than 800 mm of rainfall in June 2018. In Barmer, Jhunjhunu, Bikaner and Ganganagar normal rainfall is less than 300 mm. Jalore, Sirohi and Barmer experienced a deviation of more than -40 mm compared to normal rainfall in 2018. In Sikar, Pratagarh and Sawai Madhopur rainfall in the same year was 30 mm higher than normal.

Food Insecurity Level

Combining all the four dimensions and the outcomes of their analysis, the final characteristic of the food insecurity level was obtained. The following four food insecurity zones were identified in Rajasthan:

Very High Food insecurity

The districts of Banswara, Dungarpur, Udaipur, Bharatpur, Rajsamand, Dhaulpur and Jalore have a very high level of food insecurity. It can be noticed that Banswara is 5th in terms of food unavailability, has 5th rank in food inaccessibility, 7th rank in inadequate food consumption and 3rd in food instability. Dungarpur has a very high level of food inaccessibility and inadequate food consumption, while it is also ranked 14th in food unavailability and 16th in food instability.

High Food Insecurity

Pali, Barmer, Pratapgarh, Nagaur, Sirohi, Jodhpur, Tonk and Churu are high in food insecurity. Barmer ranks first in food unavailability and second in food instability. Barmer stands at 27th place in terms of food inaccessibility and 16th in terms of inadequate consumption of food.

Moderate Food Insecurity

The districts of Jhalawar, Karoli, Bundi, Baran, Ajmer, Jaisalmer, Bhilwara and Sawai Madhopur lie in the moderate zone of food insecurity. Bundi and Baran are ranked high in inadequate food consumption while food unavailability there is low to moderate. Jaisalmer is marked by high food unavailability and food instability but other two indicators i.e., food inaccessibility and inadequate consumption of food, are both low.

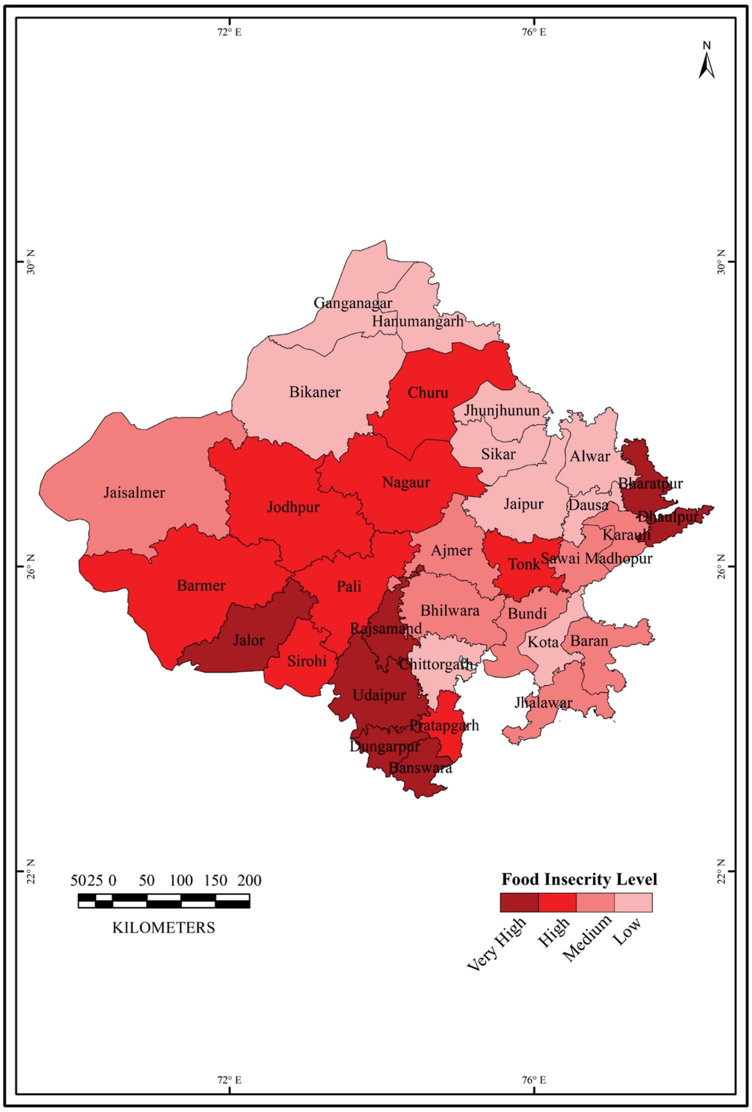

Fig. 7. Food Insecurity Level

Table 1. Ranking of the Districts on the basis of Four Dimensions of Food Insecurity

Districts	Ranks			
Food insecure zone	Food unavailability	Food Inaccessibly	Inadequate Consumption	Food instability
Banswara	5	5	7	3
Dungarpur	14	2	3	16
Udaipur	13	3	2	13
Bharatpur	8	1	20	14
Rajsamand	4	14	45	30
Dhaulpur	12	4	19	8
Jalore	2	21	11	9
Pali	15	9	15	17
Barmer	1	27	16	2
Pratapgarh	17	23	5	24
Nagaur	7	6	26	23
Sirohi	20	22	7	18
Jodhpur	9	16	18	6
Tonk	10	28	14	5
Churu	3	13	27	19
Jhalawar	29	15	10	31
Karoli	19	10	22	4
Bundi	32	19	4	7
Baran	33	12	6	21
Ajmer	21	17	17	20
Jaisalmer	6	24	25	2
Bhilwara	16	31	13	25
Sawai Madhopur	18	18	24	29
Kota	31	25	8	32
Alwar	24	11	21	11
Jhunjhunu	26	7	30	26
Bikaner	11	29	23	23
Sikar	22	8	33	27
Chittorgarh	28	32	9	33
Dausa	23	20	31	12
GangaNagar	27	30	28	10
Hanumangarh	25	33	32	15
Jaipur	30	27	30	28

Low Food Insecurity

Kota, Alwar, Jhunjhunu, Bikaner, Sikar, Chittorgarh, Dausa, Ganganagar, Hanumangarh and Jaipur are characterized by low food insecurity. This means that these districts are the most secure in Rajasthan in terms of food. Alwar and Sikar are high in terms of food inaccessibility but they have a lot of area under food grain and production is also high. These districts also have more than 96 percent of households with safe drinking water. Sikar has around 48 percent of households with clean fuel for cooking. Alwar district has a high share of insured crop area. The deviation of rainfall from normal is also positive. Therefore, most of the indicators are conducive to food security (Fig. 7).

DISCUSSION

This paper analyses the food insecurity situation in 33 districts of Rajasthan. The analysis is based on several indicators, which were assessed under four broad dimensions, namely food unavailability, food inaccessibility, inadequate consumption of food and food instability. It is to be noted that food includes sufficient and safe food, as well as water and fuel to cook it. Various indicators that characterize food insecurity under the four main dimensions are presented in the paper. Considering the results (Table 1) it can be clearly seen that each indicator has its own relevance. The variation of each indicator reflects its significant role in evaluating food insecurity as Rajasthan is extremely diverse in terms of its physiographic and demographic factors. The state has food secure districts like Jaipur, Hanumangarh, Ganganagar, Alwar, Sikar and Bikaner. In general, in these districts, all the parameters are positive to food security. In districts of Banswara, Dungarpur, Udaipur, Bharatpur, Rajsamand, Dhaulpur, Jalore food insecurity is very high. The policies formulated by the government regarding food insecurity need to focus on the different dimensions and their status. This is especially the case for districts like Barmer, which has low double-cropped to the net sown area so its food production is also low. It is also marked by low forested area, safe drinking water and fuel for cooking are not properly available, there is a high number of underweight children and anaemic people, rainfall deficit is high and insured cropped area is also very low. The Banswara district has very high food unavailability, food inaccessibility, food instability and inadequate consumption of food. The district ranks fifth, fifth, third and seventh respectively in all four dimensions. Similarly, Dungarpur is very high in food inaccessibility and inadequate consumption of food. Therefore, policies should focus more on improving both these indicators in this district. Main workers and marginal workers there are very low in number and people are mainly engaged in agricultural labour, which does not ensure the security of income. In Dungarpur, the average size of land holdings is very low along with the net domestic product. The parts of Dungarpur, Rajasmand, Banswara, Bharatpur and Udaipur have a tribal population and because of their poverty and backwardness, they are affected the most by the food insecurity.

Food insecurity cannot be just characterized by scarcity of food grains. Due to semi-arid conditions, many districts of Rajasthan are not able to produce a lot of food. Because of that, there is a need for better PDS (Public Distribution System) to adhere to the calorie and nutrition requirements of the localities. The situation in districts with very high food insecurity level can be worse in case of rainfall deficiency or drought year, so it is important to ensure the cropped area and explain the farmers the importance of crop insurance. Nutrition security is another important concern and Public Distribution System should not only focus on food grain distribution but also on distribution of protein and iron-rich food items at subsidised and affordable rates. Distribution of clean fuel, safe drinking water and milk should also be a part of a food security mission. Sustainable Development Goal of zero hunger can be achieved by understanding the holistic nature of food security. Thus, it is important to measure food security by considering its various parameters, which can provide a real picture as well as the scope of improvement to make it a realistic goal to achieve. ■

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RESEARCH PAPER

MONITORING LAND USE AND LAND COVER CHANGES USING GEOSPATIAL TECHNIQUES, A CASE STUDY OF FATEH JANG, ATTOCK, PAKISTAN

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ABSTRACT. Change of land use and land cover (LULC) has been a key issue of natural resource conservation policies and environmental monitoring. In this study, we used multi-temporal remote sensing data and spatial analysis to assess the land cover changes in Fateh Jhang, Attock District, Pakistan. Landsat 7 (ETM+) for the years 2000, 2005 and 2010 and Landsat 8 (OLI/TIRS) for the year 2015 were classified using the maximum likelihood algorithms into built-up area, barren land, vegetation and water area. Post-classification methods of change detection were then used to assess the variation that took place over the study period. It was found that the area of vegetation has decreased by about 176.19 sq. km from 2000 to 2015 as it was converted to other land cover types. The built-up area has increased by 5.75%. The Overall Accuracy and Kappa coefficient were estimated at 0.92 and 0.77, 0.92 and 0.78, 0.90 and 0.76, 0.92 and 0.74, for the years 2000, 2005, 2010 and 2015, respectively. It turned out that economic development, climate change and population growth are the main driving forces behind the change. Future research will examine the effects of changing land use types on Land Surface Temperature (LST) over a given time period.

KEY WORDS: Remote sensing; Geo-spatial techniques; Change detection; Land use; Land cover; Driving forces

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INTRODUCTION

Natural and human-induced changes in an urban environment are of concern nowadays due to their influence on the environment and human health (Han et al. 2015), which makes the research of LULC dynamics fundamental for proper natural resource planning and utilization as well as its management (Rawat and Kumar 2015). Conventional approaches for collecting population data, conducting surveys and evaluating environmental samples are not appropriate for complex multi-factorial ecological studies (Dong et al. 2009). For many of the challenges often encountered in environmental research that include processing of multidisciplinary data, more advanced techniques such as satellite Remote Sensing (RS) and Geographic Information Systems (GIS) are required. Such tools provide necessary information for the analysis and environmental management of natural resources (L. Li et al. 2016).

One of the recent development trends is to perform geospatial studies using integrated analysis of satellite and geographical data. GIS is an optimized computer hardware and software system that can record, archive, retrieve, control, interpret and view geographically referenced (spatial) information to help development-oriented management and decision-making processes (Mahmood et al. 2014). GIS and RS have a wide range of applications in the fields of environment, agriculture and combined eco-environmental assessment (Behera et al. 2012; Qian 2016). Several researchers have focused on the negative impact of LULC changes on the ecological features of an area (Yulianto et al. 2019). Human-induced environmental changes are generating regional combinations of environmental factors that could slip beyond the envelope within which many of a region's terrestrial plants have grown within the next 50 to 100 years (X. Li et al. 2016).

Lu et. al (2004) explored several methods for the LULC change detection. A land use prediction model for a given period of time can be established by analysing chronological LULC changes. The model could give a framework for the real land use analysis, preparation, management and environmental protection in a region as well as recommendations for the local social and economic improvement (Galicia and García-Romero 2007; Lu et al. 2004; Masum and Islam 2020; Reis 2008). Up-to-date knowledge on land cover changes calls for technical improvements in the methods for identifying LULC of any area (Mishra et al. 2016; Pervez et al. 2016). RS and GIS are essential and the most common techniques for obtaining detailed and timely spatial data on LULC and to analyse its regional changes (Lee et al. 2012; Pradhan et al. 2009; Singh S. and Rai 2018). Satellite imagery can be used to easily track land use changes, providing an outstanding foundation of statistics from which the information on LULC dynamics can be retrieved, tested and reproduced (Nachappa et al. 2019; Singh S.K. et al. 2018). Remote Sensing is thus commonly used at different scales for monitoring and managing the land use (Basim and Ali 2018; Hua 2017; Olokeogun et al. 2014). GIS offers a versatile framework for compilation, storage, display and review of digital data needed for identification of the landscape changes (Bansod and Dandekar 2018; Mishra et al. 2016; Tariq A. and Shu 2020; Vasenev et al. 2019; Vishwakarma et al. 2016).

The use of RS and GIS in numerous areas, including tracking and management of natural resources, land use transition, urban land use, environmental and demographic research, has been of great value to the property managers. Pixel-based information allows us to understand the interaction between different types of land cover and contributes to the design of improved methods for interacting with the landscape. Therefore, in the present research RS and geospatial methods were applied to assess the degree of urban land use change in Fateh Jhang district, particularly concerning the replacement of vegetation and natural land cover. The main purpose of this research was to use satellite imagery from the years 2000 to 2015 to identify and measure the LULC in the study area. The main objectives of this study were to identify the LULC changes in Fateh Jhang from 2000 to 2015, highlight the driving factors of LULC changes through combining remote sensing, environmental, geographical and socioeconomic data, and propose future sustainable land management practices to the policymakers to achieve land and sustainable development goals of the United Nations (UN).

MATERIALS AND METHODS

Study Area

Fateh Jhang is situated between 33°20´ N to 33°55´ N latitude and 72°23´ E to 73°01´ E longitude, covering an area of 1407.48 sq. km with elevation ranging from 336 to 939 meters asl (above sea level) and an estimated population of 340,414 people. The tehsil comprises 14 union councils (UCs) out of which only two UCs are urban (see Figure 1). It is located on the road between Islamabad and Kohat, 50 km from Islamabad and 48 km from Attock (Arshad et al. 2012). The soil in the study area was formed on calcareous loess deposits and is characterized as fine-textured, well-drained and moderately deep. Fateh Jhang consists of three distinct regions. In the northern part of the study area, north of the Kala-Chitta hills, there is a broad plateau, which is significantly broken down by ravines. The rich Sohan valley lies south of the Khairi-Murat town (near Dhari village) whereas a rugged plain lies between the two sides of the hills, narrow in the east and stretching westward (see Figure 1). Climate conditions vary from one region to another depending on the altitude. The soils of Fateh Jhang vary according to climate variation (Shaheen et al. 2015). In the city, the temperature is ranging from 45°C in summer to 15°C in winter. The daily mean maximum and minimum summer temperatures are 39 °C and 27 °C respectively (A. Tariq et al. 2020).

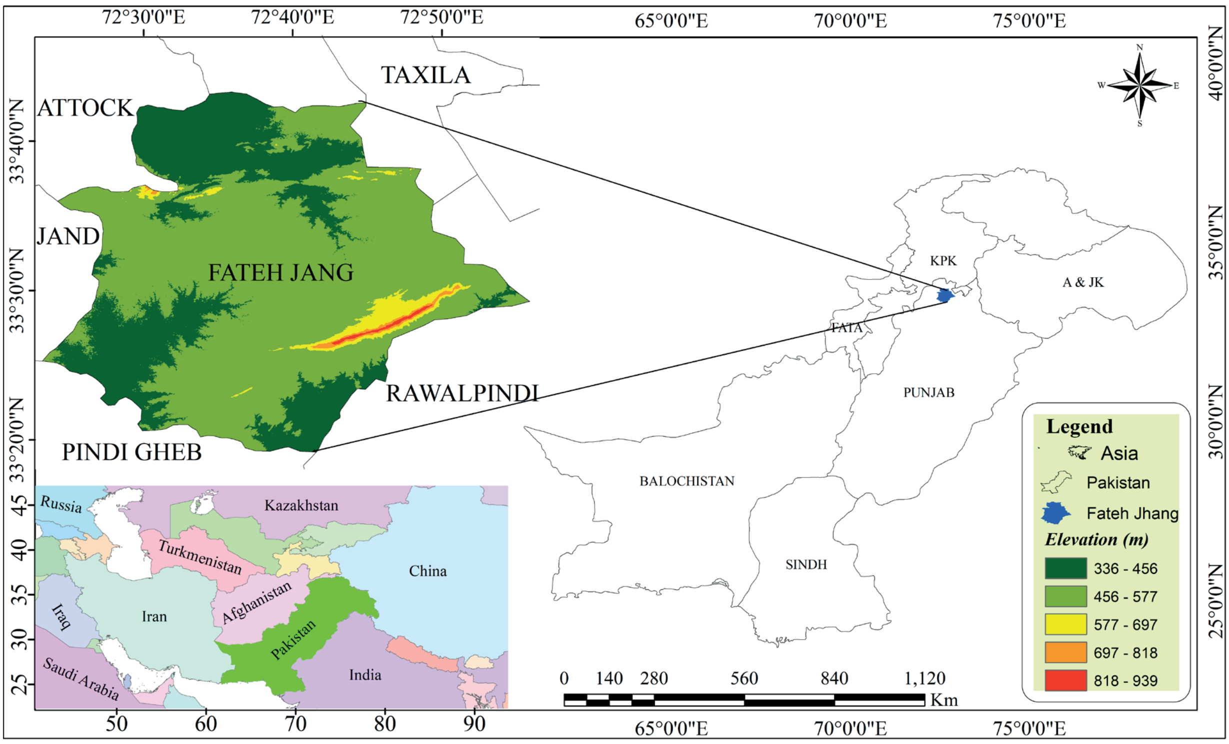

Fig. 1. Map of the Study area

Data acquisitions and processing

For the present research, the Landsat 7 and 8 data for the years 2000, 2005, 2010 and 2015 were used. All the data were collected free of charge from the USGS-EROS (https://www.usgs.gov) and chosen so that the cloud cover is less than 10% to improve the accuracy. Summary of the data used in the study is presented in Table 1. The shapefiles were created for the respective areas and the area of interest (AOI) was extracted using Erdas Imagine 2016 (Day, product level-1 G) and referenced using Universal Transverse Mercator (UTM) Projection System. The LULC maps of the study area were produced using ETM+ images with 8 bands (of which band 6 was a thermal band) and 30 m spatial resolution Landsat 7 images (bands 1–5 and 7). Using the method described by Jiménez-Muñoz et al. (2014), the thermal bands with 60 m spatial resolution were resampled to 30 m. To obtain the LULC map from Landsat 8, 11-band images were used (bands 1–7 and 9 were OLI, 8 was panchromatic and 10 and 11 were thermal) (Table 2). Landsat 8 images had a spatial resolution of 30 m, radiometric resolution of 12 bit and temporal resolution of 16 days. To match the data distribution, thermal bands with 100 m spatial resolution were also resampled to 30 m according to the method by Jiménez-Muñoz et al. (2014). Additionally, the authors committed to gathering field data over a five-month period. The collected data were used to classify several types of land cover within the study area. The primary purpose of the field survey was to collect land cover parcel data with the aid of GPS (global positioning system), which helped to demarcate the parcel boundaries using GIS software and historic maps. These GPS points were overlaid on the satellite image for boundary delineation and mapping. Field surveys were performed with the help of GPS, Maps.me and OSM-Tracker (both Open-Street-Map open-source mobile applications) for collecting the coordinates of different land cover types in the study area. High-resolution elevation data from Shuttle Radar Topography Mission (SRTM) were downloaded from the EarthData extraction tool "Application for Extraction and Exploration of Ready Samples (AppEEARS)" (https://lpdaac.usgs.gov/tools/appeears/) to produce the digital elevation model (DEM) of the study area. Vector data for tehsil and river systems as well as supplementary details were collected using RS and GIS Lab.

Methodology

The designed research procedure is presented in Figure 2 and includes using ArcMap 10.6, Erdas Imagine 2016 and Envi 5.4 tools to analyse different types of LULC and the interactions between them.

Image pre-processing and LULC

In Envi (5.4-version), the satellite data for 2000, 2005, 2010 and 2015 were optimized for noise reduction

Table 1. Data-collection used in the study

Data	Acquisition date	Source	Processing level
Landsat 7 (ETM)	22 May 2000	USGS Earth Explorer	TIER 1
Landsat 7 (ETM)	12 May 2005	USGS Earth Explorer	TIER 1
Landsat 7 (ETM)	16 May 2010	USGS Earth Explorer	TIER 1
Landsat 8 (OLI/TIRS)	12 May 2015	USGS Earth Explorer	TIER 1
SRTM	11 Nov 2010	Earth Data	
Maximum Temperature	1998-2016	Pakistan Meteorological Department	Interpolated Maps
Maximum Temperature	1998-2016	Pakistan Meteorological Department	Interpolated Maps
Precipitation	2000-2015	Pakistan Meteorological Department	Interpolated Maps

Table 2. Depiction of Landsat 7 and Landsat 8

S.No	Landsat7 (ETM+)			Bands	Landsat 8 (OLI & TIRS)		
	Resolution (Meter)	Wavelength (Micrometer)	Band Name		Band Name	Wavelength (Micrometers)	Resolution (Meter)
1	30	0.45-0.52	Blue		Ultra-Blue (coastal/aerosol)	0.435-0.451	30
2	30	0.52-0.60	Green		Blue	0.452-0.512	30
3	30	0.63-0.69	Red		Green	0.533-0.590	30
4	30	0.77-0.90	NIR		Red	0.636-0.673	30
5	30	1.55-1.75	SWIR1		NIR	0.851-0.879	30
6	60*(30)	10.40-12.50	Thermal		SWIR1	1.566-1.651	30
7	30	2.09-2.35	SWIR2		SWIR2	2.107-2.294	30
8	15	0.52-0.90	Panchromatic		Panchromatic	0.503-0.676	15
9					Cirrus	1.363-1.384	30
10					TIRS1	10.60-11.19	100*(30)
11					TIRS2	11.50-12.51	100*(30)

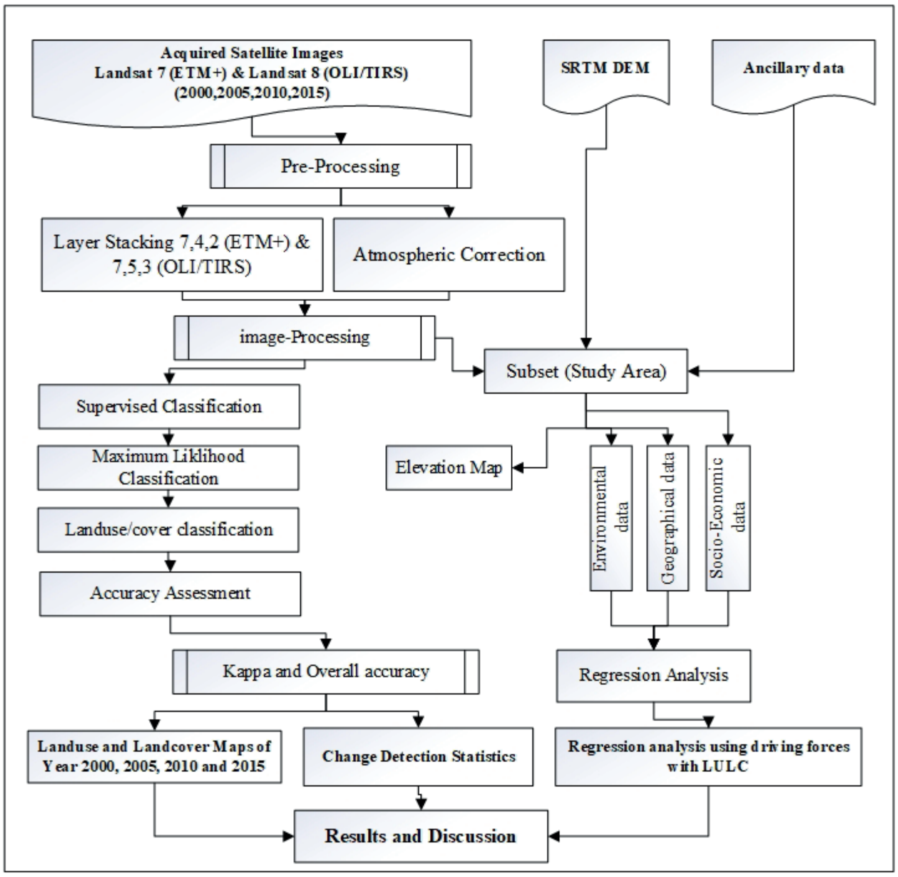

Fig. 2. Research methodology

purposes (Rasti et al. 2018). This was necessary for gathering certain relevant information on the data, such as the kind of sensors, utilized to collect the data, the angle of the sun at the time and date of data acquisition to identify the ambient conditions at the time of capture (Scheffler and Karrasch 2013). Before calibration of data for 2013, scanning lines were eliminated using Landsat_gapfill (Envi extension/plugin) to improve the visual appearance of the images. According to the USGS-EROS (https://www.usgs.gov/faqs/what-landsat-7-etm-slc-data), a mechanical failure of the Scan Line Corrector (SLC) resulted in gaps known as scan lines in all Landsat 7 (ETM+) images which were collected after 31st May, 2003. Nonetheless, these items carried the identical geometric and radiometric properties as the data composed before the SLC failure and therefore can still be used. The ability of Envi and ArcMap to exchange and use information allowed to eradicate the scan lines. Envi 5.4 has the potential to calibrate multispectral bands in one go, saving time compared to previous models in which adjustment was performed on each band separately. The files for Envi must be prepared in TIFF format to interpret and group the bands in a directory. The resulting band format is an Envi file with the scanning lines removed using Landsat-gapfil.Sav and with an extension .hdr and .emp. Thus, the data on each available band for the year 2015 was also removed from the scan line in 2015 and the resulting TIFF file for each band was transferred in Arc-Map 10.6.

The research has gone through strict site preparation which included using information collected from the field for the supervised data classification for the year 2015 to determine the land cover types for each of the Landsat classes. In addition to the classified data from 2015, the data from 2010, 2005 and 2000 were classified using Google Earth as a guide. The data was then trained in ArcMap after stacking the calibrated bands in combinations of 7, 4, 2 (2000, 2005 and 2010 data) and 7, 5, 3 (2015 data) (Chen et al. 2016; Mohammady et al. 2015). Such combinations were chosen instead of 4, 3, 2 because they were more useful for land use and land cover studies as it was very challenging to use the latter when classifying the data. Meanwhile, the used combinations allowed for a clear distinction between damaged fields and barren-land as well as different types of vegetation. So, the Landsat data were all classified using regulated classification for the four different years. The supervised selection included training sites, which were chosen based on the knowledge of the analyst in the researched subject. The qualifying locations were further utilized to produce the classification of image data using the classifier algorithm by matching the required pixels based on maximum likelihood. The above-mentioned method is frequently implemented as a classification algorithm and uses mathematical judgment rule which analyses the likelihood function of a pixel for every class and assigns pixel to the most probable class (Firdaus 2014).

Unlike the supervised classification, in the unattended classification, the program produces an automatic classification either by K-means or by ISO-Data so that the analyst cannot influence the created classes (Pandya et al. 2013). In both cases, the spectral grouping produced by the classification was based on the spectral variation and did not require the user to have extensive knowledge of the area of study. Types of land use that were identified included vegetation, built-up area, barren land and water-bodies. Unlike the 2015 data, the images for 2000, 2005 and 2010 were categorized using Google Earth and the colour representation of the 7,4,2 band combination as given by Google Earth (Chen et al. 2016; Mohammady et al. 2015).

Evaluation of Training samples and Accuracy assessment

The training samples obtained from specific parts of the study area represented a total area of 1407.48 sq. km. An overview of the training samples that were used in the image classification is given in Table 3 & Figure 3. First of all, a grid polygon was created in Arc Map 10.6 using a fishnet method, then a training sample from each grid cell was collected using a random sampling method.

In addition, evaluation of the classification accuracy was done using ArcMap 10.6 for the years 2000, 2005, 2010 and 2015. The adopted method of the post-classification accuracy assessment describes the quality of the resulting data (Firdaus 2014; Pandya et al. 2013; Rwanga and Ndambuki 2017). The following formula was used to calculate the overall accuracy (OA) and Kappa coefficient (*Kc*) values:

$$Kc = \frac{N\sum_{i=1}^{i} Xii - \sum_{i=1}^{r}(x_{i+} \times x_{+i})}{N2 - \sum_{i=1}^{r}(x_{i+} \times x_{+i})} \quad (1)$$

Where
r = the number of rows,
x^i = the number of observations in row i and column i,
x_{i+} = the marginal totals of row
x_{i+i} = the marginal totals of column,
and N is the overall number of detected pixels (Firdaus 2014; Pandya et al. 2013). X corresponds to the reference value (corrected and total) of the data and has a considerable influence on the accuracy of image classification. If its value is between 0.8 and 1, then the classification can be considered accurate; when it is in the range of 0.40 to 0.80, the classification is moderately accurate and the values from 0.00 to 0.40 mean that the classification was not accurate (Firdaus 2014; Pandya et al. 2013). Apart from 2000 and 2015 classified images that were evaluated using 65 ground validity samples from Google Earth's historical data, the 2015 image was also evaluated using 65 ground validation samples collected from the field surveys. In ArcMap, the actual calculation of accuracy was done by establishing reference points or ground control points, converting reference points from vector to raster data, integrating raster data with stable images and producing the uncertainty matrixes. The spatial resolution of the Landsat images was 30*30 meter (Firdaus 2014; Kulkarni 2017; Pandya et al. 2013; Rwanga and Ndambuki 2017).

Table 4 provides details on the data quality assessment tests for the year 2015 and a summary of the error matrix. Applying the equation (1), the corresponding kappa coefficient (kc) would therefore be the following:

$$Kc = \frac{(65*(5+49+1+5) - E\{(6*5)+(52*51)+(1*1)+(7*7)\})}{(65^2 - E\{(6*5)+(52*51)+(1*1)+(7*7)\})}$$

Kc=0.78

This result is smaller than the overall accuracy (OA) which is calculated by simply dividing the number of correctly classified cells over the total number of sampled cells.

The classification conducted for the year 2015 was mostly accurate and reliable as 0.929 > 0.80 and closer to 1. The values of Kc for the years 2000, 2005, 2010 and 2015 were estimated at 0.77, 0.78, 0.76 and 0.78 respectively (Table 5). This also implies that, given the random collection of reference points, the classifications conducted on those images can be considered accurate and reliable.

Driving factors of the LULC change

According to the relevant studies, three groups of LULCC driving factors, namely socio-economic, environmental and geographical, are commonly defined. We selected five variables representing these factors. Since the paper focused mainly on analysing the relative impact of the driving forces time-series on the land use change, the neighbourhood factors in the study were considered as spatially contextual data. Geographical variables are the main determinants of the magnitude of land use changes. The possible range of LULCC is influenced by environmental factors, such as precipitation

Table 3. Summary of the training samples

Classes	Training Samples (in sq. km)			
	2000	2005	2010	2015
Vegetation	2.2	1.3	2.3	2.5
Built-up area	3.2	1.9	2.8	2.2
Bare land	0.4	2.1	2.6	2.4
Water	1.5	3.2	2.4	2.6

Table 4. 2015 error matrix table (in the number of pixels)

Classified	Barren land	Vegetation	Built-up area	water	Classified Total
Barren land	5	0	0	0	5
Vegetation	1	49	0	2	52
Built-up area	0	0	1	0	1
Water	0	2	0	5	7
Reference Total	6	51	1	7	65

Table 5. Accuracy assessment of 2000, 2005, 2010 and 2015 classification

Accuracy assessment	2000	2005	2010	2015
OA (in percentage)	0.92	0.92	0.90	0.92
Kappa (in percentage)	0.77	0.78	0.76	0.78

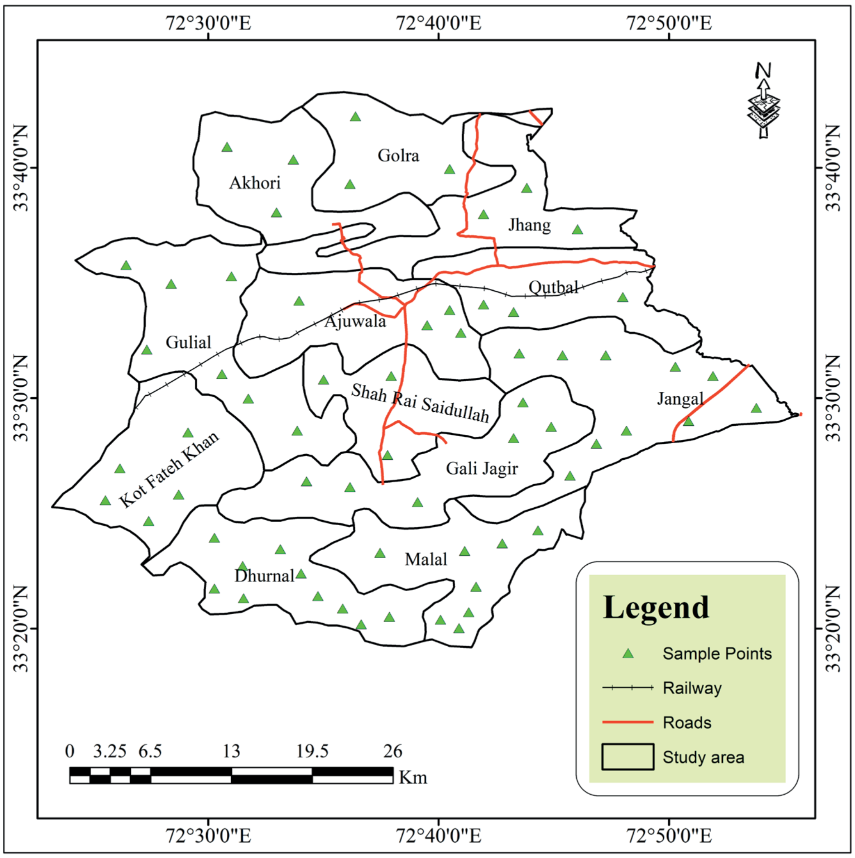

Fig. 3. Sample collection for Accuracy assessment

and temperature, which determine the water supply. Annual precipitation (x1), as well as the minimum (x2) and maximum temperature (x3) were therefore included as climate factors for the study of LULCC driving factors at Fateh Jhang. The data on the environmental factors were obtained from the Pakistan Meteorological Department, Islamabad https://www.pmd.gov.pk/. Socioeconomic data included time-series of regional gross domestic product (GDP) (*x*4) and population (*x*5). These data were acquired from the Census Department of Pakistan Statistical Bureau, Islamabad (http://www.pbs.gov.pk/content/population-census). Both those parameters were taken from Fateh Jhang 's statistical yearbook. These factors reflect the dynamics of population, urbanization, economic and industrial development, social investment and technological progress as well as conditions of the external traffic, which can potentially influence LULC changes in Fateh Jhang city. In this research, linear regression analysis was carried out to explore the underlying processes of the LULC adjustment in response to the chosen geographical, socio-economic and environmental factors. Thus, the time-series data on the four major land use types were used to explore the driving forces contributing to the land use change in Fateh Jhang. The four major land use types, that is, built-up area, vegetation, barren land and water were labelled as *y*1, *y*2, *y*3 and *y*4, respectively. A well-known multivariate statistical instrument for high-dimensional data processing is the Least Square Method (Carrascal et al. 2009; Vijayakumar et al. 2014). Multiple linear regression analysis, canonical correlation analysis, and key component analysis are included in the Least Square method function. After its application in several fields, including first chemometrics, sensory assessment, statistics, and ecology, it also emerged in social sciences and became popular (Kabir et al. 2017). The increasing popularity of the Least Square method compared to the traditional statistical analysis is partly due to its more efficient treatment of multicollinearity in the dataset, which is especially valuable in some cases when there are fewer measurements relative to the number of explanatory variables (Rosipal and Trejo 2000).

RESULTS AND DISCUSSION

Landsat 7 and 8 images were used for the years from 2000 to 2015 to study the spatial variation of land use, its dynamics and consequent adjustments. Supervised classification methods were used for all the images and the land use types were organized into four classes: vegetation, built-up area, barren land and water. The total area that was covered by the research amounted to 1407.48 sq. km. The changes observed in the land use of the study region over the sixteen years were summarized and presented in tabular format. Analysis of the classified images as shown in Figure 4a revealed that in the year 2000 vegetation covered 800.74 sq. km, which makes it the most prevalent type of land use/land cover in the study area. Barren land covered an area of 258.34 sq. km, while built-up and water classes amounted to 229.56 sq. km and 118.84 sq. km, so their share in the total area was far less significant.

The analysis of the Landsat 7 (ETM+) image for the year 2005 has shown that vegetation remained the leading class in the region with an area of 694.86 sq. km (Figure 4b). Territories that were classified as built-up areas covered 256.34 sq. km whereas the barren land and water types amounted to 337.44 and 118.84 sq. km, respectively (Khan 2015). Figure 4c shows that in 2010 vegetation and/or agricultural land also was the most common land cover type in Fateh Jhang with an area of 658.22 sq. km. The area of 288.66 sq. km corresponded to built-up territories, while barren land covered 341.76 sq. km. The remaining class was water bodies which covered a total area of 118.84 sq. km. In 2015 the total estimated built-up area was 310.55 sq. km. Vegetation/ agricultural land was still the most prominent land cover type in Fateh Jhang, covering an area of 624.55 sq. km. Barren land occupied an area of 353.54 sq. km, while water area amounted to 118.84 sq. km. From Figure 4a it can be seen that over the period between 2000 to 2005, vegetation area has changed significantly, particularly in the northern part of the study area, as it decreased by almost 105.88 sq. km, built-up area increased by 26.78 sq. km, barren

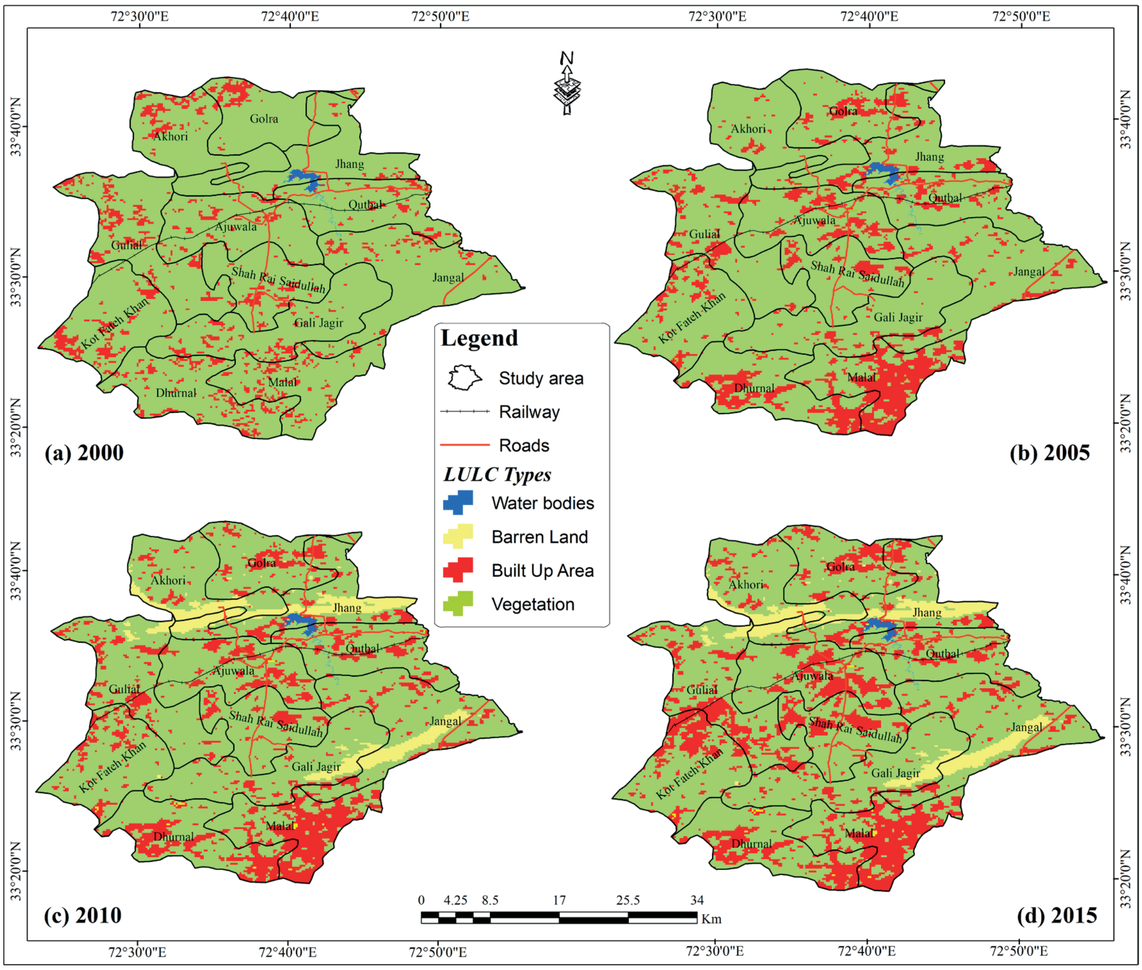

Fig. 4. Landuse Landcover maps a) 2000, b)2005, c)2010, and d)2015 of Fateh Jhang

land increased by 79.1 sq. km. Water bodies had some spatial changes during this period but their total area remained almost the same. From 2005 to 2010, there was a 32.32 sq. km increase in built-up area and 36.64 sq. km reduction of vegetation area (Figure 5). Barren land increased by 4.32 sq. km during this period. From 2010 to 2015, barren land increased by 11.78 sq. km and built-up area further increased by 21.89 sq. km in just five years. From 2000 to 2015, built-up area cover increased by 80.99 sq. km, vegetation decreased by 176.19 sq. km and barren land experienced a 95.2 sq. km increase.

Statistical description of LULC change

The results of the classification were further analysed in terms of changes that happened among the observed groups. The first group covered the period from 2000 to 2005, the second group consisted of the period from 2005 to 2010, the third group consisted of the period from 2010 to 2015 and the fourth group corresponded to the period from 2000 to 2015.

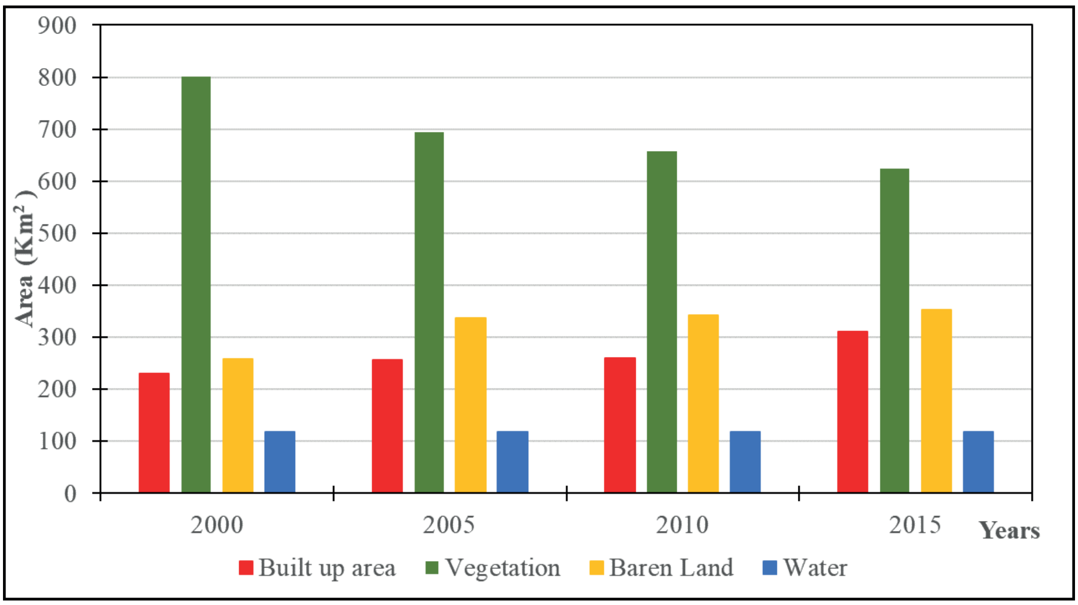

Fig. 5. The area of land use land cover types for different years

Statistical description of LULC change from 2000 to 2005

The analysis of LULC changes over the study period revealed that the total area of barren-land increased by 5.62%. It retained 52.81% of its initial area and 26.79% of it was transformed into vegetation (Table 6). The built-up area benefited 12.11% due to the transition from vegetation. Vegetation only maintained 46.24% of its initial area. Generally, from 2000 to 2005, its total area declined by 7.52%, while 26.79% of it was converted from barren land zones, 16.45% from built-up and 22.56% from water. Two of the last groups in terms of land cover change were vegetation and water, the latter witnessed an unprecedented increase of 18.17% over the study period, whereas barren land and built-up area increased by 34.23 and 121.26%, respectively.

This period reflects the most significant land cover transition in the study area. In five years, the area of vegetation shrank by 25.36%, losing 18.55% to barren land and 12.11% to built-up area. The built-up region covered 12.11% of vegetation, 19.23% of barren-land and 23.25% of water areas. Total built-up area increased by 1.9% over the period from 2000 to 2005.

Statistical description of LULC change from 2005 to 2010

Within these five years, vegetation area decreased rapidly by 2.60%, losing 11.66% to built-up area and 23.48% to barren land (Table 7). The built-up area covered 15.32% of vegetation area, 23.56% of barren-land and 19.21% of water areas. Vegetation cover was removed from 39.26% area. The barren land area mostly emerged from vegetation (23.48%) and built-up area (16.01%) and benefited more from agricultural land (21.35%) than any land cover type over the time period.

Statistical change detection of LULC from 2010 to 2015

This time span (2010-2015) had showed the utmost recent change in land cover at time of study. Within five years, vegetation area had fallen rapidly by 2.60%, losing 11.66% to the built-up area and 23.48% to the barren-land (Table 8). The built-up area had covered 15.32% of the trees area, 23.56% of the barren-land and 19.21% of the water areas. Vegetation cover was removed from 39.26% area. Barren-land areas had grown mostly from vegetation 23.48% and built-up area 16.01% and benefited more from agricultural land 21.35% than any land cover over the time period.

Table 6. Statistical description of LULC change between 2000 and 2005

		2000 INITIAL STATE%			
2005 FINAL STATE %		Built-up	Vegetation	Barren land	Water
	Built-up	50.95	12.11	19.23	23.25
	Vegetation	16.45	46.24	26.79	22.56
	Barren land	16.3	18.55	52.81	4.19
	Water	16.3	23.10	1.17	50.00
	Total	100	100.00	100.00	100
	Class Change	1.90	-7.52	5.62	0
	Image Difference	121.26	-25.36	34.23	18.17

Table 7. Statistical description of LULC change between 2005 and 2010

		2005 INITIAL STATE%			
2010 FINAL STATE %		Built-up	Vegetation	Barren land	Water
	Built-up	51.15	15.32	16.01	19.21
	Vegetation	11.66	48.7	23.48	15.49
	Barren land	23.56	26.80	50.16	15.3
	Water	13.63	9.18	10.35	50
	Total	100	100	100	100
	Class Change	2.30	-2.60	0.31	0
	Image Difference	53.29	-39.26	39.23	23.1

Table 8. Statistical description of LULC change between 2005 and 2010

		2010 INITIAL STATE%			
2015 FINAL STATE %		Built-up	Vegetation	Barren land	Water
	Built-up	50.79	20.50	12.33	18.1
	Vegetation	31.04	48.81	21.33	17.39
	Barren land	10.43	24.50	50.42	14.51
	Water	7.76	6.20	15.92	50
	Total	100	100	100	100
	Class Change	1.56	-2.39	0.84	0
	Image Difference	62.35	42.23	45.23	25.01

Statistical description of LULC change from 2000 to 2015

The changes that occurred over the sixteen years summarize the trend in the land use change over the study period. Identification of the land use change as presented in Table 9 showed the area of barren land has increased by 6.76% over the period, built-up area witnessed a remarkable percentage increase of 5.75% indicating a steady growth in agricultural activities and improvement in the built-up parts of the study area. Such practices emerged from the fear that farms would extend outside their defined boundaries. Although it only increased by 1.90% by 2005, it also gained 2.30% and 1.56% in 2010 and 2015 respectively.

Relationship between Different Land Use Types and the Driving Factors

Changes to the Fateh Jhang LULC were driven by a variety of environmental, geographical and socioeconomic factors. While population increase was one of the basic reasons for the urban sprawl, the role of secondary factors e.g., economic development had to be examined as well. To identify the impact of each independent variable on built-up area, vegetation, barren land and water, five variables (i.e., annual precipitation (*x*1), minimum temperature (x2), maximum temperature (*x*3), gross domestic product (GDP) (*x*4), and population (*x*5) were analysed to create a model. Table 10 illustrates the results in terms of VIP (Variable Importance in Progression) values and the contribution of environmental, geographical and socio-economic factors to the LULC change.

The impact of all these components on the land use change trend in the study area was confirmed by evaluating regression between the land use characteristics and variables, describing the environmental, population and economic influences. The determination coefficient of 0.88, 0.98, 0.86, and 0.99 was calculated for the built-up area, vegetation, barren land and water bodies respectively, which indicates that 88%, 98%, 86% and 99% of the variation in land use types during the study period might be described by the selected underlying factors. The census data showed a significant increase in population during the study period. Urbanization and the establishment of new housing settlements caused a fast urban sprawl, which was mostly caused by the migration of rural population to cities. The growing population increased the pressure on the limited resource base which supposedly added to the urban land enlargement by de-forestation and filling of the low-lying fields.

Table 9. Statistical description of LULC change between 2000 and 2015

2000 INITIAL STATE%					
2015 FINAL STATE %		Built-up	Vegetation	Barren land	Water
	Built-up	52.90	33.91	10.23	19.3
	Vegetation	17.65	43.74	35.23	14.99
	Barren land	14.75	16.23	53.38	15.71
	Water	14.75	6.12	1.16	50
	Total	100	100	100	100
	Class Change	5.75	-12.52	6.76	0
	Image Difference	43.22	-47.25	25.23	22.1

Table 10. Analysis of the relationship between LULCC and its key driving factors

LULC Type (y)	Precipitation (x1)	Min Temp (x2)	Max temp (x3)	GDP (x4)	Population (x5)	R^2	Adjusted R^2	SE of Estimate
Built up area (y1)	-0.027	0.068	0.104	0.101	0.93	0.88	0.76	3.45
Vegetation (y2)	-0.030	-0.106	-0.117	-0.108	-0.087	0.98	0.86	4.36
Barren land (y3)	-0.402	-0.103	-0.112	-0.110	0.067	0.86	0.99	2.81
Water (y4)	-0.040	0.27	0.161	0.127	0.050	0.99	0.99	7.35

Predictors: (constant), Population, GDP, Max Temperature, Min Temperature, Rainfall)

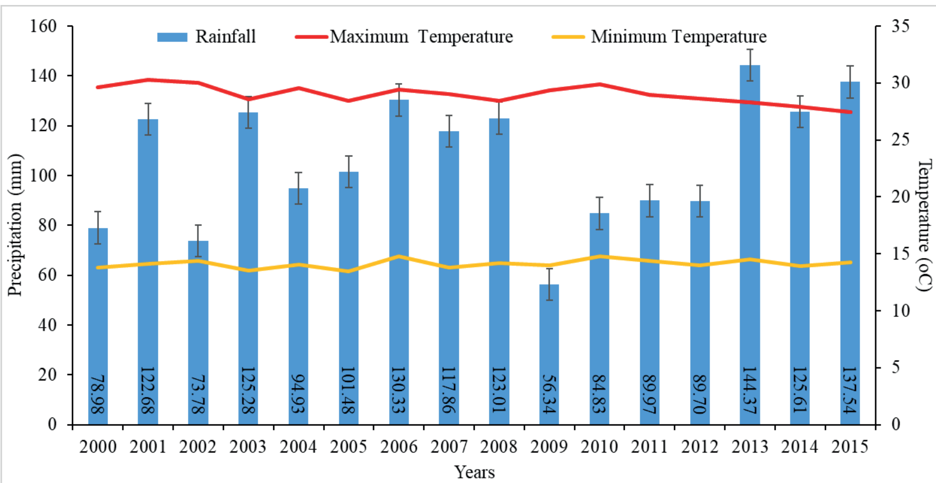

Fig. 6. Variation in Temperature (°C) and Precipitation (mm) in Fateh Jhang from 2000 to 2015

There may be both positive and negative consequences of urban development on the environment but an uncontrolled urban sprawl will surely lead to undesirable effects. Both developing and developed countries have comparable environmental challenges related to urban sprawl. Built-up communities keep growing constantly along with residential and commercial production and parking areas and other infrastructures, that does not allow water to infiltrate the soil. As a result, the environment changes dramatically since the transition from the original state to an urban area is a non-reversible process. As urban land expands, a variety of vulnerable resources might become endangered. The period of urbanization that occurred in the periphery has contributed to the development of new relationships between different land use types, especially where historical and current patterns in land use are established side by side. Lack of agricultural land and uncontrolled growth of built-up areas are serious challenges of the current land use which have appeared due to the development of the new urban areas, which has led to difficulties in the transformation from various modes of life in the countryside and cities. Another contributing factor for rapid urbanization is the economic development of Fateh Jhang, particularly related to the construction of Islamabad airport, which is the most recent significant project in the area (https://fp.brecorder.com/2005/11/20051115352782/). Another major factor of increasing urbanization is industrialization. During the study period, it also resulted in the invasion of enormous numbers of pastoral immigrants.

One of the fundamental ways in which global climate change is projected to affect the economic activities in the area is through the impact of temperature and precipitation on agricultural production. The important ecological elements such as forest nitrogen cycle and agricultural productivity seem to be affected by climate change (Figure 6) (Raza et al. 2019; Rustad et al. 2012). Changes in precipitation, for example, may cause changes in hydrological fluxes, which in turn could result in changes in development, decomposition and absorption of nutrients. Correspondingly, temperature increase could also lead to changes in hydrological fluxes, soil disintegration and faster behavioural expansion, causing reduced yields and accelerated maturation (Bonan 2008; Hanson and Weltzin 2000). Precipitation is the most important factor in the continuing degradation of forests and agricultural land (Mousa et al. 2020). Higher rainfall has required a higher degree of output in some places of Pakistan and offered more water for irrigation. Due to the damage of fertile soils with extreme floods caused by regular rainfall or drought, the reverse effects were reported in some areas. The decreasing rate of woody biomass, on the other hand, is the second maximum in the world. It ranges from 4 to 6% annually (UNEP 2005). The climatic conditions that have escalated as a result of man-made and natural processes over the years are related to the reduction of forest area. The effect of temperature and precipitation on the vegetation area is confirmed by the regression analysis as the maximum temperature has increased and precipitation reduced over the years (Figure 6). As for driving factors, we have discussed three major groups of factors, including geographical, environmental and socio-economic factors. All these variables (land enlargement, deforestation, immigration, economical changes, population growth, urbanization etc.) were characterized by population growth, GDP, precipitation and temperature. Intergovernmental Panel on Climate Change (IPCC) states that the shifts in ambient humidity and rainfall are led by an increase in the global average temperature. The effects of temperature rise include extreme flooding, storms, dried up rivers that were seasonal reservoirs until recently and erratic conditions such as irregular span of the rainfall season, which could be delayed, shortened or interrupted by recurrent drought incidents. All these processes are also visible when analysing the climate conditions in Fateh Jhang. We are trying to overcome all the above-mentioned factors by aiming at reaching a balance between urbanization, conserving water bodies, woodlands and vegetation area by implementing new management techniques. This research has described the structure of the study area, which improves our understanding of the land use and land cover changes during the past years and allows for site-specific recommendations to facilitate and enable more efficient land use planning and design for both agricultural and built-up areas.

CONCLUSIONS

In this research, digital image processing techniques were used to evaluate the LULC and identify its changes. The analysis showed that during the period from 2000 to 2015, urban areas increased, consequently causing a significant reduction of vegetation and barren land area. The increase in water area was insignificant. The main objectives of this study were to identify the LULC changes in Fateh Jhang from 2000 to 2015 and highlight the driving factors of LULC changes through combining remote sensing, environmental, geographical and socioeconomic data. It was estimated that between 2000 and 2015 the built-up area increased from 16.31% to 22.06% of the total area, while vegetation decreased from 56.89% to 44.37% and barren land increased from 18.35% to 25.12% respectively. The change of vegetation and barren land into urban territories has caused varied and extensive environmental degradation of the study area, the main negative outcome of which was related to the slum growth that accompanies quick urban development. Socio-economic development and population growth are the main driving factors of urban land expansion. The findings of this research indicate rapid growth of built-up land and decline in agricultural land and vegetation area during 2000-2015. The study revealed a strong influence of integrated driving factors on land use and land cover at the regional and national scale. The region of Fateh Jhang in Pakistan has undergone rapid, wide-ranging changes in the LULC intensified by the conversion of natural resources for food purpose, urbanization and other socio-economic benefits. This research would be helpful to the urban planning and design department for land sustainability development.

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RESEARCH PAPER

EXPLAINING THE EFFECTIVENESS OF FOREST AND WATER MANAGEMENT AND ITS SPATIAL DISTRIBUTION IN THE METROPOLITAN DISTRICT OF QUITO

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ABSTRACT. The effective implementation of Sustainable Development Goals (SDGs) related to forests (SDG15) and water resources (SDG6) have significant implications for achieving quality of life for people in urban and rural areas. We carried out a study in the rural parishes of the Metropolitan District of Quito (MDQ), Ecuador. The objective of the study was to assess how biophysical factors, institutional capacity and institutional complexity influence the perceived effectiveness of forest and water management. Ordinal logistic regressions were applied and spatial lag regressions were also calculated to assess the possible spatial correlation of the dependent variables. Additionally, spatial autocorrelation analyses (Gi* and Anselin Local Moran´s I) were applied to assess the perceived effectiveness. The regressions results show that the number of stakeholders involved in the management of each resource, used as a proxy for institutional complexity, was a significant variable (p-value = 0.003 for forest resource management and p-value = 0.027 for water resource management) when explaining perceived effectiveness. The spatial autocorrelation results show spatial hotspots (90% and 99% confidence) and a cluster (95 % confidence) of forest management effectiveness as well as some spatial outliers (95% confidence) of water and forest management effectiveness. These findings were put in context to assess the current institutional arrangements used by local actors to implement SDGs 6 and 15. The results obtained may be useful for improving local public policies that seek integrated implementation for SDGs 6 and 15, while the applied methods can be transferred to the study of other SDGs

KEY WORDS: localization, policy effectiveness, local governments, water, forest, spatial analysis

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INTRODUCTION

The localization of Sustainable Development Goals (SDGs) is a keystone for achieving the ambitious transformation proposed by the 17 objectives contained in Agenda 2030. According to the UN, localization is the «process of defining; implementing; and monitoring strategies at the local level for achieving global, national and subnational sustainable goals and targets» (United Nations Development Programme 2014). Localization relies heavily on local governments to implement context-relevant interventions in interaction with other actors (Slack 2014; Reddy 2016). Effective natural resources management is one of the areas where cooperation among government and non-governmental actors is required to implement interventions that act upon the characteristics of the locale within broader policy directives (K. P. Andersson and Ostrom 2008). However, it is well documented that local governments in the Global South often exhibit low institutional capacity and lack the financial resources needed to contribute to the effective implementation of public interventions required by the SDGs (Eakin and Lemos 2006; Xue, Weng and Yu 2018). Therefore, our main research questions relate to how to characterize the effectiveness of forest and water management in local rural areas and how does the effectiveness vary spatially?

Among the 17 objectives of Agenda 2030, UN member states have prioritized issues such as ensuring access to water and sanitation for all (SDG6) and achieving the sustainable management of forests (SDG15). Additionally, according to SDG11, which calls to «Make cities and human settlements inclusive, safe, resilient and sustainable», subnational governments as well as local communities, private and non-governmental sectors must work together towards supporting positive economic, social and environmental links between urban, peri-urban and rural areas.

The effective implementation of SDGs related to water and forests in rural areas is fundamental to maintain and improve the quality of life for urban dwellers, especially for those living in the Global South (Okunola 2016). Additionally, the capacity of ecosystems to maintain their essential functions directly influences people´s well-being in rural areas where livelihood is highly dependent on forested land and water resources (Belay and Bewket 2015).

Despite the long-term interest in investigating environmental decentralization at the local level, empirical studies on how local governance conditions affect the political priority received by different SDGs are only emerging (see Cisneros, Cabrera-Barona and López 2020). Our research continues this line of work, highlighting the role of institutions in tackling environmental issues through local interventions in Ecuador. To do so, it investigates the contribution of biophysical and institutional factors to the effectiveness of water and forest management in the rural sections of the study area. Biophysical characteristics of forests and water resources, institutional complexity of management initiatives and institutional capacity of local governments are used to explain effectiveness. This is complemented with the analysis of spatial autocorrelation of the effectiveness to grasp insights from the spatial dynamics of the water and forest management effectiveness.

Ecuador was an early adopter of SDGs as an umbrella for its public policies, and local governments started incorporating them into their local development plans as early as 2016, which makes it a good candidate for studying the joint implementation of Agenda 2030. Additional work on the issue of decentralization of natural resources management in the context of Agenda 2030 and SDGs is vital for at least two reasons. First, measuring and reporting the existing levels of engagement with SDGs can inform strategies to assist local governments and their partners in designing and implementing better interventions. Additionally, agencies in charge of institutionalizing Agenda 2030 at the national level require independent assessments of the conditions that help local governments achieve their desired environmental outcomes to design appropriate support mechanisms.

The article continues with the presentation of a conceptual background for the study of decentralization of natural resources management in the context of the post-2015 development agenda, including topics of institutional capacity and complexity as well as spatial interactions. After this, the section on materials and methods is presented. It contains a description of the study area, variables along with the regression and spatial methods. The next section presents the results which are followed by a discussion section where the findings are contextualized. The last section of the article offers general insights regarding the localization of SDGs and future research related to this issue.

CONCEPTUAL BACKGROUND

The idea that local government enjoys a privileged position to facilitate the mobilization of local development stakeholders for promoting inclusive sustainable development within their respective localities, is far from new. Decades of studies of decentralization policies highlight the need for local governments to develop the capacity to localize policies to effectuate change towards sustainability (Reddy 2016). Decentralization efforts have occurred in several waves, but most recently, they have been identified with the promotion of efficiency and the enhancement of public services, as well as with support for more open and accountable forms of government (Larson and Ribot 2004). Regarding environmental decentralization processes, previous research shows that they often occurred too hastily, reducing the potential of decentralization to produce more democratic and accountable institutions (Ribot, Agrawal and Larson 2006). For over three decades, governments have adopted decentralization policies to put the management of environmental resources closer to those directly impacted by them. Strategies for the devolution of responsibilities have varied from deconcentration of national agencies to the transfer of competencies to the lower levels of government or sectoral authorities. In some contexts, resources have been privatized (Wilder and Romero Lankao 2006) seeking to improve environmental outcomes. The move towards decentralization influences new interactions at the local level and creates new dynamics across scales that may or may not produce the desired results. Decentralization thus includes localization but it is not limited to it, as it also refers to the evolution of the interaction between different levels of government to deliver policy.

One particularly productive strand of the literature on decentralization that sheds light on the localization of SDGs is inspired by the works of Elinor Ostrom and the Bloomington School of Political Economy regarding the management of shared resources (e.g., infrastructure, common-pool resources). This study highlights the capacity of local actors to create local arrangements for managing resources. These arrangements, often informal collaborations between actors, are framed but not determined by the formal rules and norms of decentralization or other policies. The abundant literature produced by and after Elinor Ostrom highlights that local arrangements emerge in response to the characteristics of the resources under management (e.g., forests or water), the interaction of the actors governed by institutions and, in the context of environmental decentralization, the capacity of local governments to implement policy (Anderies and Jansen 2013).

The characteristics of the resources largely determine the scope and demand for resources that the implementation of public interventions will have. Given the very large difference among settings, actors tailor rules to diverse combinations of biophysical attributes, such as the size of the resource or the mobility of its resource units (e.g., water or trees). Therefore, as Ostrom (2005) suggests, analysts should not assume uniformity across all situations within a country. In particular, the relative size of a resource may bring more actors together, require that interventions generate more or larger behavioral changes and demand more resources for monitoring and management.

Sustaining the resources shared by urban and rural areas is a challenging task, and not one form of governance is fit for achieving this goal (Kooiman 2003; Young 2003). In reality, a wide range of actors, including local governments, not-profit organizations and local communities interact in complex social networks that define the rules and norms or institutions by which they use shared resources (Rydin and Falleth 2006; Bodin and Prell 2011; Henry and Vollan 2014). We follow the broad definition of institutions as the prescriptions that humans use to organize all forms of repetitive and structured interactions (Anderies and Janssen 2013).

The influence of institutions on policy outcomes depends largely on how actors define the appropriateness of the rules and norms in the face of specific environmental challenges along with how they use them (Ostrom 2008). Batterbury and Fernando (2006) argue that new governance regimes (e.g., the decentralization model adopted in Ecuador in 2008) alter the capabilities of state and civil society actors in ways that are often at odds with the legal prescriptions enshrined in law or in management policy that mandate collaboration across scales to produce desirable policy outcomes.

Therefore, the institutional complexity or institutional landscape in a given jurisdiction creates a variety of challenges for effectively allocating resources for public action. Complex governance arrangements often require the collaboration of an extended number of actors across multiple levels along with the definition and use of a large number of rules to tackle existing environmental challenges (Berardo and Lubell 2016). Local governments may participate in such arrangements even when the institutional capacities they have are limited. Some will join as free riders, letting partners do what they are not capable of or willing to do. Others will join to monitor the behavior of their peers to make strategic decisions about their engagement with natural resources management (Ostrom 2005). In sum, a large number of actors and rules increases the complexity of collaborative arrangements because they require more resources to produce and sustain collective action, and often there is competition among groups of actors for the provision of one public good or service (Ostrom 2008; 2005), such as when different levels of government share competencies over a policy issue.

The institutional capacity of local governments to implement their assigned competencies is critical to achieving the desired policy outcomes. In his literature review on municipal performance in forest management, Andersson (2003) shows that institutional capacity is one of the main factors explaining the production of desirable management outcomes. The literature on environmental decentralization shows that institutional capacity is of particular importance for natural resource governance (de Oliveira 2002; Andersson and Ostrom 2008; Fiszbein 1997). This paper follows Fiszbein´s (1997) definition of local capacity as the existence of the government tools in the areas of labor, capital and technology. Local governments need financial resources, qualified personnel and the ability to organize their internal affairs, as well as to engage with other actors. Institutional capacity is of particular importance for the localization of SDGs or the translation of global, regional, and national objectives into context-appropriate interventions (Wymann von Dach et al. 2018). In the context of the previous conceptual background, it can be concluded that the biophysical characteristics of the natural resources, governance arrangements and institutional capacity of local governments are associated with policy outcomes that subsequently represent the success or failure of SDG implementation. One challenge is how to account for these policy outcomes when there are no detailed and official indicators or statistics available, especially in rural areas. The perceived effectiveness has been proved to adequately represent the management of nature-related phenomena at a local level (Pradhan et al. 2017) and to be associated with social behaviour, policy implementation and use of natural resources (Pradhan et al. 2017; Wan, Shen and Yu 2014). In this context, the perceived effectiveness of forest and water management is assessed considering the characteristics of their respective natural resources, the complexity of governance arrangements and the institutional capacity of local governments. The perceived effectiveness was identified from the elected officials of local governments.

Local governments do not face the dynamics of localization in a vacuum. In principle, they develop patterns of interactions due to shared (interpretations of) problems that relate to the spatial distribution of natural resources as well as the resources needed to formulate and implement policies. Zuindeau (2006) argues for using a spatial approach to understand the challenges related to sustainable development, in particular those arising between the logics of sustainability and competitiveness. Thus, the effectiveness of SDG-related actions also has spatial implications because the satisfactory performance of some policy-oriented actions in one territory may lead to their adoption in the neighbouring jurisdictions with similar problems (Nicholson-Crotty and Carley 2016). As Cook, An, and Favero (2018) argue, spatial analysis of policy implementation highlights interdependencies between jurisdictions that will contribute to alleviating problems such as increasing rates of deforestation or poor water management practices. For this reason, studying the spatial distribution of the perceived effectiveness of water and forest management and evaluating interdependencies (that can be identified by spatial autocorrelation) between areas where this effectiveness is expressed are crucial approaches for a better understanding of the natural resources management in the local governments of the study area.

MATERIALS AND METHODS

Our study site is located in the rural zone of a metropolitan area in Ecuador. Ecuador is one of the most biodiverse countries in the World (Myers et al. 2000; Bass et al. 2010) as 20% of its landmass territory is composed of protected areas that include diverse forests and watersheds (Cuesta et al. 2017). This study was carried out in the rural parishes of the Metropolitan District of Quito (MDQ), a District that includes the capital city of Quito. The MDQ encompasses 32 urban parishes and 33 rural parishes which are the lowest level of government in the country. According to the last Ecuadorian Population and Housing Census, the MDQ had 2.2. million inhabitants (INEC 2010). For 2020, the projected MDQ population is 2.7 million (INEC 2020). The MDQ houses around 20 percent of Ecuador's urban population in the city of Quito (located at 2850 meters above sea level, m.a.s.l), a city with political, financial and symbolic resources to distinctively respond to SDGs compared to the rest of the country (Horn and Grugel 2018). The urban parishes that form the city of Quito (see Figure 1) are managed by an elected Mayor and a City Council. On the other hand, residents of the rural parishes elect a local government (Juntas Parroquiales) with competencies that occasionally overlap with those of the city of Quito, the province of Pichincha and the national government.

The MDQ has an area of 4231 square kilometers with 54 % of it covered by forests and other natural areas. The ecosystems of the District are diverse as they are influenced by the altitudinal variations, from the valleys (2500 m.a.s.l) located at the east of the city of Quito, to the Pichincha volcano complex (4794 m.a.s.l.) located at the west of the city, including the tropical forests (around 1200 m.a.s.l.) located in the northwest of the District. The MDQ contains several river basins and other bodies of water, some of its main rivers are San Pedro, Pita, Machángara, Guayllabamba and Mindo, located mostly in the rural parishes.

Local initiatives for water and forest management are shaped by the history of environmental decentralization in Ecuador. In the late 1990s, the fragmentation of the political system reinforced bottom-up demands for decentralization and forced the transference of competencies from the Ecuadorian Ministry of the environment to other sectors and levels of government even before the national authority had consolidated as such. This reduced the capacity of both the national and local authorities to perform their assigned roles (Faust et al. 2008). Between the years 2000 and 2008, when the new decentralization regulations were approved as part of a new constitution, Ecuador lived a period of decentralization *á la carte* (Bedón Tamayo and Guerra Terán 2012). Each local government requested additional competencies creating a complex system for the transfer of financial resources. The aim of the decentralization policy was that deepening decentralization should set a configuration of public interventions where local governments have an important role in making decisions and implementing policies with their allies.

Considering this context, it is crucial to determine what local governments are doing to localize SDGs and how successful their initiatives are according to their particular characteristics.

To document the SDG-related initiatives undertaken by local governments and their partners as well as their outcomes, we used a standardized survey questionnaire divided into three sections. The first section gathered information about a wide array of policy initiatives in which local governments participate, including environmental issues. This section also provided information about the public, private and social actors involved in the implementation of these initiatives. The second section gathered information on the perceived effectiveness of the actions identified in section 1. We were able to apply the questionnaire in 31 of 33 rural parishes (n = 31). Respondents evaluated the achieved effectiveness of each policy issue on a 3-point Likert scale. In all cases, the respondent was the president of the parish and completion of the survey took about 1 hour and 10 minutes on average. All parish presidents had been in office for an average of 8 years before participating in the study, which provides them with enough knowledge on the issues of interest. The third section gathered information about the existing institutional capacities of the local government to implement those initiatives.

Policy effectiveness is the dependent variable in this study. Given that objective measures of policy effectiveness are often unavailable in developing countries (Geddes 1994; Eakin and Lemos 2006) we conducted this study using the perception of policy effectiveness as a proxy. The perceived effectiveness of public activity towards SDGs was defined as the extent to which public interventions are producing the desired management outcomes according to those

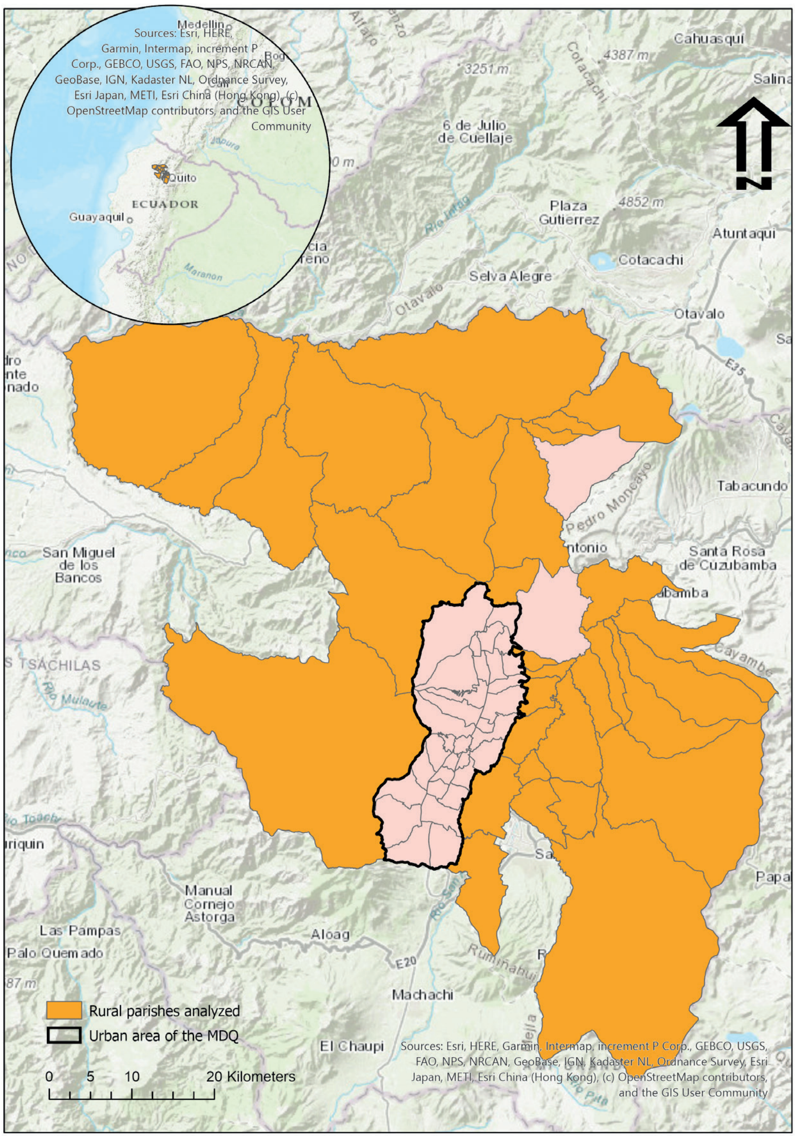

Fig. 1. Study area

Source: the authors. Study area generated based on geoinformation provided by the open-access database of the Municipality of the Metropolitan District of Quito promoting them. We used the acronym EFFO to refer to the perceived effectiveness of policies related to forest issues and EFWA for the perceived effectiveness of water policies. Policy initiatives related to each natural resource tackle several subdimensions. Our survey shows that, for the case of forests, rural parishes work on forest conservation, controlling the expansion of the agricultural frontier and forest-fire prevention. For the case of water, rural parishes work on increasing access to drinking water and sanitation and managing the growth in water-demand.

The first independent variable relates to the characteristics of the biophysical context where local governments and their allies intervene. The percentage of the forested regions (WOFO) and the number of drains per capita (WA3) were used for each parish as a proxy to the biophysical characteristics. WOFO was calculated using the land use map of the Metropolitan District of Quito and WA3 was calculated using open-access information provided by the Municipality of Quito. The assumption is that jurisdictions with extensive forested areas or more natural drains may face more significant management challenges.

The second independent variable is institutional complexity which we study by measuring the number of stakeholders involved for each resource, namely forests (GOFO) and water (GOWA). Each one of these resources is managed through institutions that are put in place by many actors in several venues according to specific rules and norms. In the MDQ, these venues include local decision-making venues as well as cross-scale initiatives. We used the count of actors participating in the management of each environmental component as a proxy to institutional complexity because our data shows that the number of actors correlates perfectly with the number of venues.

The third independent variable is the institutional capacity of the rural parishes. To measure this variable, we used a score of the number of areas with weak capacity (CA) in each rural parish reported by the parish president. This score was constructed using dummy variables representing the lack of institutional capacity across five domains: administration, finance, planning, project design and implementation, and social participation. The higher is the score, the weaker is the institutional capacity of the local government.

Since EFFO and EFWA are ordinal variables, ordinal logistic regressions were applied applied to evaluate how the independent variables influence the scores of perceived effectiveness. Considering the number of parishes studied (n = 31), and the three predictors used, the statistical power of the performed regression was higher than 0.8 (large effect size, α = 0.05, two tails).

Additionally, using bivariate analysis, the relationships between the effectiveness and the independent variables was assessed to explore how will each independent variable in isolation explain EFFO and EFWA.

Others have used geospatial information extracted from remote sensing to measure the implementation of SDG 15 in China (Liu, Bai and Chen 2019). However, there is little spatial analysis applied to SDGs-related policy actions based on subjective measures. In this context, spatial lag regressions were calculated to assess whether spatial dependencies of perceived effectiveness exist, which would mean that spatial distribution of rural parishes influences the perception of effectiveness measured across them. The assumption is that neighboring parishes should exhibit similar levels of perceived effectiveness because they are more likely to share problems than non-neighboring ones (e.g., forest fires or increasing water demand). The Getis-Ord Gi* statistic was also applied to identify hotspots and coldspots of perceived effectiveness of policy implementation in the rural parishes. The Gi* statistic identifies entities (parishes) with high values of perceived effectiveness that are surrounded by other parishes with high values of perceived effectiveness. Finally, the Anselin Local Moran´s I was calculated to identify spatial clusters and outliers for perceived effectiveness.

RESULTS

As expected from the literature, we found a diversity of actors involved in the implementation of SDG-related initiatives in each rural parish of the MDQ. The number of actors reported as partners of rural parishes is 13 on average. These actors include public sector organizations from other levels of government, as well as non-governmental actors such as grassroots organizations and private companies. Also, regarding institutional capacity, a mode of 3 was found and the closer this variable is to 5, which is the number of institutional areas evaluated, the lower is the capacity. Table 1 shows the results of the ordinal logistic regressions that associate institutional capacity and complexity, as well as the characteristics of forests and water with perceived effectiveness.

In the case of the regression with the perceived effectiveness water, with of forest management as the dependent variable, only the number of stakeholders involved (GOFO) was found to be significant. For the perceived effectiveness of water management as the dependent variable, the number of stakeholders involved (GOWA) was also found significant. The pseudo R^2 indicates that the calculated EFFO and EFWA models may explain 21% and 31% of the variance of perceived effectiveness, respectively. In the EFFO model, the significance level of the test of parallel lines (TPL) shows the existence of the same slope coefficients across response categories.

Table 1. Ordinal logistic regression results

EFFO	Covariates	Estimates	Significance
Pseudo R^2: 0.210	CA	-0.048	0.867
TPL: 0.200	GOFO	0.302	0.003
	WOFO	0.003	0.763
EFWA			
Pseudo R^2: 0.310	CA	-0.464	0.130
TPL: 0.000	GOWA	0.272	0.027
	WA3	5,923	0,174

Source: the authors

Table 2 shows the results of several ordinal logistic regressions that consider only one independent variable. GOFO was again identified as a significant predictor of EFFO, but in the case of EFWA model, the covariates CA and GOWA show to be significant predictors of EFWA (95% and 99% confidence level, respectively). GOFO may explain 21% of the variance of EFFO. CA may explain 12% of the variance of EFWA, while GOWA may explain 20% of EFWA´s variance.

Table 3 shows the results of the performed spatial lag regressions. In the case of the regression with the perceived effectiveness of forest management as the dependent variable, the number of stakeholders (GOFO) is significant, mirroring the result obtained in the ordinal regression. The R^2 indicates that the calculated model may explain 28% of the variance of perceived effectiveness. The additional covariate obtained in this regression, EFFO-S, which represents the spatial dependency of perceived effectiveness, is not significant, which suggests that there is no influence on the observations of perceived effectiveness by neighboring observations. The Breusch-Pagan (BP) test of significance indicates that the assumption of homoscedasticity is accomplished for the model. The Likelihood Ratio (LR) test of significance confirms that the dependent variable does not have spatial effects.

In the case of the regression with the perceived effectiveness of water management as the dependent variable, the number of stakeholders (GOWA) is also significant, as it was in the results obtained for the ordinal regression. In this case, the R^2 indicates that the calculated model may explain 28% of the variance of the perceived effectiveness. The additional covariate obtained in this regression, EFWA-S, representing the spatial dependency of perceived effectiveness was not significant, which suggests that there is no influence on perceived effectiveness observations by neighboring observations. The significance results for the Breusch-Pagan (BP) test and the Likelihood Ratio (LR) test indicate the homoscedasticity condition and the absence of spatial effects, respectively.

Figure 2 shows the results of the Gi* statistic. Hotspots for the perceived effectiveness of forest management were identified in two western rural parishes of the Metropolitan District of Quito, while significant coldspots appear in some eastern rural parishes (Figure 2a). In the case of the perceived effectiveness of water management, only coldspots were found in two eastern rural parishes (Figure 2b).

Figure 3a presents the results of the Anselin Local Moran´s I, which identifies spatial clusters and outliers at 95 % of confidence. This measure defined a northern parish as a cluster of high perceived effectiveness of forest management. On the other hand, clusters of low perceived effectiveness of forest management were identified in eastern parishes. One eastern parish was identified as an outlier in terms of forest management; that is a parish with high perceived effectiveness of forest management surrounded by parishes with low effectiveness. In Figure 3b, the Anselin Local Moran´s I identified one low-high outlier (low EFWA surrounded by parishes with high EFWAs) in a northern parish, and two high-low outliers (high EFWA surrounded by parishes with low EFWA).

DISCUSSION

This study is a contribution to the ongoing discussion on the localization of Agenda 2030 and SDGs in developing countries framed under the larger discussions of environmental decentralization. The focus of this paper is on how biophysical and institutional variables explain the local-based perception of the effectiveness of

Table 2. Ordinal logistic regression results considering only one independent variable

EFFO	Estimate	Significance
Model with only CA as covariate Pseudo R^2: 0.01	0.142	0.610
Model with only GOFO as a covariate Pseudo R^2: 0.21	0.290	0.003
Model with only WOFO as a covariate Pseudo R^2: 0.00	0.000	0.997
EFWA		
Model with only CA as a covariate Pseudo R^2: 0.12	-0.634	0.034
Model with only GOWA as a covariate Pseudo R^2: 0.20	0.336	0.008
Model with the only WA3 as a covariate Pseudo R^2: 0.12	7.997	0.063

Source: the authors

Table 3. Spatial lag regression

EFFO	Covariates	Coefficients	Significance
R^2: 0.280	CA	0.154	0.631
BP: 0.123	GOFO	0.215	0.021
LR: 0.131	WOFO	0.003	0.781
	EFFO-S	0.294	0.125
EFWA			
R^2: 0.280	CA	-0.188	0.611
BP: 0.323	GOWA	0.346	0.007
LR: 0.345	WA3	2.533	0.593
	EFWA-S	0.205	0.302

Source: the authors

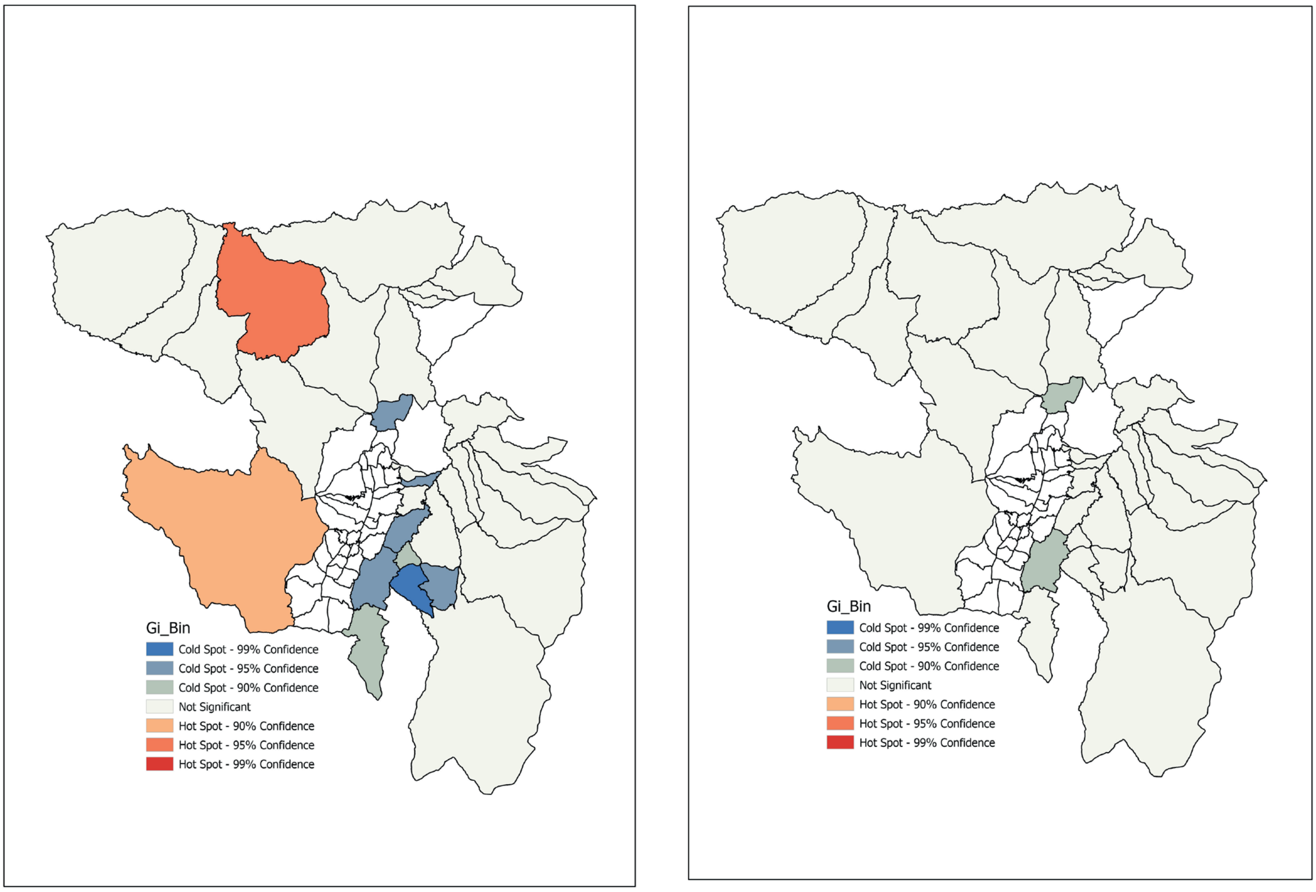

Fig. 2. Results of Gi* statistic for (a) Perceived effectiveness of forest management; (b) Perceived effectiveness of water management

Source: the authors

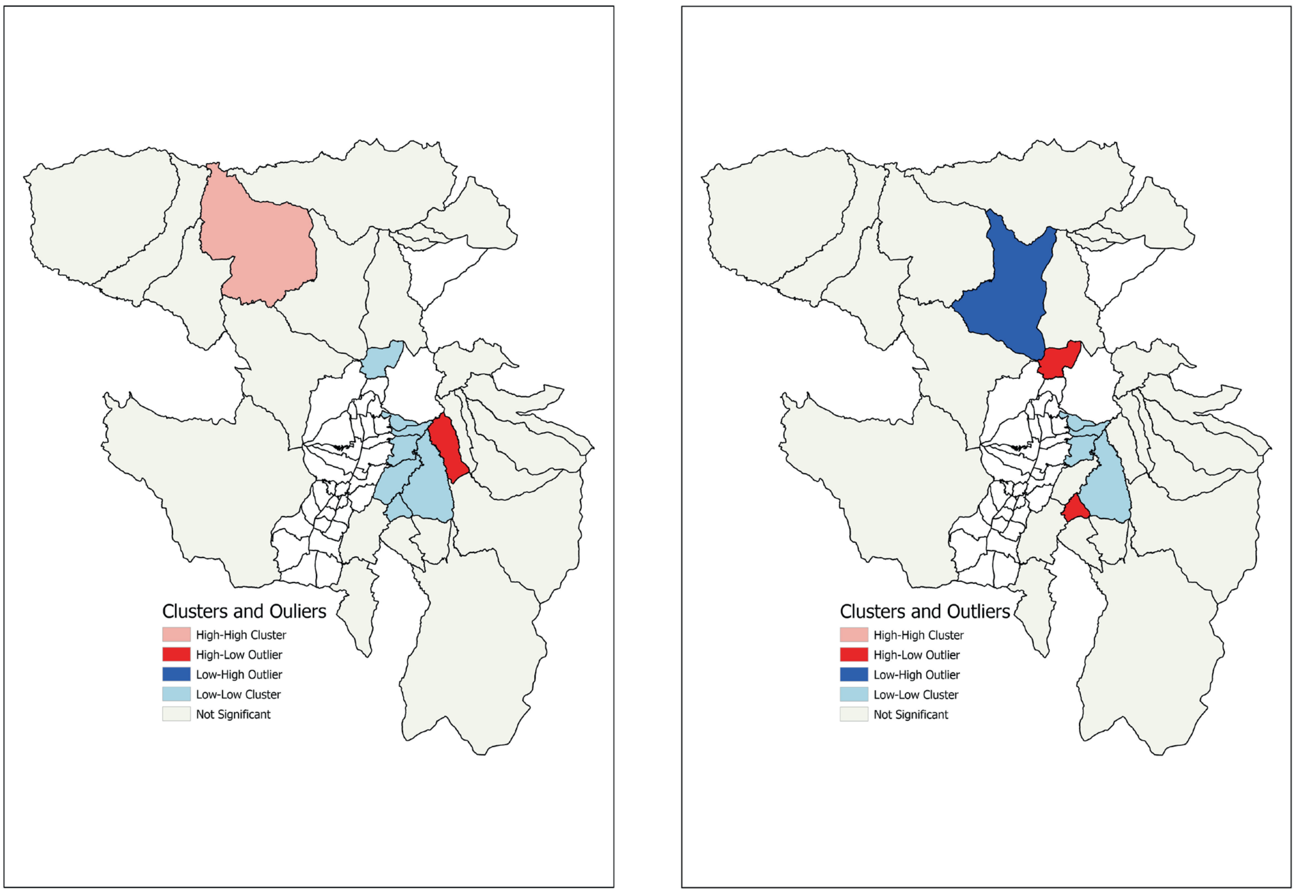

Fig. 3. Results of Anselin Local Moran´s I for (a) Perceived effectiveness of forest management; (b) Perceived effectiveness of water management

Source: the authors

environmental management related to forests and water. The originality of the approach lies in the fact that we linked subjective measures of policymaking (institutional capacity and institutional complexity) with objective measures of water and forest resources (percentage of the forested regions and number of drains per capita) and performed statistical and spatial analyses to understand the outcomes of public interventions (effectiveness of the water and forest management). To our knowledge, this is the first study to deal with the objective-subjective and spatial issues of SDGs in Latin America.

The regression analysis of the survey data showed no significant relationship between the characteristics of the natural resources of interest (forests and water) and the perceived effectiveness of the management of these resources. This is surprising considering the striking differences in forested areas and the number of drainages across rural parishes.

However, the most striking result from our analyses is the lack of significance of the local government's capacity as a predictor of perceived effectiveness for both forest and water management. In other words, the ability to organize their internal affairs, to plan and bring local actors into implementing SDG-related actions does not seem to affect the effectiveness of forest and water management. One possible explanation for this finding relates to the fact that despite their differences, rural parishes still have very limited resources to design and implement SDG-related initiatives. The Ecuadorian legislation allows governments of urban municipalities to use a wide array of tools to collect revenue but makes rural parishes dependent on transfers from the central government (Díaz-Cassou and Viscarra Andrade 2017; Dávila, Villares and Placencia 2018). During fieldwork, respondents offered anecdotal evidence that these transfers were, in most cases, only sufficient to cover the salaries of a very basic staff. For this reason, most of their work is related to facilitating interactions of other actors in their jurisdiction. Our findings suggest that instead of being the main actors in the localization of SDGs, rural parishes may be only responding to initiatives headed by other actors. Only in the bivariate analysis of water management, the capacity of the local governments was found to be significant. This suggests that some interaction effects between variables could be at play and also that capacity is more important for water than forest management, given that in this context, water management usually requires to maintain higher levels of capital spending.

The significance of the institutional complexity studied using the number of stakeholders involved in forest and water management (GOFO and GOWA) matches findings from previous research that identifies social actors and their activities as drivers of water governance regimes (Wiek and Larson 2012). This body of research suggests that hydro-social cycles are inherently political, historical and cultural (Wiegleb and Bruns 2018). Our findings should be interpreted considering what we now know about institutional capacity. Parishes interact with several actors for the localization of public interventions towards SDGs and, as the number of actors increases, the perception of effectiveness also increases. This significant relationship could be the consequence of officials in local governments getting the feeling that things are getting done while instead, much time is spent organizing and facilitating repeated interactions. This phenomenon has been described by Leach and Sabatier (2005) as the ´halo effect´ and explains why the overall perception of effectiveness is high across parishes regardless of the forested area and the density of drainages, as well as the self-reported institutional capacity. However, this upward bias in the perception of environmental improvement should be tested empirically using objective data.

The spatial analysis shows that the perception of effectiveness by neighboring authorities do not influence each other. This finding is indicative of the possible lack of interactions among the local authorities of parishes, which is a problem from the localization perspective because shared problems are better tackled by joint initiatives. Moreover, this finding adds credibility to the idea that some ´halo effect´ is at play. If actors objectively share problems, such as forest fires and water scarcity, but they perceive that management is effective despite their lack of interactions, something is skewing that perception.

Additionally, this finding supports the idea that actors at other levels of government draw parishes towards interventions related to SDGs. However, this is not necessarily a problem for localization given that its idea is that local government involvement exists in a significative manner rather than local governments leading all processes. Nevertheless, this finding strengthens our doubts about the appropriateness of the policy initiatives in terms of solving local problems due to the skewed perception of policy effectiveness.

On the other hand, scale effects may also affect the non-spatial dependency of the perceived effectiveness variable at the parish level. Moreover, other relationships among local stakeholders (at village or neighborhood level) may present spatial autocorrelation of perceived effectiveness. Further research will be required to explore spatial tendencies of the dependent variable at different scales.

The spatial analysis found hotspots as well as coldspots of perceived effectiveness for both forests and water. The distribution of these spots can be explained by the pattern of the urban frontier expansion. In our fieldwork, this phenomenon was identified as one of the most common concerns among presidents of rural parishes. The city of Quito and its conurbations are expanding aggressively towards the eastern parishes reducing their capacity to manage the remnants of existing forested lands. The rules and norms that govern the interactions between rural parishes and the metropolitan government explain this phenomenon. Although rural parishes define a local development plan that includes the management of the natural environment in their jurisdiction, the metropolitan government of Quito is in charge of granting all building permits. For instance, the eastern parish of Cumbayá is administratively considered a rural parish. Still, in reality, this parish is practically urban given its low percentage of non-urban land-use. It constitutes one of the most attractive areas for urban development due to its proximity to the new international airport. Therefore, it is not surprising that in this parish and its neighboring parishes (Figure 2a) coldspots of perceived effectiveness in forest management were identified. In other words, the most urbanized rural parishes report less effective forest management.

On the other hand, the two western rural parishes of Lloa and Nanegal are the hotspots of perceived effectiveness in forest management. These parishes have large areas of sub-tropical forests and lay beyond the current urban expansion of Quito. Nanegal was also identified as a cluster of high perceived effectiveness in forest management (Figure 3a). This parish sits within an area where private and community forest reserves have been created in the past two decades. In addition, our data show that a great diversity of actors takes part in the implementation of interventions in this area which also suggests the presence of a halo effect.

Additionally, the eastern rural parish of Puembo was identified as a spatial outlier in terms of forest management. Several states belonging to high-income residents and agro-industrial companies are located in this rural parish. The land is often occupied by forest plantations with exotic species, especially eucalyptus. This may influence the perception of the high effectiveness of forest management compared to their neighbors. However, the composition of property ownership suggests that fewer interactions among actors are present in this parish in comparison with their more populated neighbors.

In terms of water, Figure 2b shows significant low levels of perceived effectiveness of water management in two parishes, Pomasqui and Conocoto. This situation is also related to the pattern of the city expansion. In the past two decades, the urban sprawl has been relentless in those areas. However, this growth is qualitatively different from that of some eastern parishes such as Cumbayá, as it is mainly devoted to tackling demand from lower socioeconomic groups, which involves a more significant number of developers, some of them informal, and fewer resources to protect the water streams.

The cluster analysis shows that the northern parish of Calacali is a territory with low perceived effectiveness of water management surrounded by parishes with high perceived effectiveness (Figure 3b). Calacali is the northern rural parish with relatively dry weather and a low density of drains compared with their most tropical parochial neighbors such as Nanegal. We could assume that the local authorities and stakeholders in Calacali may have little incentives for managing water bodies due to its low population density and water resource characteristics.

On the other hand, two parishes, Pomasqui and Guangopolo, were found to be high-low outliers in water management, meaning that authorities in these parishes report higher perceived effectiveness compared to their neighbors. Both parishes have experienced continuous urbanization in the last 20 years and rank among the most densely populated in the sample. Therefore, urban residents and the recent economic development of both areas with a highway connecting them to the city may be offering political incentives for local authorities to manage water resources or at least to interact frequently with other actors, creating the ´halo effect´.

Finally, institutional complexity expressed in the number of stakeholders is influential for the management of forests and water in the rural parishes. However, this finding does not imply that an effective and permanent network of stakeholders oriented towards the implementation of SDGs exists. On the contrary, our study shows that institutional complexity plays a role in how local governments implement SDG-related actions. In particular, the way intergovernmental interactions are designed and executed is still constraining the participation of the lowest levels for the government. Moreover, the spatial regression analysis suggested a lack of communication between the lowest levels of government despite their shared environmental problems and the need to complement each other´s lack of institutional capacity.

The lack of policy coherence highlighted by the different priorities of the city and the parish governments suggests that although some mechanisms of citizen participation have been implemented in the MDQ, there are several challenges for proper participatory governance, such as patronage practices embedded in hierarchical structures and corporate management models (Córdova 2011).

CONCLUSIONS

The localization of Agenda 2030 and its 17 SDGs relies on the participation of the levels of government that are closer to the people to formulate and implement actions in ways that are relevant to the context. However, the involvement of local governments needs a nurturing environment, one that provides resources and helps to close the gaps in institutional capacity. Localization needs to be supported by decentralization policies that create the conditions to achieve it. Our approach to the study of the effectiveness of SDG-related actions in the rural area of the Metropolitan District of Quito shows what happens when such an environment is not nurturing but harming. In this case, the presence of certain types of interactions across different levels of government and among actors are isolating the rural parishes from each other and creating a ´halo effect´.

Better strategies are required to ensure that the participation of local governments in policy implementation is meaningful. Joint evaluation of shared problems could help authorities in charge of the implementation of Agenda 2030 to have more assessment of the outcomes of the localization of interventions. Indeed, it is increasing the diversity of interactions that may help actors have a better understanding of the state of natural resources in their jurisdictions.

Future studies should look into whether different objective measures of environmental interventions could influence perceived effectiveness in other ways. In this case, the scale of the analysis did not allow us to determine more detailed characteristics of the SDGs-related interventions. Some communities in the rural parishes may have specific governance configurations than those reported by parish authorities. Additionally, continuing research into spatial methods to produce and assess SDGs indicators appears fully justified because of the implications of geo-located SDGs actions and achievements for decision making and planning, especially at the local level. In this sense, spatial analysis needs to incorporate qualitative measures beyond the traditional GIS-based indicators in order to understand SDG localization from a more comprehensive and pluralistic perspective.

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RESEARCH PAPER

MAPPING FOREST AND AGROFORESTRY UNITS FOR ENVIRONMENTAL PLANNING. STUDY CASE TRANSBOUNDARY REGION MEXICO-GUATEMALA

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ABSTRACT. The cross-border region of Mexico and Guatemala is part of the continuum in the aspects of relief, climate, hydrography, geology, land cover and land use of Mesoamerica, one of the most biologically diverse regions on the planet. Historically, the region has been continuously affected by meteorological phenomena, such as mass movement in the highland and floods in the lowland, which affected cities, communities and production activities year after year and led to the loss and deterioration of the ecosystems. To handle this problem, a proposal for environmental planning is suggested. The final objective is to provide key information that concerns the implementation of Sustainable Development Goals, particularly related to the protection and restoration of forest areas. In this study, spatial analysis and modeling were applied to map homogeneous units for environmental planning in the Mexico-Guatemala trans-border region. Additionally, forest area as a proportion of the total land area, its share inside the natural protected areas and distribution by ecosystem type were calculated for 2010 and 2019. From the data analysis it was found that the total forest area in the region has decreased from 47% in 2010 to 43 % in 2019; 27% and 25% of the total area, respectively, correspond to forests within the natural protected areas. The principal ecosystem type in the Natural Protected Areas corresponds to tropical forest. Two conclusions can be drawn, that agroforestry zoning is an important tool to monitor forest areas in the context of achieving Sustainable Development Goals and that the natural protected areas play a fundamental role in the preservation of the forest in the region.

KEY WORDS: Mapping, forest, agroforestry, natural protected area

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INTRODUCTION

The cross-border region[1] of Mexico and Guatemala is a part of the continuum in the aspects of relief, climate, hydrography, geology, land cover and land use of Mesoamerica, one of the most biologically diverse regions on the planet. It is one of the most important areas among the world's 25 biodiversity "hotspots" in terms of species diversity and endemism (Conservation International – México and Central América Program, 2004).

In this region, natural vegetation with a little degree of intervention (forests and wetlands), which is found mainly in natural protected areas, comprises 42.7% of the total area. The other 54.7% of the area corresponds to the coverage associated with anthropogenic action that includes grassland, agriculture, plantations, shrub vegetation and urban areas (Lopez D. y Saavedra A., 2019). Many of the agricultural areas are located on hillside lands with slopes of 12-50% and higher and shallow soils, which are not suitable for such purposes. For this reason, the agricultural activity causes the processes of land degradation (water erosion, deforestation, loss of biodiversity) in highland, which translates into floods in the lower areas due to the high runoff generated in the upper parts of the watershed. In the last two decades, the cross-border region has become a territory of major social changes due to the impact of the different socio-economic, political and environmental processes.

Historically, the region has been continuously affected by meteorological phenomena, such as mass movement in the highland and floods in the lowland, which affected cities, communities, production activities and natural resources year after year. This vulnerability increases with global warming and increasing human intervention (fires, deforestation and drying of wetlands) as well as from inadequate land use and management leading to the loss and deterioration of the ecosystems, which modifies the hydrological dynamics of watersheds.

In response to this problem, a proposal for environmental planning and management with an emphasis on forest and agroforestry systems is suggested. Based on this, appropriate public, federal, local and binational policies that allow the cross-border region to ensure the quality of life, environmental sustainability and shared development can be adopted.

[1] The area considered here is the one defined by the authors in the Project: "The natural environment and land suitability as a base for rural management, Cross-border Mexico-Guatemala".

The final objective is to provide the information for decision-making that ensures the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems, including forests, wetlands and mountains, in line with the obligations under international agreements, as stated by the Sustainable Development Goals, particularly the **Goal 15:** *Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss. Additionally, as part of the data analysis, the following indicators proposed for this goal will be reflected: the proportion of forest area in the total land area and proportion of important sites for terrestrial and freshwater biodiversity that are covered by protected areas, by ecosystem type. Finally, an analysis of the evolution of these indicators for the considered area between the years 2010 and 2019 will be conducted.*

Zoning and management of forest areas is a key element to encourage their protection and restoration as well as promote sustainable use of terrestrial ecosystems

Zoning as an instrument of planning facilitates the identification of geographical areas with a combination of physical, biological, human and institutional features that can be interpreted in terms of objectives for the management. The application of this instrument must be supported by information that enables the analysis of different environmental processes describing the heterogeneity of the study area (Ortiz-Lozano et al. 2009).

The zoning of the aptitude of territory represents its division into homogeneous zones based on environmental criteria, which is considered a synthesis of the biophysical, socio-cultural and economic conditions, and at the same time, a basis for a proposal for environmental management. This analysis allows to produce differentiated recommendations of the interventions and actions that have to be taken. The zoning seeks to ensure an adequate supply of environmental goods and services that responds to the objectives of management through the optimization of the uses of territory in specific units (Valenzuela and Silva 2003).

The territorial zoning, which is usually seen as a methodological tool that allows the spatial differentiation of geographical areas, has been applied for planning and arranging of the territory (López et al. 2012; López D. and Saavedra A. 2007, 2019; López D., Saavedra A. and Castellanos L. 2016; Domínguez et al. 2008). The use of this approach as a basis for land-use regulation enriches the knowledge of natural resources distribution, its dynamics in time and tolerance of the environment to human intervention. Also, it allows to evaluate the productive aptitude of the territory and the potential conflicts between the aptitude and the current use of soil. In this sense, the spatial arrangement in "homogeneous" units in this project will constitute the physical natural sustenance for the design and application of policies and programs of land management.

MATERIAL AND METHODS

The study area

The study area (Figure 1) covers an approximate surface of 116,008.6 Km^2 and consists of five physiographic regions: the Yucatán platform in the north, the Sierra Madre of Chiapas and Guatemala, the Central American Cordillera and the Central Depression of Chiapas in the central part, and the Pacific Plain towards the southwest (Saavedra A. and Castellanos L. 2013).

The study area includes parts of the Mexican states of Chiapas, Campeche and Tabasco. The first two occupy most of the area as Chiapas represents about half of the delimited area. On the Guatemala side, there are the departments of Petén (the largest in the study area), Alta Verapaz, Quiché, Huehuetenango, San Marcos, Quetzaltenango and Retalhuleu. According to the data from the EMIF survey (www.colef.mx/emif), at the end of 2016, a number of people crossed the Mexican border from the south for work reasons, of which more than 700,000 were from Guatemala. This indicates the enormous scale of the current regional exchange processes (Tonatiuh 2017a).

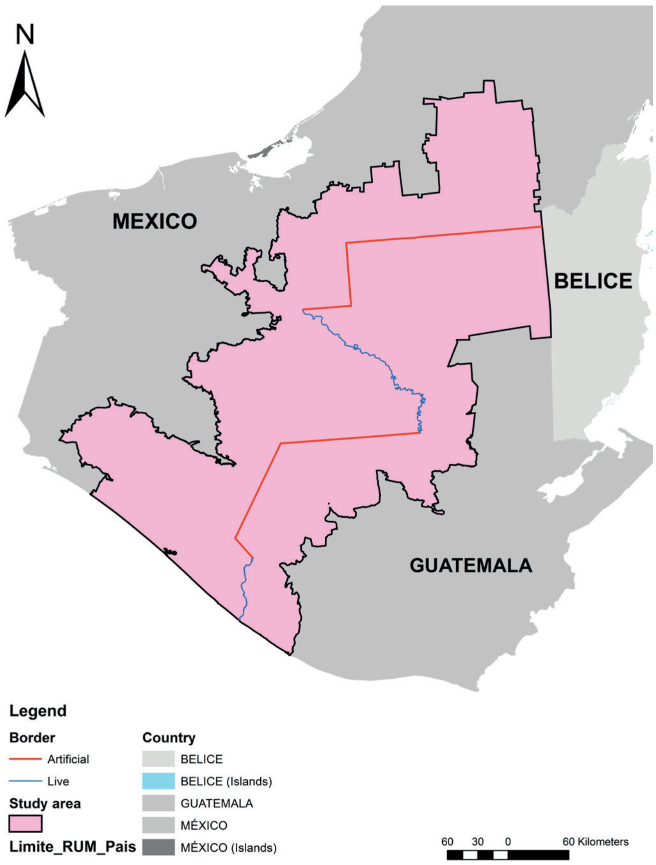


Fig. 1. The area of the cross-border region of Mexico and Guatemala

In terms of the localities distribution, there is a large concentration of these in the southwestern sector of the border, which translates into a very marked distribution of population density as it shows its highest values in a low number of municipalities on both sides of the border.

Various Natural Protected Areas (NPAs) have been decreed to preserve and protect the natural heritage in the cross-border region, their location is shown in Figure 2. In Mexico, the NPAs that stand out for their size are the Biosphere Reserves (La Sepultura, El Triunfo, La Encrucijada) on the Pacific side and "Montes Azules" and "Calakmul" on the Gulf of Mexico and Caribbean sides. In Guatemala, the study region covers most of the Maya Biosphere Reserve (RBM) as well as the "Sierra de Lacandon" National Parks and "Laguna del Tigre". The NPAs on both sides of the border include various ecosystems that gather great biological and cultural diversity, which corresponds particularly to tropical rain forests that persist as a continuum, especially in the northeast and center of the study area, and to a lesser extent in the southwest sector. On the contrary, the natural ecosystems outside the protected natural areas are mostly transformed by the different production activities that have caused great changes in land use.

Most of the study area corresponds to lowlands with altitudes less than 500 meters above sea level, the slope in these areas is below 7%. The rest of the area, approximately a third, is located within 1000 and 4000 meters above sea level and has predominant slopes of 12-25% and 25-50% as well as small sectors with slopes of 50-75% and greater than 75%.

Methodology

In this study, spatial analysis and modeling were used to identify and map homogeneous units for environmental planning and management in the Mexico-Guatemala trans-border region, the used methodological approach is presented in Figure 3. The data used in this study include: Digital elevation model. Elevation data were obtained with a spatial resolution of 30 meters (ASTER GDEM version 3); from this DEM the slope was calculated.

Soils map (INEGI, SERIE II, 2008) and for Guatemala the database of Winograd M. and Farrow A. (2000)

Land cover and land use map (INEGI Series V and Series VI; CONANP, MAGA - PGGR, Guatemala, 2010 and updated with Sentinel images, 2019)

Land suitability map (Lopez D. and Saavedra A. 2019)

Natural protected areas map (CONANP, México – IGN, Guatemala)

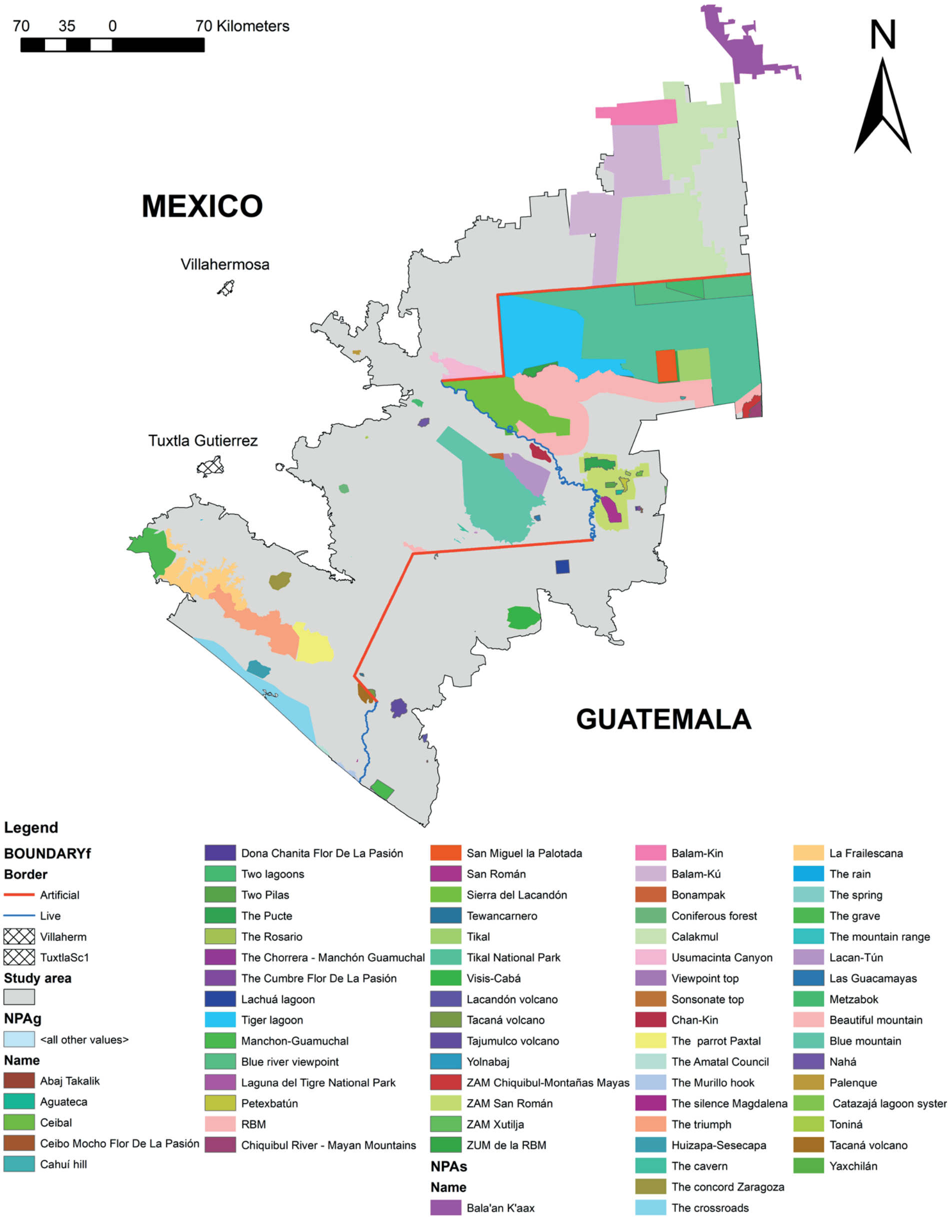


Fig. 2. Natural protected areas in the Mexico-Guatemala cross-border region

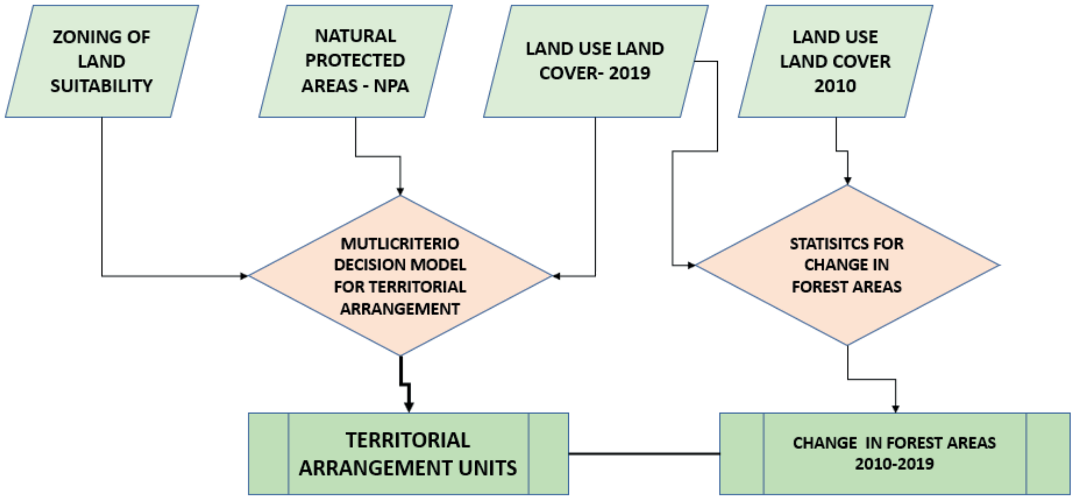


Fig. 3. Methodological approach

The units of land suitability were defined by the Land capability classification system developed by the Soil Conservation Service of the United States-USDA, 1965, adapted by IGAC, 2001, which was modified for the present study based on the available pedological information (listed above); the classification of soils in this map is referring to the FAO classification system (FAO/UNESCO, 1998). The first two dominant soils (Group1 and Group 2 in such database) were considered in the development and choice of the criteria for the limiting factors. Susceptibility to erosion, the slope (%), natural drainage, susceptibility to flooding, effective depth, soil fertility and salinity/sodium conditions were considered as the limiting factors.

Land suitability is the base for the territorial arrangement, which was modeled together with the current land use and land cover through rules of decision and having the natural protected areas as a frame. The rules of decision were defined using "Criteria for the integration of the territorial arrangement with an emphasis in forest and agroforestry systems" of the Mexican National Forest Commission-CONAFOR (CONAFOR, 2011) as a base, which was adapted and modified for the present study. The implementation of the rules of decision was made through a conditional algorithm using the "Modeler" module of ERDAS Imagine, Version 10.0. The result was the map of the territorial arrangement, which was structured in zones, sub-zones and management units.

Criteria for the integration of the territorial arrangement with an emphasis on forest and agroforestry systems.

In this study, the criteria for the territorial arrangement were based on the "Agreement on the integration and organization of the Forestry Zoning" by CONAFOR, which has been adapted and modified by the authors. According to the Article 4 of the above-mentioned agreement, the structure of the Forest Zoning distinguishes three categories: 1) areas of conservation and restricted or prohibited use; 2) production /use areas; 3) restoration areas. To account for the lowland, which requires regulation of the runoff originated from the highland, the spatial arrangement proposed in this study included a special category "regulatory and buffer area". In the next paragraph, the criteria that define the zones, subzones and management units are described.

I. Conservation and restricted or prohibited use zones. These areas were identified by their specific natural conditions or by their protection status. Two subzones were distinguished: a) Subzone of land in the Natural Protected Areas. These areas are subject to a special regime of protection, conservation and restoration according to categories established in the General Law of the Ecological balance and environmental protection (DOF 05-11-2013); b) Subzone of land for Conservation – Protection. This subzone includes natural areas that are marked by very steep slopes or are covered by natural vegetation (temperate and tropical forests).

II. Regulatory and buffer zone. This is a type of land, the physiographic position and natural vegetation cover of which play an important role in the environmental regulation and buffering of water flows, including wetlands (bodies of water and hydrophilic vegetation). Only one sub-zone is defined: a) Sub-zone of land for buffering and wetlands protection.

III. Production / use zone. This area has conditions of vegetation and soil suitable for agricultural, livestock and forestry production in a sustainable way, including timber and non-timber production for multiple uses: firewood, construction, live fences, food, fodder, medical and handicraft. Includes four sub-zones: a). Subzone of lowland with high to moderate suitability, which corresponds to land with slight to moderate limitations for agricultural, livestock and forestry (plantations) production; b) subzone of lowland with restricted suitability to some uses. It is suitable for the livestock and forestry plantation, with species improved and adapted to the specific conditions of these environments; c) subzone of hilly land with moderate aptitude; d) subzone of hilly land with low aptitude.

IV. Restoration zones. This corresponds to terrain with forestry aptitude, that is devoted to other uses or is in the process of degradation from inadequate land use and management. These areas comprise two sub-zones: a) Subzone of hilly land with very severe susceptibility to water erosion and b) Subzone of hilly land with shrubby secondary vegetation of the tropical humid and temperate forest, with moderate to severe susceptibility to water erosion.

RESULTS AND DISCUSSION

Agroforestry zoning

The results of zoning are presented on the map in Figure 4. From the perspective of sustainable development goals, the information presented in Figure 4 can be summarized as follows: a) conservation areas are proposed for all territories with forest cover whether they are inside or outside the natural protected areas, this would allow to at least maintain the proportion of the forest cover in the study area; b) areas for restoration of vegetation cover with different priority levels are proposed. The higher priority is assigned for the areas delimited as restoration/ conservation zones since they are located on very steep slopes, where the presence of natural vegetation is essential to avoid land degradation processes. The second priority is given to the lands located in the natural protected areas, which have been transformed by the impact of anthropogenic activities and currently have shrub vegetation cover. In the third place, there are the areas delimited on the map as restoration – exploitation zones, which are currently dedicated to annual crops, an activity that is not very suitable for steep slopes. In these areas, it proposed to restore the natural vegetation or to dedicate them to more environmentally friendly crops, such as agroforestry(coffee).

Land cover – land use inside and outside the natural protect areas

The results of the spatial analysis of the land cover and land use distribution inside and outside the natural protected areas (NAP) for the years 2010 and 2019 are shown in Figures 5 to 9 and Table 1. In the study area, the following ecosystems can be distinguished: agroecosystem (crops, pasture, plantation), mangrove swamp - wetland, mountain mesophyll, temperate and tropical forest (perennial, sub-deciduous). Table 1 shows the areas for each of the land use and land cover types, Figures 5 and 6 show their spatial distribution. According to the table, in 2010, the forest area comprised a total of 55,078.17 km^2, which is equivalent to 47.5% of the study area, and 27.7% corresponded to forests in the natural protected areas. In 2019, forests covered an area of 49,817.78 km^2, which is equivalent to 43.2% of the study area, with 25.2% being located within the natural protected areas. According to these data, there was a decrease in the total forest area of approximately 4%, while in the natural protected areas it decreased by approximately 2%. However, it is important to mention that the natural protected areas make up approximately 60% of forests in the study area, in general, this amount remains constant over the considered period.
On the other hand, the area of anthropogenic coverage has increased from 43,190.8 km^2 in 2010, which is equivalent to 37.2% of the total area, to 53,017.7 km^2 or 45.2% of the total area, in 2019. A significant increase has occurred in the area of plantations and oil palm, mainly in the Guatemala sector.

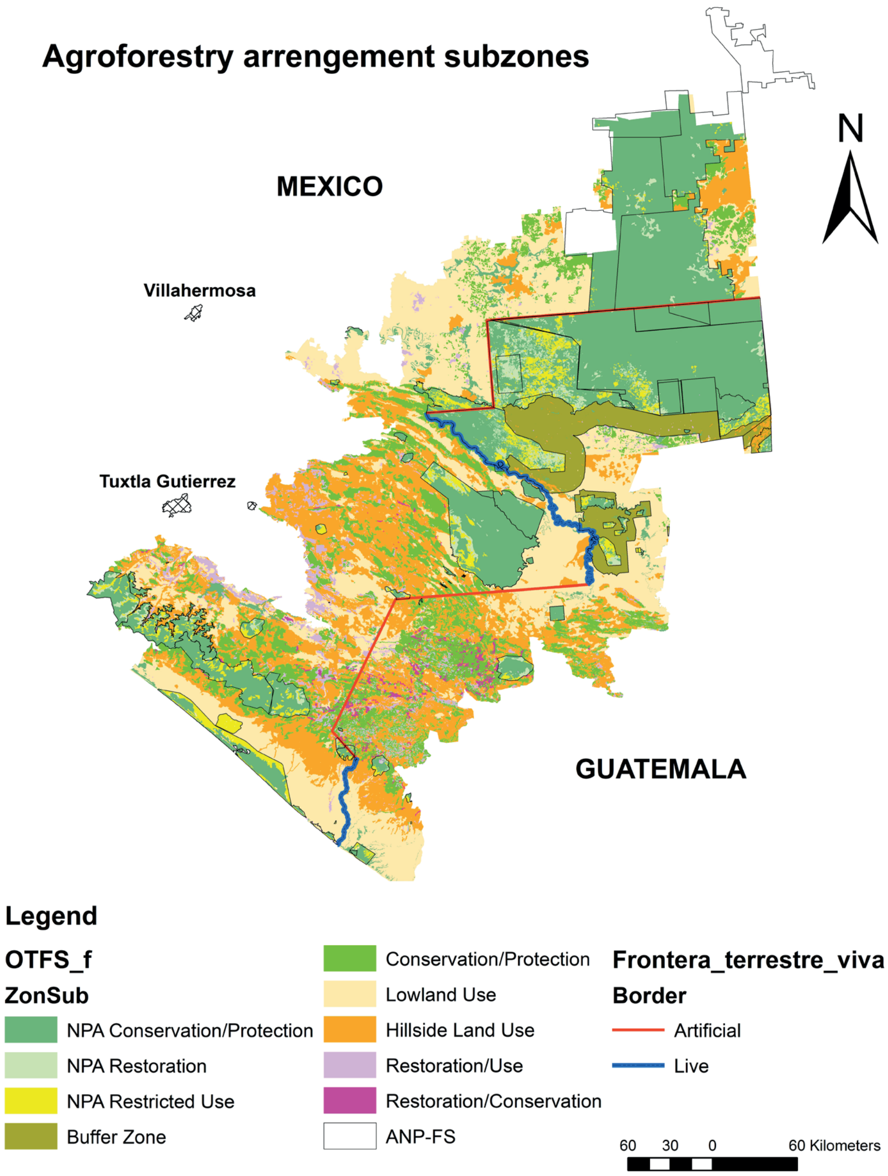


Fig. 4. Agroforest Zoning the Mexico – Guatemala trans-border region

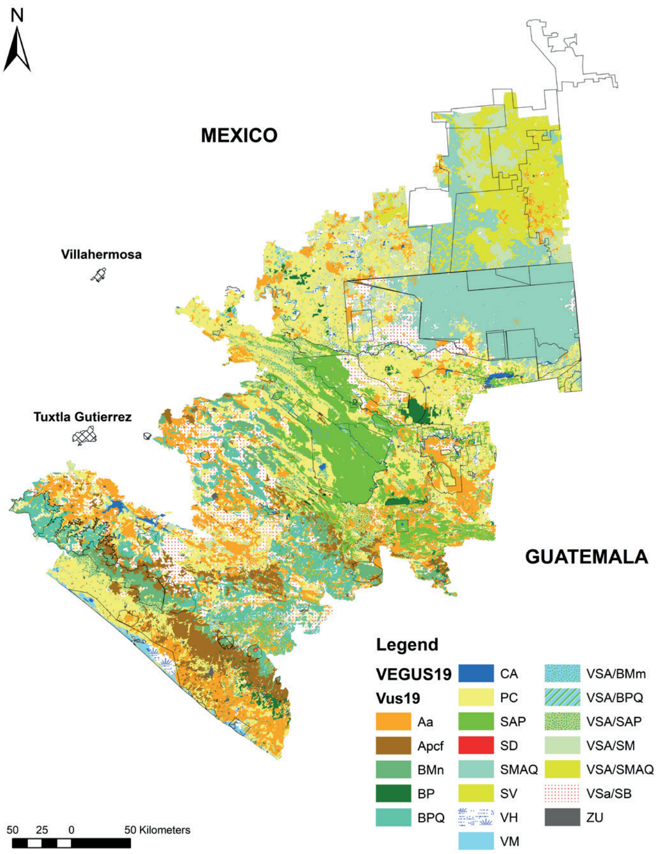


Fig. 5. Land cover and land use in the Mexico – Guatemala trans-border region 2019

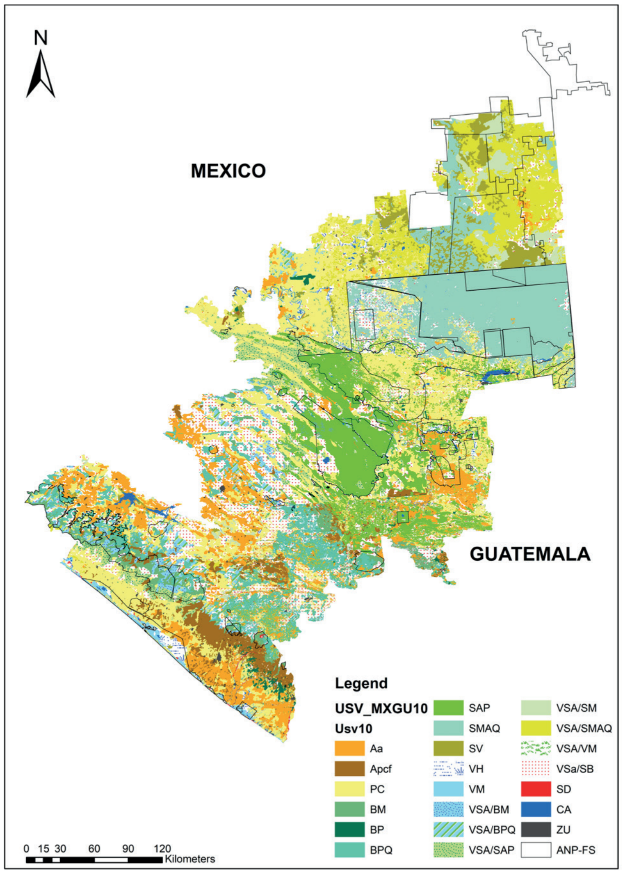
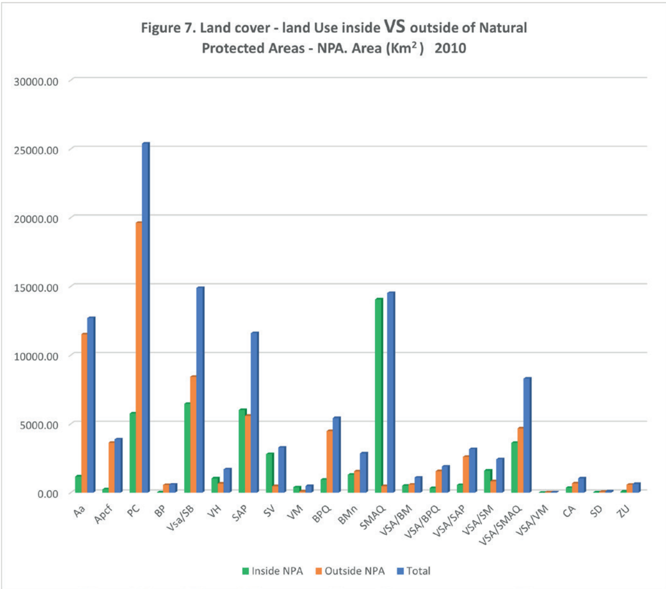


Fig. 6. Land cover and land use in the Mexico – Guatemala trans-border region 2010

Table 1. Land cover and land use inside and outside the Natural Protected areas- NPA (2010-2019)

Land cover/Land use		Area (km²) 2010			Area (km²) 2019		
Description	Symbol	Inside NPA	Outside NPA	Total	Inside NPA	Outside NPA	Total
Agriculture	Aa	1182.15	11519.1	12701.23	1951.12	14433.56	16384.68
Coffee, mango	Apcf	245.87	3631.86	3877.73	798.89	5112.46	5911.35
Pastures	PC	5760.04	19628.55	25388.59	6919.85	21762.90	28682.75
Plantation	BP	25.70	560.98	586.69	301.62	896.86	1198.48
Forest shrub	VSA/SB	6459.34	8431.63	14890.97	3146.51	7530.98	10677.49
Wetland	VH	1039.67	659.40	1699.08	981.67	623.29	1604.96
Perennial Tropical forest	SAP	6011.03	5592.76	11603.79	4961.21	4154.14	9115.35
Others forest	SV	2802.59	471.54	3274.14	2005.09	737	2742.10
mangrove swamp	VM	386.98	91.26	478.24	386.98	87.59	474.57
Temperate forest	BPQ	944.69	4480.33	5425.02	1188.38	4972.31	6160.69
Mountain mesophyll forest	BMn	1308.43	1547.33	2855.77	1385.28	2053.22	3438.50
High to medium perennial tropical forest	SMAQ	14054.74	471.54	14526.28	13325	478.75	13803.74
Arboreal Mountain mesophyll forest	VSA/BM	512.24	584.50	1096.74	10.27	66.16	76.43
Arboreal Temperate forest - Pinus Quercus	VSA/BP	329.94	1566.27	1896.16	43.51	199.17	242.68
Arboreal Perennial Tropical forest	VSA/SAP	557.07	2608.25	3165.32	532.51	2509.66	3042.17
Arboreal Others forest	VSA/SM	1601.56	830.30	2431.86	5464.72	4790.85	10255.57
High to medium tropical forest	VSA/ SMAQ	3624.34	4676.0	8300.34	22.03	0	22.03
Arboreal mangrove swamp	VSA/VM	0	24.51	24.51	0		0
Water	CA	356.16	681.03	1037.19	281.33	595.26	876.59
Bare soil	SD	23.34	67.30	90.64	9.73	4.43	14.16
Urban area	ZU	60.27	576.38	636.65	76.02	764.39	840.41
				116,008.6			116,008.6



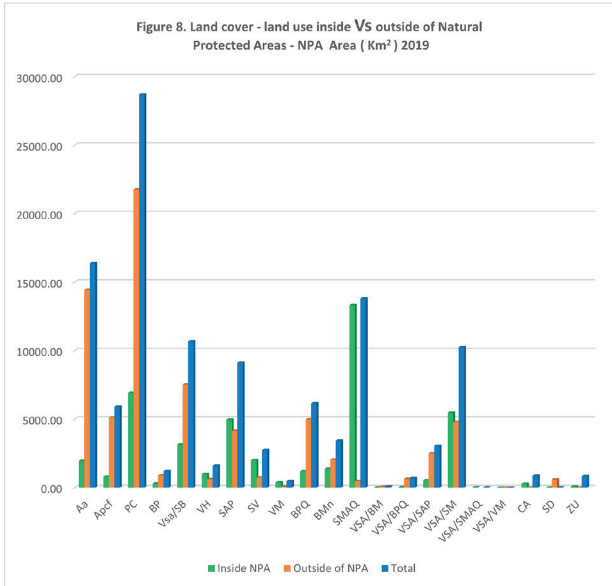


Fig. 7-8. Land cover and land use in the Mexico-Guatemala trans-border region (2010 - 2019)

The total area of forest cover, as well as the proportion of different ecosystems within the natural protected areas for the years 2010 and 2019 is shown in Figure 9. It can be seen that the most important ecosystem according to its area is tropical forest, among which the medium-high evergreen forest (SMAQ) and high evergreen forest (SAP) stands out. The former remains more or less constant over the study period and is mostly found within NPAs. The evergreen high forest (SAP) underwent the most significant changes due to the advancement of the Agricultural frontier. Other types of tropical forests are SV and VSA / SM, which include sub-deciduous, dry and thorny forests. The second most important ecosystem is temperate forest (BPQ), in general, it remains constant and only a small portion of it is found within NPAs. The third forest ecosystem consists of the mountain mesophyll forest. Finally, there is a small area entirely located within NPAs covered by mangrove forests, which is an ecosystem of high relevance from the perspective of its ecosystem functionality.

The area covered by shrub vegetation, which includes the lands where anthropogenic activity has put strong pressure on the ecosystems described above is also shown in Figure 9. In some cases, selective extraction of the arboreal vegetation was made, in other cases, the forest was completely removed to establish agriculture, generally by slash-and-burn cultivation shifting method. The shrub vegetation in these cases corresponds to secondary vegetation of different age (7-18 years). These areas may be subject to restoration of the original vegetation cover, the priority depends on several factors, such as slope (steep slope areas have higher priority), whether or not it corresponds to one protected area, and the quality of soil (which determines the suitability).

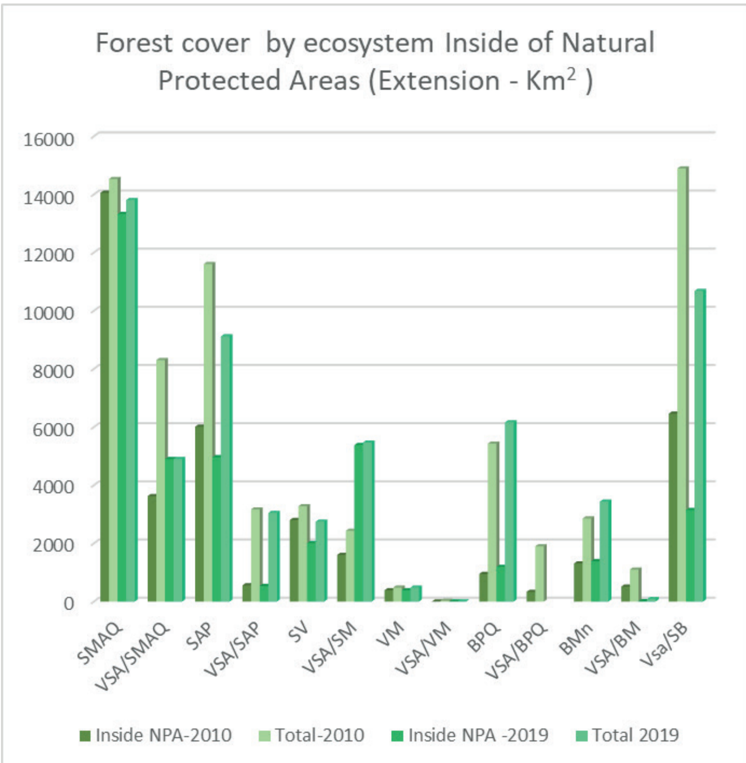


Fig. 9. Forest cover by ecosystem in the Mexico-Guatemala trans-border region 2010-2019[2]

[2] For desription of symbols see Table 1

Nowadays, the NPAs, particularly in the Mexico-Guatemala cross-border region, are a viable legal instrument as well as a planning tool that must be regularly strengthened to conserve their biological and cultural wealth. This has to be done by ensuring the continuity of the ecological and natural evolutionary processes, the natural supply of environmental goods and services as well as the permanence of natural resources that are necessary to maintain biological diversity, human and population well-being. From the data analyzed (Figure 9) it is evident, that NPAs play a fundamental role in the achievement of the Sustainable Development Goals, particularly Goal 15: Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, halt and reverse land degradation and halt biodiversity loss.

The social valuation of nature at all levels is a fundamental element since it allows to ensure the essence and existence of NPAs. Greater financial support is also required to strengthen the environmental services through both national and binational programs and policies that promote and encourage the natural protected areas so that they can continue to contribute greatly to the Sustainable Development Goals.

Conclusions and recommendations

From the spatial analysis and modeling of agroforestry, that was performed to map the homogeneous units for environmental planning in the Mexico-Guatemala border region, the following conclusions and recommendations can be drawn:

- The Agroforestry zoning is an important tool to monitor forest areas in the context of achieving Sustainable Development Goals. In this study, it was used to define conservation and restoration areas.
- The total forest area in the region decreased from 47% in 2010 to 43 % in 2019. About 60% of the forest area is located inside the Natural Protected Areas and its principal ecosystem (according to its area) corresponds to the tropical forest (medium-high evergreen forest and high evergreen forest).
- It is evident that the natural protected areas play a fundamental role in the preservation of the forest in the region. The Natural protected areas (NPAs) are a viable legal instrument and a planning tool that must be strengthened regularly for the conservation of their natural resources, biological and cultural wealth as well as sustainable development.
- Zoning and management of forest areas and NPAs based on land suitability as well as agroforestry use are key tools to protect, restore and promote the adequate and sustainable use of terrestrial ecosystems and maintain their biological diversity.
- Hilly terrain with forestry aptitude and severe susceptibility to water erosion, which is currently devoted to annual agriculture, must be restored to its natural vegetation in order to reverse land degradation
- Natural vegetation or agroforestry must be promoted in high lands for environmental services to avoid the advancement of agricultural area. ■

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RESEARCH PAPER

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ASSESSING CITY GREENNESS USING TREE CANOPY COVER: THE CASE OF YOGYAKARTA, INDONESIA

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ABSTRACT. The study aims to measure the greenness of an Indonesia city using tree canopy cover data. Rapid physical development brings impacts to the loss of urban trees, which leads to the increase of flooding risk, local temperature and pollution level. To address the issues, a baseline assessment of urban tree canopy existence is necessary as inputs for effective urban environmental management policies. The methods used in this research include 1) remote sensing and spatial analysis, and 2) simple quantitative analysis. Furthermore, three indicators are used in assessing the greenness, including 1) size of the canopy, 2) canopy cover percentage, and 3) canopy per capita. The results found that the city of Yogyakarta has a low level of greenness based on the canopy size in which covers only 467.37 ha or 14.38% of the total area. The second finding is Yogyakarta has an unequal distribution of canopy cover percentage in each district (kecamatan). The third finding is Yogyakarta City has a canopy per capita rate of 10.93 sq m/person. This number is below the UN recommendation of 15sq m / person. It indicates that residents have poor access to urban greenery. Additionally, the article discusses that the three indicators used have strength and weakness in measuring the level of greenness. Therefore, the assessment objectives must be taken into account. We recommend the use of each indicator as follows: 1) the canopy size is used as an initial inventory of the existence and distribution of the canopy, 2) the canopy cover percentage canopy percentage for measuring and comparing the level of greenness spatially and visually between areas, 3) the canopy per capita is used to measure the possibility of access and interaction of residents with the presence of a tree canopy. Cities' authority can use the information to measure the achievement of SDGs number 11, 13, or 15.

KEY WORDS: canopy cover; canopy per capita; city greenness; tree canopy; urban trees

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INTRODUCTION

The trees that live in urban areas, which are often called urban trees, provide essential benefits for the sustainability of the built environment. In urban areas with predominated impervious surfaces such as buildings and full of vehicle smoke pollution, some problems may appear including flooding, poor air quality, and hot local climate. Urban trees can provide ecosystem services to regulate those impacts and balance the environment, such as by absorbing stormwater run-off to reduce the risk of flooding (Y. Chen & Borelli 2016; Farrugia, Hudson, & McCulloch 2013; Pappalardo, La Rosa, Campisano, & La Greca 2017), reducing air pollution (Ferranti, MacKenzie, Ashworth, & Hewitt 2019; Martin, Chappelka, Loewenstein, & Keever 2012) and moderating local climate (Ali & Patnaik 2019; X. Chen et al. 2019; Norton et al. 2015; Zhou, Wang, & Cadenasso 2017). Besides, the existence of urban trees can also mitigate climate change in cities because of trees' ability to absorb carbon emissions (McGovern & Pasher 2016; Russo et al. 2014; Tang, Chen, & Zhao 2016). The existence of trees also provides space for biodiversity to live in (Aronson et al. 2017; Fineschi & Loreto 2020; Parmehr, Amati, Taylor, & Livesley 2016; Trees & Design Action Group 2014). In the context of human and natural interactions, the presence of urban trees also positively influence residents' well-being and health (Fineschi & Loreto 2020; Soga & Gaston 2020; Ulmer et al. 2016). Accordingly, Sustainable Development Goals (SDGs) see urban trees as a significant aspect to achieve at least 3 goals which are Goal 11: Resilient and Sustainable cities, Goal 13: Climate Action, and Goal 15: Life on Land (Turner–Skoff & Cavender 2019; United Nations 2019).

Rapid physical development happening in cities often results in the loss of trees (Brunner & Cozens 2013; Guo, Morgenroth & Conway 2018; Guo, Morgenroth, Conway & Xu 2019; Nowak & Greenfield 2018). The continued impact of the urban trees and its canopy loss will lead to reduced ecosystem services provided by trees for cities (Elmes et al. 2017; Riley & Gardiner 2020). It means that environmental impacts are likely to happen more frequently in cities due to urban trees loss, such as urban heat island, flooding, and higher pollution. Awareness and concern for urban trees encourage urban environmental policies to maintain the existence of trees and tree canopies and try to raise their quantities and qualities (City of Melbourne 2012; Lavy &

Hagelman 2017, 2019; Martin et al. 2012; Papastavrou 2019; Phelan, Hurley, & Bush 2019). Thus, to formulate better policies regarding urban trees management, cities need baseline information on urban tree canopy to (Intasen, Hauer, Werner, & Larsen 2017; McGee, Day, Wynne, & White 2012; Parmehr et al. 2016).

The purpose of this research is to measure the greenness of an Indonesia city using tree canopy cover data. Tree canopy is often used as a proxy to measure the level of greenness of an area (Ellis & Mathews 2019; Nowak & Greenfield 2018; Riley & Gardiner 2020). The article contributes to the literature of urban tree canopy management and planning by utilising three indicators: 1) canopy size for assessing the existence of tree canopy, 2) the canopy cover percentage for assessing distribution and equality of tree canopy, and 3) the number of canopy per capita as a proxy for assessing the accessibility of residents to interact with nature.

MATERIALS AND METHODS

Yogyakarta was chosen to be the case study in this research because it is one of the Indonesian cities with a fast growth rate. Yogyakarta is the capital of the Yogyakarta Special Region. The physical size of Yogyakarta is 3,249.31 Ha. The total population of Yogyakarta City in 2018 was 427,498 with a density of 131.57 persons / Ha. The population growth in Yogyakarta City is at an average of 1.14% per year based on 2016-2019 data. Yogyakarta has 14 districts with various sizes. The development of Yogyakarta City is considered rapid and has caused several environmental impacts. A study explained that the level of air pollution in Yogyakarta City is increasing due to development activities (Saptutyningsih & Ma'ruf 2015). Another research revealed that an urban heat island has occurred in several areas in the city of Yogyakarta as a result of the intensification of built elements along with the decline of natural elements in thea city (Husna, Fawzi & Nur 2018). Thus, our research argues that a solution to overcome the issues is to maintain and increase the existence of urban trees, because they provide ecosystem services such as pollution removal (Ferranti et al. 2019; Martin et al. 2012), moderation of the local climate (Ali & Patnaik 2019; X. Chen et al. 2019; Farrugia et al. 2013) and other beneficial services. Based on this background, Yogyakarta City is an appropriate case study for the research.

The research method used is a combination of: (1) Satellite Imagery Processing and Spatial Analysis, and (2) Simple Quantitative Analysis. The methods are described below.

Satellite Imagery Processing and Spatial Analysis

The method used to obtain tree canopy data is through a high-resolution satellite imagery processing. The higher the resolution of an image, the more detailed and accurate the quality of the processing results (Godinho, Guiomar, & Gil 2018; McGee et al. 2012; Parmehr et al. 2016). Tree canopy data are generated from high-resolution satellite imagery with a spatial resolution of 0.44 m. Images with this resolution can provide sharp and clear images so that they are suitable for use as the materials for identifying urban tree canopies. Furthermore, the image is processed using the Envi Map application. The result of the identification of the canopy is a raster format map which is then converted into polygon shapefile format.

We apply a multi-spectral classification with a supervised classification analysis type as well as a maximum likelihood feature. This technique is effective and straightforward in identifying tree canopies in large-scale areas such as cities or wider (Bravo-Bello, Martinez-Trinidad, Valdez-Lazalde, Romero-Sanchez & Martinez-Trinidad 2020; Ossola & Hopton 2018). Moreover, the classes used in this classification include tree canopies, grass, open land, buildings, roads, and bodies of water. From the identification results, then the tree canopy polygons are separated for further analysis, the illustration of the tree canopy identification results can be seen in Figure 1. below.

Furthermore, spatial analysis is applied to calculate the size and the distribution of tree canopy according to district administrative boundaries. The spatial analysis used is simple, i.e. 1) 'intersect' between tree canopy polygons and district administrative boundaries, 2) 'calculate geometry' to obtain the size of tree canopy per district. The results of this spatial analysis were used in the second step, which is simple quantitative analysis.

Fig. 1. Illustration of Canopy Identification Method

Simple Quantitative Analysis

The simple quantitative analysis carried out includes 1) calculating the canopy cover percentage in the district area, and 2) calculating the canopy per capita for each district to assess its sufficiency based on the UN standard of 15 sqm/ person.

The canopy cover percentage is used to compare canopy cover in different boundary sizes (Campagnaro, Sitzia, Cambria, & Semenzato 2019) such as cities, sub-districts / suburbs, even neighbourhoods. The smaller the canopy cover percentage in an area means that there is less surface covered by tree canopy, which results in a lower greenness level (Seiferling, Naik, Ratti, & Proulx 2017). This condition has the same consequences for the ecosystem services that trees can provide, the smaller the canopy cover percentage; as a result, the smaller the ecosystem services provided by urban trees (McGovern & Pasher 2016). Then, to calculate the rate of canopy cover in the area, a simple formula is used:

%Can = [CanS (Ha) / Area (Ha)] x 100

%Can : percentage of canopy for each district
CanS (Ha) : tree canopy size in hectares within the districts
Area (Ha) : district size in hectares

The second indicator used is canopy per capita, which is a proxy used to measure the likelihood of residents access to natural components such as trees (UN HABITAT 2016). The literature states that the interaction between humans and nature is important due to various benefits such as maintaining the mental and physical health of city residents (Fineschi & Loreto 2020; Greene, Robinson & Millward 2018; Soga & Gaston 2020). Rest on this concept, the article argues that the greater the number of canopy per capita, the more likely it is for the public to access and gain socio-cultural benefits from urban trees. To calculate the canopy size per capita for each district, the following formula is used (UN HABITAT 2016):

Can/Cap = [CanS (sqm) / Pop]

Can/Cap : canopy per capita for each district
CanS (sqm) : tree canopy sizes in sqm within district
Pop : total population per district

The study also estimates potential carbon sequestration per year and total potential carbon storage of canopy. To estimate potential carbon sequestration and storage of urban tree canopy, we follow numbers of carbon sequestration and storage of urban trees from a previous study (Nowak, Greenfield, Hoehn, & Lapoint 2013). The previous study take U.S. cities as case for their research. They found that the net carbon sequestration of urban trees is 0.226 kg / m^2 / year and the total carbon storage is 7.69 kg / m^2. Then, the following formula are used:

CarbonSeq = Netseq x CanS (sqm)

where,
CarbonSeq : estimated potential carbon sequestration of urban tree canopy per year
Netseq : 0.266 kg / m^2 / year
CanS (sqm) : tree canopy sizes in sqm within district
and

CarbonStor = Stor x CanS (sqm)

CarbonStor : estimated potential carbon sequestration of urban tree canopy in total
Stor : 7.69 kg / m^2
CanS (sqm) : tree canopy sizes in sqm within the district

It is important to note that the estimation in this study is not a direct measurement. It aims to illustrate rough estimation of urban tree canopy potential to support climate change mitigation. For this reason, further estimation with a more sophisticated method may be needed.

RESULTS

The research used three indicators to measure the level of the greenness of a city and its distribution between districts. The first is the canopy size. The canopy size is the most basic data generated from the spatial analysis. The second information is the canopy cover percentage that compares the canopy size to districts size. The third information is the canopy area per capita calculated by dividing the canopy size by the number of people living in the area. The findings of each information are described as follows.

Canopy Size

The analysis results show that the total canopy size of Yogyakarta is 467.37 Ha. Also, when using actual canopy size data in each district, the tree canopy size distribution ranges from 6.46 Ha - 134.19 Ha. Umbulharjo is the district with the widest canopy (134.19 ha) and Pakualaman hase the smallest canopy size (6.46 ha). The detailed pattern of canopy size distribution per district can be seen in Table 2. Of the 14 districts, the average number of canopy size is 33.38 Ha, and the mean value is 21.92 Ha. The size of each district relates to the size of the district boundaries. Based on the size of the district, Umbulharjo is the largest district (812 hectares), and Pakualaman is the district with the smallest size (63 hectares). The rankings that appear in canopy size have a similarity to the order of district boundaries size (See Figure 2 for a graph illustrating this pattern). Therefore, it was concluded that canopy size data could provide an initial depiction of the existence and distribution of tree canopies. Still, the information cannot be the only benchmark in assessing the level of the greenness of an area. Consequently, further information is needed, such as the percentage of canopy and canopy cover per capita.

Table 1. Data and Sources

No.	Data	Function	Sources
1	Yogyakarta Satellite Imagery 2018	For classifying and identifying tree canopy. The classification results are then converted into tree canopy polygons.	Yogyakarta Land and Spatial Planning Board
2	District Administrative Boundary	As a unit of analysis and visualisation	
3	The population of 2018*	Calculation of population density and canopy per capita	Yogyakarta in Figures (Statistics Board)
4	District area size	Estimation of population density and canopy cover per district	

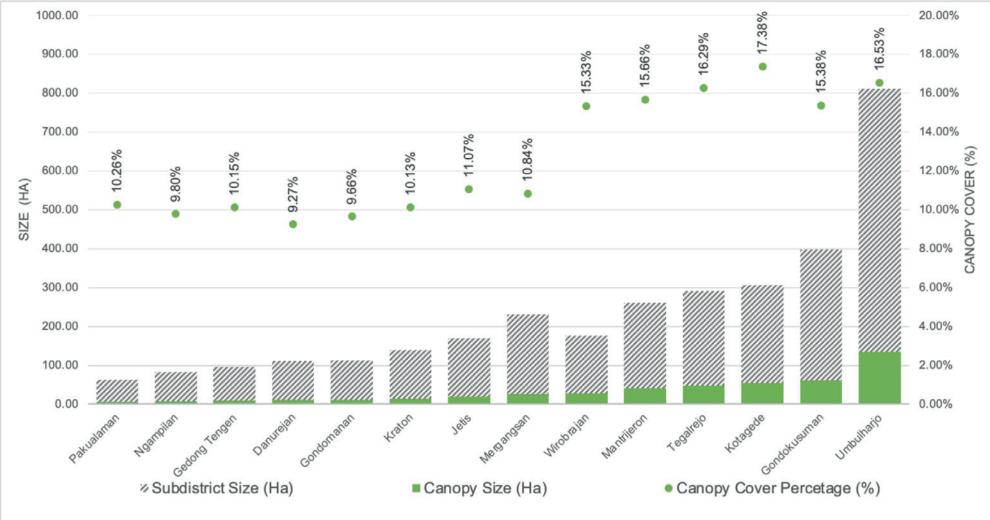

Fig. 2. Canopy size and Canopy Cover Percentage

Canopy Cover Percentage

The canopy cover percentage is obtained by dividing the canopy size by the size of an area (district). The canopy cover percentage in Yogyakarta City currently only reaches 14.38% or 467.37 Ha of the total size of Yogyakarta City of 3,249.31 Ha. If we compare the canopy cover percentage in Yogyakarta with several noteworthy green cities in the world (Liu & Jensen 2018), the canopy cover in Yogyakarta is relatively low. For example, Singapore has a canopy cover percentage of 29.3% and Geneva has 21.4% (data source: Treepedia; methods used see (Li et al. 2015; Seiferling et al. 2017)). There is also Melbourne with an actual canopy cover rate of 22% and a target of increasing the canopy of up to 40% by 2040 (City of Melbourne 2012). A brief look at these cities provides an overview of the direction of the tree canopy policy that Yogyakarta City needs to formulate, namely the protection and addition of urban tree canopies.

Next is the canopy cover percentage at the district level. The results of the calculation of the canopy cover percentage in the districts of Yogyakarta ranged from 9.27% - 17.38% with an average number of 12.70% (see Table 2). Based on the canopy cover percentage, there is a similar trend even though there has been a slight change in the ranks (see Figure 2 for a graph that illustrates it). The district with the most extensive canopy cover is Kotagede with 17.38% covering the area. Umbulharjo, which has the largest canopy size, was in second place for the canopy cover percentage with 16.53%. The district with the lowest rate of canopy cover is Danurejan with 9.27%. It is observed that the level of greenness in the city of Yogyakarta is not evenly distributed to each district (see Figure 4).

Canopy per Capita

Using population data in 2018, the canopy per capita in Yogyakarta City is 10.93 sqm/person. This number is still below the standard set by the UN, which is 15 sqm/person (UN HABITAT, 2016) hence requiring an escalation of about 4.07 sqm/person (See Figure 3). If we look at the data at the district level, the rate of canopy per capita in Yogyakarta ranges from 4.69 sqm/person - 14.45 sqm/person. This means that all districts in Yogyakarta City have canopy per capita number below the UN recommendation. In Figure 3, a graph of the distribution of canopy per capita for each district is presented as well as the additional gaps that can be potentially added. The district with the lowest canopy per capita was Ngampilan (4.69 sqm/person), and the district with the most extensive canopy per capita was Umbulharjo (14.45 sqm/person). The spatial distribution pattern can be seen on the map contained in Figure 4. Moreover, based on the data from 14 districts, it is obtained an average value of 9.29 sqm/person and a mean value of 8.10 sqm/person. All of the information indicates that there is still a lack of canopy size in Yogyakarta City to facilitate access and interactions of residents with natural components such as trees.

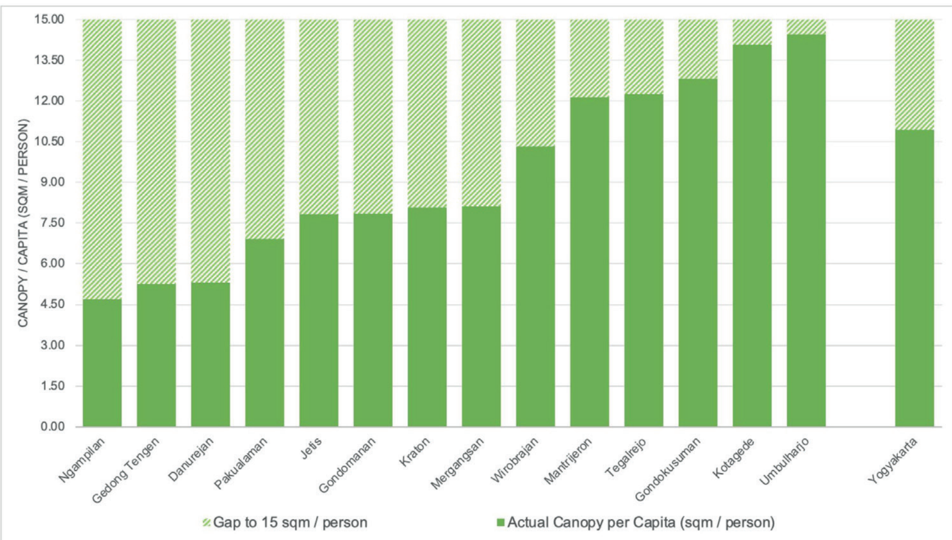

Fig. 3. Canopy per Capita and the Gap

Potential Carbon Sequestration and Storage

The study also analyse a rough estimation of carbon sequestration and storage of urban trees. The finding simply shows that the larger the size of canopy cover, the larger the potential number of carbon absrobed and stored by urban trees. Based on the estimation, the largest potential carbon sequestration is in Umbulharjo (303.45 t C / year) and the lowest potential carbon storage is in Pakualaman (14.61 t C / year). The total city-level potential carbon sequestration is 1,056.25 t C / year, while the average carbon sequestration is 75.45 t C / year and the median is 49.55 t C / year. In addition, city-level potential carbon storage is 35,940.44 t C while the average is 2,567.17 t C and the median is 1,685.90 t C. Table 2 column I and J provide detailed estimation of carbon sequestration and storage for all districts.

DISCUSSION

Strengths and Weaknesses of Indicators

This research uses three different types of information to measure the greenness level of a city, namely the canopy size, the canopy cover percentage, and canopy per capita. Cities authority may use the information as one of indicators to measure achievement of SDGs, especially for Goals 11, 13, and 15 (Turner–Skoff & Cavender 2019). The three types of information have their respective strengths and weaknesses in measuring the greenness of a city. The strengths and weaknesses identified by the authors are presented in Table 3.

Policy Implications

The article discusses policy recommendations into two parts: the first part is the general policy implications for cities in Indonesia; the second part is the policy implications that specifically targets Yogyakarta City as the case study used in this research. The first is related to policy recommendations for cities in Indonesia. The results of this research indicate that Yogyakarta City has a relatively low level of greenness based on information on canopy size, canopy cover percentage, and canopy per capita. This condition is likely to occur in other Indonesian cities (Ramdhoni, Rushayati & Prasetyo 2016). In Indonesia, the current green infrastructure policy framework only regulates mandatory size for green open space in urban areas. It mandates urban areas to have at least 30% open space, consisting of 20% public open space and 10% private open space. Additionally, in terms of urban trees, there is a policy guideline that helps local authorities to increase urban greeneries with various green open space design and planning strategies. The guideline, however, does not integrate the urban tree preservation with other urban development permit schemes. In addition, the absence of urban tree management policy plays a significant role in the decreased numbers of urban trees (Guo et al. 2019; Nowak & Greenfield 2018; Phelan et al. 2019). This article recommends a policy framework for better urban trees planning and management in Indonesian cities that integrate urban trees preservation, technology, and permit schemes (See Figure 5).

Accordingly, the first recommendation in this research is that there is a need for similar studies to assesses the

Table 2. Canopy Distribution in Yogyakarta City

A	B	C	D	E	F	G	H	I	J
District	Area Size (ha)	Population (2018)	Population Density / ha	Canopy size (ha)	Canopy size (sqm)	Canopy cover percentage (%)	Canopy per capita (sqm/ person)	Potential Carbon Sequestration (t C / year)	Potential Carbon Storage (t C)
Formula	Area	Pop	Pop/Area	CanS (Ha)	CanS (sqm)	CanS / Area x 100	CanS (sqm) / Pop	netseq x CanS (sqm)	Stor x CanS (sqm)
Ngampilan	82.00	17,117	208.74	8.03	80,346.46	9.80%	4.69	18.16	617.86
Gedong Tengen	96.00	18,546	193.19	9.74	97,399.06	10.15%	5.25	22.01	749.00
Danurejan	110.31	19,223	174.26	10.22	102,207.24	9.27%	5.32	23.10	785.97
Pakualaman	63.00	9,336	148.19	6.46	64,634.69	10.26%	6.92	14.61	497.04
Kraton	140.00	17,575	125.54	14.19	141,870.49	10.13%	8.07	32.06	1,090.98
Jetis	170.00	24,036	141.39	18.81	188,123.27	11.07%	7.83	42.52	1,446.67
Gondomanan	112.00	13,781	123.04	10.82	108,176.14	9.66%	7.85	24.45	831.87
Mergangsan	231.00	30,836	133.49	25.03	250,342.07	10.84%	8.12	56.58	1,925.13
Wirobrajan	176.00	26,134	148.49	26.98	269,817.42	15.33%	10.32	60.98	2,074.90
Mantrijeron	261.00	33,688	129.07	40.88	408,802.07	15.66%	12.13	92.39	3,143.69
Tegalrejo	291.00	38,691	132.96	47.41	474,066.63	16.29%	12.25	107.14	3,645.57
Kotagede	307.00	37,937	123.57	53.37	533,698.02	17.38%	14.07	120.62	4,104.14
Umbulharjo	812.00	92,867	114.37	134.19	1,341,925.62	16.53%	14.45	303.28	10,319.41
Gondokusuman	398.00	47,731	119.93	61.23	612,250.24	15.38%	12.83	138.37	4,708.20
Average (Mean)				33.38	333,832.82	12.70%	9.29	75.45	2,567.17
Median				21.92	219,232.67	10.95%	8.10	49.55	1,685.90
City Level	3,249.31	427,498.00	131.57	467.37	4,673,659.42	14.38%	10.93	1,056.25	35,940.44

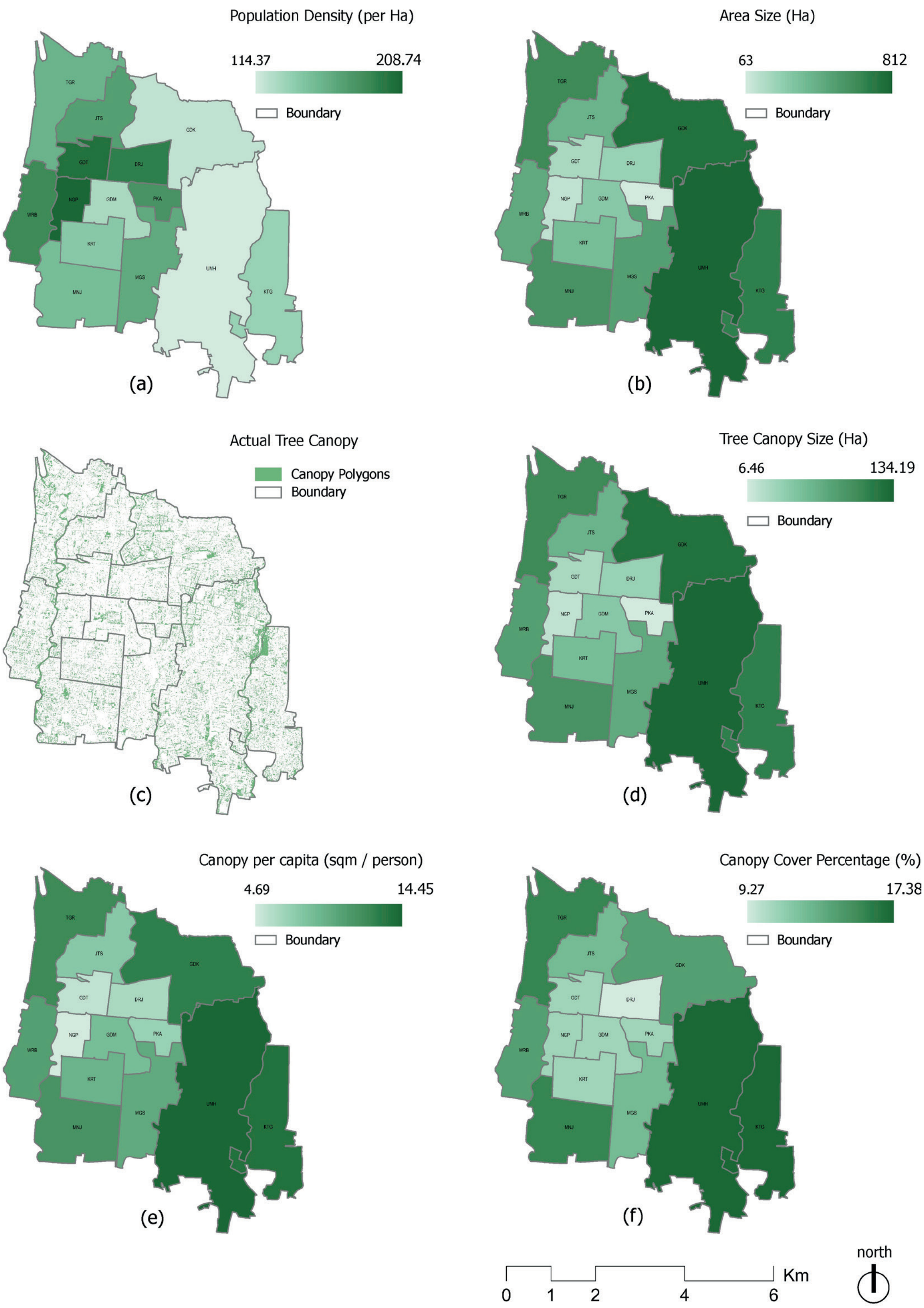

Fig. 4. (a) Population density; (b) Sizes of the districts; (c) Actual tree canopy polygons; (d) Tree canopy size per districts; (e) Canopy per capita; (f) Canopy cover percentage. Details in numbers are presented in Table 2

existence of urban tree canopy in Indonesian cities. baseline information regarding the presence of urban trees is required to formulate more effective policies for managing urban trees and its ecosystem services (Intasen et al. 2017; McGee et al. 2012; Parmehr et al. 2016) that can contribute to create more sustainable Indonesian cities. Further studies on urban trees in Indonesian cities may also add more detailed information such as the types, losses, gain, key ecosystem services, even health status of the trees.

The second recommendation is that urban trees should be put as the priority development programs and activities. It aims to increase the level of the greenness of cities in Indonesia asl well as to achieve SDGs Goal 11, 13, and 15. This recommendation can be adopted by agencies in charge of the environment and open space sector. Accordingly, business as usual policies related to urban trees need to be transformed into more innovative approaches to preserve and increase the existence of urban trees (Trees & Design Action Group 2012, 2014). For example, by integrating the control and conservation of urban trees with zoning regulations (Davey Resource Group 2015; Phelan et al. 2019), construction permits (Guo et al. 2019; Morgenroth, O'Neil-Dunne, & Apiolaza 2017), and development permits as exemplified in many other cities in the world (Hilbert et al. 2019; Lavy & Hagelman 2017, 2019). At the same time, programs and activities to grow more trees also need to be implemented in a visionary and measurable way. The City of Melbourne, for instance, created an 'Urban Forest

Strategy' which includes a series of long-term oriented programs and actions accompanied by regular monitoring and evaluation (City of Melbourne 2012). One of their targets is to achieve 40% canopy cover percentage in public realms which must be completed by 2040 along with various annual programs and activities to achieve this target. Another example comes from Singapore that plans urban forestry rehabilitation that covers every scale and land use types such as protected natural area, streetscapes, parks, even vacant lands (Davison 2005) and applying the biophilic concept to their urban environments (Singapore National Parks Board, accessed on August 2020)

The third recommendation is an engagement of stakeholders which is also an essential aspect of urban tree management (Brunner & Cozens 2013; Drillet et al. 2020; Papastavrou 2019; Trees & Design Action Group 2014). As explained above that protection of trees needs to be integrated into land-use permit schemes such as zoning, construction and development permits. As every stakeholders have roles in protecting and even increasing the number of urban trees, it is necessary to involve a variety of stakeholders. Those stakeholders include government as the policymaker, regulator, and license issuer (Lavy & Hagelman 2019; van der Jagt & Lawrence 2019), contractors and developers as parties carrying out physical construction (Guo et al. 2018; Morgenroth et al. 2017; Phelan et al. 2019), as well as city residents as private land owners (Conway 2016; Davis & Jones 2014).

The implications of the second policy are specifically addressed for the City of Yogyakarta. First, this research finds a pattern that the level of greenness in the city centre area is relatively lower, as indicated by the canopy size and the lower percentage of canopy cover. They are Ngampilan, Danurejan, Pakualaman, Keraton, Gedongtengen, Gondomanan (see Figure 4 and Table 2 for details). These districts have lower tree canopy due to rapid physical development and population growth that led to urban trees removal. The population density map (Figure 4 (a)) demonstrates that these areas have relatively higher population density that other districts. According to the existing land use, the areas are also dominated by built-up uses such as housing, commercial and services, as well as industries. Besides, an absence of urban tree demolition permits in the city is one of the potential causes of urban trees shortage.

Thus, the local authority can prioritise those areas for trees planting sites, to increase canopy size and the percentage of tree canopy cover. As stated in a previous study that increasing the canopy size and canopy cover percentage can increase aesthetics (Conway 2016), while simultaneouslyproviding more ecosystem services to the city. Those ecosystem services include reducing pollution (Ferranti et al. 2019; Martin et al. 2012), providing thermal comfort (Ali & Patnaik 2019; X. Chen et al. 2019; Farrugia et al. 2013), reducing the potential for flooding (Y. Chen & Borelli 2016; Farrugia et al. 2013; Pappalardo et al. 2017), even absorbing carbon and helping to mitigate climate change (McGovern & Pasher 2016; Russo et al. 2014; Tang et al. 2016).

In this second part, the findings show that all districts in Yogyakarta City have a canopy per capita below the UN recommendation rate of 15 sqm/person. This condition indicates the low likelihood of residents interacting with the urban green component. A city should ideally be able to accommodate its residents to interact with nature. With a relatively dynamic population and an increasing trend, keeping pace with population growth and development activities with urban tree planting (to grow the canopy per capita) is a strategic policy recommendation for the City of Yogyakarta. The priority of adding trees can be directed at districts with a small canopy per capita (for example, below 10 sqm/person) so city residents can have more even access to tree canopies. The second priority is to grow the number of canopy per capita in districts that are already close to the UN recommendation rate. That way the distribution of the canopy per capita will be more even. The even distribution of the canopy provides equal access for residents to interact with urban trees. The interaction of city residents with environmental elements such as trees can maintain the mental and physical health of residents (Fineschi & Loreto 2020; Greene et al. 2018; Soga & Gaston 2020). The interaction between residents and trees can also enhance understanding and knowledge about environmental conservation, especially in the protection of urban trees (Davis & Jones 2014).

Limitations and Potential for Future Research

This research acknowledges several weaknesses that can be improved in further research. Firstly, as by aiming

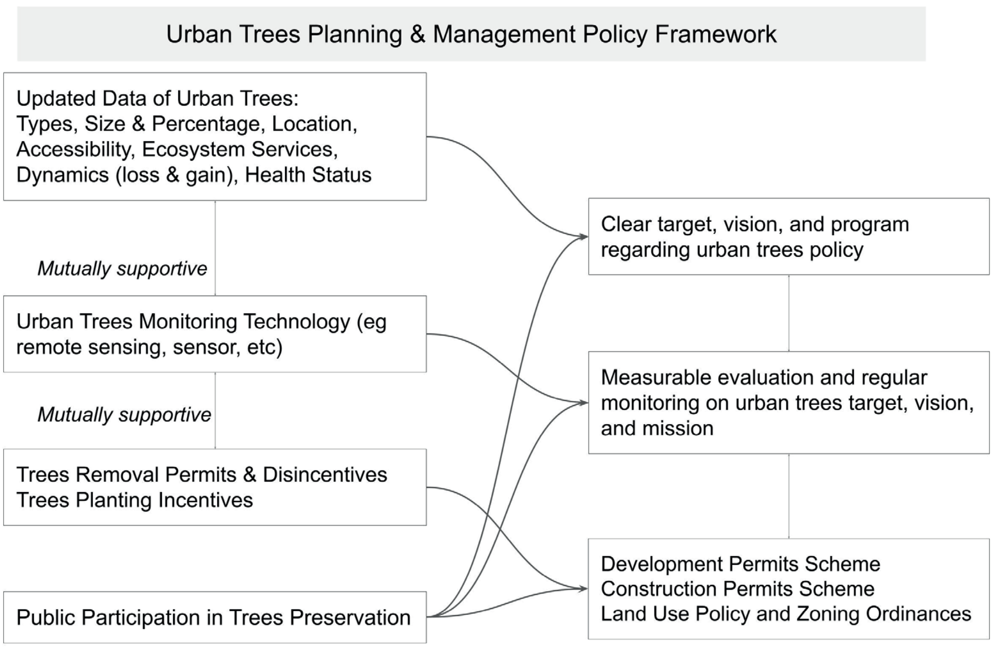

Fig. 5. Urban Trees Planning and Management Policy Framework

Table 3. Weaknesses, Strengths, and Recommendations for Usage

Type of Information	Data Needed	Strength	Weakness	Recommended Usage
Canopy size	Only canopy size	Provides preliminary information on the extent and distribution of canopy displayed in data by area (district or smaller)	Using only the canopy size can cause bias in assessing the level of greenness because the canopy size can be affected by the size of the area	As an initial data inventory for further analysis
Canopy cover percentage	1. Canopy size 2. Area / Boundary Size	The percentage unit allows a fairer way to compate greenery levels between areas	Data characteristics tend to be static, especially in the size component. Static data potentially influences business-as-usual policy formulation	1. To compare the level of greenness between areas (such as districts, sub-districts, neighbourhoods) 2. As input for regulating ecosystem services, such as local climate moderation (such as thermal comfort / reducing urban heat island) and stormwater run-off regulation
Canopy Per capita (sqm/person)	1. Canopy size 2. Total Population	Describes the socio-environmental aspects and serves as an approach in measuring the accessibility of urban residents to interact with the natural components of the city (trees)	With its dynamic characteristics especially on the components of the population, the indicator requires an adjustment of the target every year. Assessment activities also need to be an annual routine	1. To measure the accessibility of residents' interactions with natural components, especially urban trees 2. As an approach for analysis related to cultural ecosystem services, such as recreation and inspiration
Potential Carbon Sequestration and Storage	1. Canopy size 2. Carbon sequestration ability 3. Carbon storage ability For direct measurement, more data may be needed such as tree species, size, old, etc	Describes the climate change mitigation potential of urban trees to further influence urban tree preservation and urban environmental policies.	Direct measurement of carbon sequestration and storage of urban trees need more sophisticated methods, detailed data, and larger samples.	1. To understand the current state of urban trees' ability in mitigating climate crisis 2. As the baseline data for carbon offset scheme

for a baseline assessment, this research does not use spatio-temporal data. To get temporal data of canopy, high-resolution satellite images from the past years are necessary (Ellis & Mathews 2019). By using temporal data, the information obtained can include the dynamics of the presence of the canopy (Ossola & Hopton 2018). In other words, the research can identify information regarding the gains and losses of the canopy and the area where canopy gains and losses occur (Davey Resource Group 2015; Ellis & Mathews 2019; McGovern & Pasher 2016). Besides, by using spatio-temporal data, the loss of ecosystem services resulting from declined tree canopy size can also be estimated (McGovern & Pasher 2016; Riley & Gardiner 2020). By estimating ecosystem services, strategies to protect or even increase the number of trees in urban areas can be formulated effectively based on evidence (evidence-based policy). Secondly, cross-sectoral analysis is also recommended for future research in urban tree canopy field, especially in Indonesian cities context. For instance, future research may link canopy cover data with socio-demographic characteristics (Hostetler, Rogan, Martin, Delauer, & Oneil-Dunne 2013; Lavy & Hagelman 2017), with development policies, as well as land-use dynamics (Davey Resource Group 2015; Ellis & Mathews 2019; Phelan et al. 2019). Future research can also utilise spatial modelling to identify a potential area for tree planting. Possible methods include multi-criteria analysis based on remote sensing and GIS (geographic information systems)(Bravo-Bello et al. 2020; Davey Resource Group 2015). Lastly, future research may also combine tree canopy assessment and more sophisticated methods in directly estimating potential carbon sequestration and carbon storage (McGovern & Pasher 2016) in order to assist cities in taking a role in mitigating climate crisis (Bayulken, Huisingh, & Fisher 2021; Frantzeskaki 2019; Petri, Wilson, & Koeser 2019).

CONCLUSIONS

This research has measured the level of the greenness of an Indonesian city by using the presence and distribution of urban tree canopy. The methods used in this research are remote sensing, spatial analysis, and simple quantitative analysis. The spatial distribution of the tree canopy has been identified identified and analysed. From the urban tree canopy data, we present three types of information, namely: 1) canopy size for assessing the existence of tree canopy, 2) the canopy cover percentage for assessing distribution and equality of tree canopy, and 3) the number of canopy per capita as a proxy for assessing the accessibility of residents to interact with nature.

The findings show that the total canopy size of the city of Yogyakarta is only 467.37 hectares. The tree canopy size distribution per district ranges from 6.46 Ha - 134.19 Ha. Of the 14 districts, the average canopy size number is 33.38

Ha, and the median value is 21.92 Ha. Next, the percentage of canopy cover in Yogyakarta is only 14.38% covering the area of the city. If we look at the districts level, the canopy cover percentage in districts in Yogyakarta ranges from 9.27% -17.38% of the area. This number is relatively lower compared to green cities in the world, such as Singapore and Melbourne. Additionally, this research found that the number of canopy per capita in Yogyakarta City is still below the UN recommendation rate of 15 sqm/person. The canopy per capita rates in the Yogyakarta districts are only around 4.69 sqm/person - 14.45 sqm/person. These findings suggest that an integrated, visionary and measurable policy is needed to protect and to plant more trees in Yogyakarta strategically. Moreover, the three indicators used have strenghts and weaknesses in measuring the level of greenness. This research recommends the use of each indicator as follows: 1) canopy size information as an initial data inventory for further analysis, 2) Canopy cover percentage to measure and compare the levels of greenness spatially and visually between areas, 3) Canopy per capita is recommended to measure the possibility of access and interaction of residents with the presence of tree canopies. Cities' authority can also use the information to measure the achievement of SDGs number 11, 13, or 15.

Finally, as a preliminary research this study proposes several recommended improvements for further research. First, following research may use temporal data to identify the dynamics of urban tree canopy from year to year. In addition, future studies may also utilise a more sophisticated spatial analysis such as multi-criteria site selection and modelling to identify new tree planting sites.

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RESEARCH PAPER

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SUSTAINABLE URBAN DEVELOPMENT AND ECOLOGICAL EXTERNALITIES: RUSSIAN CASE

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ABSTRACT. Inclusive, safe, resilient and sustainable cities are included in Sustainable development Goals. The choice between environmental and social well-being is a very acute issue. It is necessary to take into account the interaction of three city dimensions: economic, ecological and social. The aim of the paper is to evaluate externalities in terms of population for 114 Russian cities all over the country considering all three dimensions.

The methods are the analysis of statistical data by econometric methods and their processing including geographical visualization. The data was taken from the Federal State Statistics Service database. The main results are the followings. The methodology for evaluation of externalities and estimation a hypothetical «efficient city size» in terms of population for Russian cities has been elaborated. The access to high-paying jobs and the availability of social benefits is often associated with living or moving to cities or regions with an unfavorable environment. Some cities feature an extremely high growth rate, dense population and often a low level of management and economic development.

Then there was demonstrated how to achieve a hypothetical «efficient city size» by means of environmental management and changes in city area. This should be helpful in achieving the Sustainable Development Goals (especially the Goal 11) and some targets mentioned in the «New Urban Agenda». It is essential to pay attention to the function of a city and its spatial organization. Some other measures to rise efficiency were proposed as well.

KEY WORDS: Sustainable development, urban planning, ecological externalities, efficient city size, environmental management

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INTRODUCTION

The modern human economic system, despite all societal efforts, still remains imperfect. Indeed, the global environmental and economic crisis is caused by the presence of external effects (externalities). The internalization of such externalities gives rise to debates among researchers from Pigou (Pigou 1946) to Coase (Coase 1960). The existence of externalities in fact makes it impossible to measure social costs and social well-being by market means. This is a well-known phenomenon called «market short-sightedness»: the market «can see» over a period of no more than ten years. There are numerous crucial aspects beyond the market we must consider before making decisions. This task is rather difficult for modern science. There exists the opinion that the internalization of externalities can hinder the market. However, they offer a solution for market problems by means of the market itself.

One example of externalities is climate change and its consequences; people do too little to reduce greenhouse gas emissions, and climate change is becoming increasingly acute. Here we can observe temporal externalities (between generations), as well as conflicts of interest between individuals (local externalities). Alternative energy sources have the potential to become one of many solutions to this problem.

If we want our natural resources to not be exhausted too quickly, and the degradation of the environment to not become irreversible, we must do our best. One should use, for example, the concept of the total economic value of the environment, which is well-known in environmental economics and includes use value, non-use value, optional value and existence value. This concept is quite useful for the estimation of urban forests' non-use value for urban development decision makers (Alekseeva, Kudryavtseva, Menshikh 2016).

According to the 2030 Agenda for Sustainable development the Goal 11 is «Make cities and human settlements inclusive, safe, resilient and sustainable»[1].

Externalities disrupt efficiency in urban economy and make it difficult to reach prompt decisions. According to UN experts, in 2050 more than 66% of the world's population will live in urban areas. It is also projected that the global urban population will grow by 2.5 billion between 2014 and 2050. About 90% of this growth will be concentrated in Asia and Africa. The most rapid urban growth over the last decades has been recorded in countries where income per person is above average: Brazil, Iran, Mexico and China. In the coming years, rapid growth is instead expected in countries with below average and low incomes, increasing the urban population from 39% and 30% to 57% and 48% by 2050, respectively[2].

By 2030, six out of every ten people will be living in cities. At the same time, cities in developed countries and cities experiencing rapid growth in developing counties over the last decades, along with those only starting to grow (generally in Africa, Latin America and in the Caribbean Islands) demand profound investigations of urban processes and the development of urban planning. Some cities feature an extremely high growth rate, dense population and often a low level of management and economic development. These problems became more acute during the COVID19 pandemic.

Small and medium-sized cities often face the problem of depopulation or urban shrinkage (Haase et al 2018). The solution of many urban social, economic and environmental problems demands an integrated approach.

Background

There are multiple studies devoted to ranking world cities. One should notice the recent study based on the geographic size index for megacities taking into account territory, population and gross domestic product (Sluka, Tikunov, Chereshnia 2019).

Some research pointed out that despite of new emerging factors and indicators significant for modern cities such as creativity and intelligence, the urban sustainability remains the most important of them (Rodrigues, Franco 2019).

In recent years, in Russia one can observe increasing volume of scientific papers on indicators of sustainable development: some of them devoted to indicators of implementation of sustainable development environmental goals in Russia (Bobylev et al. 2018); some of them devoted to indicators of sustainability for cities (Bobylev, Kudryavtseva, Solovyova 2014; Porfiryev, Bobylev 2018). Sustainable regional development should also be provided in terms of social (Zubarevich 2019) as well as environmental dimensions (Bobylev, Kudryavtseva, Yakovleva 2015). Institutional modernization and regional policy should be taken into account (Zubarevich 2015; Zubarevich 2017); principles of sustainable development should be implemented in this country by means of new priorities (Pakhomova, Richter, Malyshkov 2013).

One should avoid old mistakes in urban development. Within traditional neo-classical theories, scientists attempted to define the «optimal» city size, instead of what is «effective.» When a city grows, the economy of scale is at play. But this is true only before the city reaches a certain size. Nevertheless, if there are some structural transformations, for example, the development of innovative sectors or strengthening communications with other cities, the efficient size increases (Capello, Camagni 2000; Camagni, Capello, Caragliu 2013). The so-called «optimal» size proposed for modern European cities is from 55,500 to 360,000 residents without the structural transformations mentioned above, and from 1,000,000 to 2,100,000 inhabitants with them.

Numerous studies have focused on the issue of «urban sprawl» and its negative impact on the environment (Kahn 2000), society (Downs 1999), and health (Zhao, Kaestner 2010).

In the framework of the traditional theory of urban economics, there is an inverted U-shaped relationship between the size of a city and income per employed resident. The optimal size of the city is at the point of providing maximum income (quality of life not considered). Benefits from «economy of scale» have been investigated through the urban systems approach (Henderson 1974, 1977, 1988), and another approach was provided by a new economic geography (transportation costs taken into account) (Krugman 1991, 1995).

Some Asian countries like Japan and South Korea have introduced policies that limit population growth in large cities. The Japanese government began to limit the growth of Tokyo and neighboring areas in the 1950s. Similarly, in 1984 in South Korea there was a plan for rebuilding the capital city region to help combat urban sprawl. Many other countries are now facing a choice of various urbanization methods. For example, scientists from China often consider employment and wages, but quality of life is not mentioned (Hong Gao, Ming Lu, Hiroshi Sato 2015). Their estimates show that it is more likely for individuals to get a job in large cities, and the least-qualified employees have the most to gain from city scale.

The choice between environmental and social well-being is a very acute issue for many people in Russia (Kudryavtseva, Malikova 2019). The access to high-paying jobs and the availability of social benefits is associated with living or moving to cities or regions with an unfavorable environment. The most profitable economic sectors and highest incomes are found in the energy and raw materials industries, which simultaneously cause severe damage to the environment. Currently, 15% of Russia's urban population lives in cities with 'high' and 'very high' degrees of air pollution (44 cities, 16.4 million people). A classic example is Moscow which is a city with a vibrant cultural environment but poor ecological circumstances. A rather ambiguous air pollution situation can be observed in this city. Indeed, there has been a reduction in emissions of some pollutants, but due to rapid automobilization, the total pollutant load in Moscow oblast has increased. In Moscow, 93.5% of total emissions come from vehicles. Despite of this, many people in Russia buy flats in big cities in order to save money or hoping to move there later so the price for realty in such cities becomes higher than it might be (Kuricheva E.K., Popov A.A. 2016). The issue of urbanization and negative externalities has been considered in many Russian studies (Zemskova O.V. 2015, Malikova O. 2017). The «efficient city size» taking into account the environment and economy is up to 5-6 million residents for Moscow respectively[3].

[1] https://sustainabledevelopment.un.org/post2015/transformingourworld

[2] United Nations, Department of Economic and Social Affairs, Population Division (2014). World Urbanization Prospects: The 2014 Revision, Highlights (ST / ESA / SER.A / 352)

[3] Zemskova O.V. (2015). Socio-economic causes and environmental consequences of overpopulation (the example of Moscow and the Moscow region). Author's abstract of the dissertation. M., MSU named after MV Lomonosov

Small and medium-sized cities might be more comfortable to live in, but today the industries typical for small and medium-sized cities (food, textiles, a part of the engineering industry) are in stagnation. Thus, two connected issues must be addressed: (i) the development of small towns and (ii) the development of manufacturing industries oriented towards the consumer sector and local markets.

The problems of the differences in the development of large, small and medium-sized cities in Russia are also related to the peculiarities of the management and taxation system. Most of the taxes are not collected at the place of the actual production activity of the company but at the place of registration of the company. For example, a company may carry out actual production activities in the Kostroma region (this may be wood harvesting or collecting wild plants), but Moscow may be the place of registration. The head office, accounting, structures involved in logistics are in Moscow. Accordingly, taxes will be paid at the place of registration, and not at the place of receipt of resources and production. In this case the region loses twice, because the region (i) does not receive taxes from the economic activity in its own region and (ii) transfers resources for the development of another territory. Obviously, such system contributes to the development of large cities and the degradation of smaller settlements. That is why parallel tracking of flows of resources and financial flows is extremely important.

Technical progress and new technologies often provide additional boost to harmonizing the urban and rural environment. This fact must be considered when making management decisions. Here, renewable energy can be provided as a classic of technological breakthroughs in the construction of energy-passive and energy-active buildings. Unfortunately, construction technologies and «technology» of making management decisions are inertial (very slow). Future changes and the factor of technical progress are not considered (due to the focus of the businesses to achieve immediate results and present income generation). Today it is advantageous to use solar and wind energy in some Russian regions (for example, in Arctic region (Potravnyi, Yashalova, Boroukhin, Tolstoukhova 2020) in the Far East and some small cities (Grechukhina, Kudryavtseva, Yakovleva 2016). Electricity and heat in small towns can be less expensive than in megacities because of outdated solutions. «An example is the proliferation of multi-storey buildings along the perimeter of megacities. It entails the growth of environmental, transport and social problems in the future. Obviously, it is important to focus on the concept of assessing the full life cycle of buildings when making urban planning decisions, and not just the costs associated with their construction».[1]

Urbanization leads to changes in demographic processes. There is a noticeable decline in the birth rate in large cities coupled with the birth of children from parents of older age groups. A similar trend is typical for Russia. The demographic situation in Russia is characterized by a negative natural population growth. The population loss is partially compensated by positive migration inflows. The most difficult demographic situation in terms of natural population growth in Russia is taking shape in megacities – Moscow and St. Petersburg. These cities are characterized by low natural population growth but a high birth rate for women after 35 years old. The number of births of the first children after 35 years is large in comparison with other regions (Smulyanskaya 2017).

The birth of the first child in the older age groups entails certain medical risks. The risks associated with the possible deterioration of the health of such children in the future increase in conjunction with the residence of late-born children in the conditions of the less prosperous environmental situation inherent in almost all megacities. Today these problems are under-studied and require further research. However, it is obvious that in this case the action of the externalities also manifests itself. The rational desire of parents in megalopolises to postpone the birth of their first child to a later date leads to additional costs for society in the future. These costs cannot be taken into account by parents who make decisions. It is important to note that an environment unfavorable from the viewpoint of ecology exacerbates the problem markedly. The poor environmental conditions in large cities require not only measures to minimize industrial impact, but also innovative approaches to city development («eco-cities») and territorial planning.

In terms of all the external effects, small and medium-sized cities could be more competitive than megacities. However recent research highlighted the growing depopulation of small and medium-sized cities (Haase et al 2018). This problem is especially acute for mono-specialized Russian settlements (Parfenova, Gurova 2020).

MATERIALS AND METHODS

The methods of study are the analysis of statistical data by econometric methods as well as their processing including geographical visualization. Our research includes 114 most populated and significant Russian cities all over the country. Data for the calculations were taken from the Federal State Statistics Service (Rosstat) database in 2018. We define the efficient city size structure for Russian cities the way it was done by Camagni, Capello, and Caragliu (2013). However, their basic model was changed in order to specify some significant for Russia factors. It is very important to include ecological externalities in our analysis.

It is supposed that each city has benefits and costs which depend on some variables. Moreover, city size is included in both benefits and costs. As usual, Cobb-Douglas specification is used in both benefits and costs functions (Camagni et al. 2013).

$$C = size^{a_0} c_1^{a_1} \dots c_k^{a_k} \qquad B = size^{\delta_0} \delta_1^{\delta_1} \dots \delta_m^{\delta_m}$$

Here, $C_1 \dots C_k$ and $b_1 \dots b_m$ are the variables that respectively influence the net benefits of the city *B-C*; $a_1 \dots a_k$ and $\delta_1 \dots \delta_m$ are the corresponding elasticities of costs and benefits. It is proposed that δ_0 is in the interval (0,1) while a_0 is greater than one. This derives from the proposition that the growth rate of costs is increasing as the city size gets bigger.

Obviously, net benefits are to be maximized with respect to the city size. It is required that marginal costs are equal to marginal benefits of the city (with respect to the city size). So, we can derive the efficient city size. Let us do it by transforming the equation of marginal costs and benefits:

$$MCsize = a_0 size^{a0-1} c_1^{a_1} \dots c_k^{a_k} = \delta_0 size^{\delta 0-1} b_1^{\delta_1} \dots b_m^{\delta_m} = MB_{size}$$

$$size^{a_0-\delta_0} = \frac{\delta_0}{a_0} \cdot \frac{b_1^{\delta_1} \dots b_m^{\delta_m}}{c_1^{a_1} \dots c_k^{a_k}}$$

$$lnsize^* = \frac{lnb_0 - lna_0}{a_0 - \delta_0} + \sum_{i=1}^{m} \frac{\delta_i}{a_0 - \delta_0} lnb_i - \sum_{j=1}^{k} \frac{a_i}{a_0 - \delta_0} lnc_i = \mu + \sum_{i=1}^{m} \gamma_i lnb_i + \sum_{j=1}^{k} \omega_j lnc_j$$

[1] Schukin A. (2019). High-rise buildings are a toxic asset with a short lifespan Expert, 25, 28-32

Here γ_i is the quotient of two variables: elasticity of net benefit and the city size elasticity. In the same way, ω_j is the quotient of the cost elasticity and the city size elasticity. It is worthwhile noting that the coefficient γ_i is positive, while ω_j is negative. There are some conclusions that can be drawn from the derived equation. For instance, if the amount of certain benefit b_i (cost c_j) increases by 1%, then the «efficient city size» will increase by γ_i% (decreases by ω_j%).

Let us find the necessary path towards efficiency of the city without changing its size. Suppose one has the efficient value of the city size (we denote it by *size**) and the current value of the city size (we denote it by *size**). It is obvious that the «efficient city size» should change by (*size´/size*-1*)x100%. Let us respectively denote R^{bi}_{growth} and R^{ci}_{growth} as the growth rates of benefit b_i and cost c_j. So, in order to achieve the efficiency, the following equation should be fulfilled:

$$\sum_{i=1}^{m}\gamma_i R_{growth}^{c_j} + \sum_{j=1}^{k}\omega_j R_{growth}^{c_j} = \frac{size' - size^*}{size^*}$$

Suppose it is possible to exogenously change the elasticities of net benefits of the city. Then, if we still need to reach efficiency without changing the actual city size, then the following condition must be met:

$$\Delta lnsize^* = \sum_{i=1}^{m}\frac{\Delta\delta_i}{a_0-\delta_0}lnb_i - \sum_{j=1}^{k}\frac{\Delta a_j}{a_0-\delta_0}\ln c_j = \frac{size' - size^*}{size^*}$$

However, if we can change a_0 and δ_0 coefficients, then the equation will be as following:

$$\Delta lnsize^* = \frac{ln\left(1+\frac{\Delta\delta_0}{\delta_0}\right) - \ln\left(1+\frac{\Delta a_0}{a_0}\right) - (\Delta a_0 - \Delta\delta_0)lnsize^*}{a_0-\delta_0+\Delta a_0-\Delta\delta_0} = \frac{size' - size^*}{size^*}$$

RESULTS

There are some things to discuss here. When a city is overpopulated, it is possible that a part of the population of that city may leave it to go somewhere else in order to increase their utility. Thus, the city size can decrease towards the efficient value.

However, when it comes to underpopulated cities the question becomes more complicated. There is still an incentive to leave the city due to the insufficient utility, but nevertheless the size of an underpopulated city can increase due to natural growth of population and possible migration towards this city from other cities, where it is relatively worse to live in.

And this is where the problem of city management arises. In order not to let the underpopulated city slowly die as its population moves to other cities, it is necessary to change the living conditions in it. According to the model, another way is to decrease the efficient city size by increasing the cost values and decreasing the benefits values for the city. By doing this the actual city size becomes efficient.

On the other side, when it comes to managing overpopulated cities, the efficient city size must be increased. This can be done by increasing benefits and decreasing costs for the city. Once again, the actual city size will become efficient.

The ecological situation is very important for city efficiency. It is a well-known fact that environmental pollution in Russia is one of the biggest problems and yet is being neglected in many Russian cities. Ecological externalities surely affect the quality of life in a city and thus there should be a lot of attention paid to them.

Given the numerical data which includes current values of city size for each city and the variables which affect benefits and costs, we are creating a model that will give us the theoretically efficient desirable values of city size for each city under consideration and the coefficients which correspond to benefits and costs for each of them. The theoretical values of the city size (which will be denoted as $\hat{size}$) should be considered as the «efficient city size». Then, by comparing the theoretical and empirical, or actual (from official statistics) values of city size for each city the necessary city size growth (decrease) rates to reach efficiency will be calculated in order to estimate which cities are «underpopulated» or «overpopulated».

Nowadays in Russia there is a huge migration towards the largest cities, starting with regional centers and ending with cities like Moscow and Saint Petersburg. This makes bigger cities even more overpopulated and smaller cities more underpopulated. The economic structure of Russian cities does vary a lot too. Some cities are focused on primary and secondary sectors of economy like extraction and production of raw materials, manufacturing, production and construction, others are more focused on tertiary and quaternary sectors like service industry, research, banking, education, etc.

The key variables of our model are the «rent/wage ratio» and «emissions per square kilometer». These emissions are the total emissions from all polluting sources: CO, SO_2, CH_4, NOx, volatile organic substances, solid particles reflected in the federal statistics (further: emissions). There are many other ecological factors that were not included in our model (for example the availability of fresh water) but the clean air is the most important ecological factor for city dwellers in this country and it is possible to include some other factors in the model in the future. We have decided to include in this model also the variable «emissions per capita» (it is disputable if we should do it) in order not to miss some possible significant results. Such variables as the «crime rate», «average living space per capita», «amount of investment in city» and others were used as control variables (they reflect essential macro parameters of cities). It can be discussible if we should use such variables as medical support rate and crime rate but we have decided to do it here in order to demonstrate how our model runs taken into account the available data. All the variables were taken in logarithmic scale:

$$lnsize^* = \beta_0 + \beta_1 lnRW + \beta_2 lnEmis\_A + \beta_3 lnEmis\_C + V\beta + \varepsilon$$

Here, *RW* is the rent/wage ratio, *Emis_A* is the amount of emissions per square kilometer, *Emis_C* is the amount of emissions per capita and *V* stands for other control variables. β_0, β_1, β_2, β_3 and β stand for the coefficients of the variables, ε is the random error.

Below there are some results of model estimations. In total, nine models were made to represent the whole process of modelling.

The results of modelling showed that the «rent/wage ratio» has a positive impact on the hypothetical «efficient city size». The following explanations for this fact may be provided. Higher rents in the city often mean that the city's infrastructure is more developed, which increases the quality of life in the city and hence the «efficient city size».

DISCUSSION

External effects

The following modern social dilemma is well known: when a city grows, negative ecological externalities occur, causing some

Table 1. Results of model estimations

Dependent variable: Efficient city size in terms of population	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Rent/Wage ratio	1.78*** (0.36)	1.47*** (0.39)	1.47*** (0.35)	1.49*** (0.35)	1.60*** (0.35)	1.59*** (0.35)	1.58*** (0.36)	1.54*** (0.39)	1.18*** (0.41)
Emissions per square kilometer	-	-0.11 (0.08)	-0.41*** (0.12)	-0.41*** (0.12)	-0.43*** (0.11)	-0.43*** (0.11)	-0.43*** (0.12)	-0.43*** (0.11)	-0.45*** (0.12)
Emissions per capita	-	-	0.49*** (0.12)	0.52*** (0.11)	0.55*** (0.12)	0.55*** (0.12)	0.55*** (0.12)	0.56*** (0.12)	0.56*** (0.13)
Living space per capita	-	-	-	0.99** (0.44)	1.07** (0.46)	1.04** (0.49)	1.02* (0.52)	1.00* (0.54)	0.99* (0.53)
Investment in the city per capita	-	-	-	-	0.15 (0.14)	0.15 (0.14)	0.14 (0.14)	0.14 (0.14)	0.08 (0.13)
Medical support rate	-	-	-	-	-	0.04 (0.21)	0.05 (0.22)	-0.03 (0.30)	0.02 (0.29)
Crime rate	-	-	-	-	-	-	-0.06 (0.20)	-0.07 (0.21)	-0.04 (0.20)
Regional center	-	-	-	-	-	-	-	0.10 (0.31)	0.12 (0.30)
Federal city	-	-	-	-	-	-	-	-	1.02 (0.68)
Constant	5.37*** (0.12)	5.97*** (0.40)	4.90*** (0.41)	1.60 (1.51)	0.66 (1.86)	0.56 (1.89)	0.76 (2.02)	1.08 (2.17)	1.27 (2.10)
Observations	114	114	114	114	114	114	114	114	114
R^2	0.34	0.36	0.42	0.44	0.46	0.46	0.46	0.46	0.48
Adjusted R^2	0.34	0.35	0.41	0.42	0.43	0.43	0.42	0.42	0.44
Residual Std. Error	0.76	0.75	0.72	0.71	0.71	0.71	0.71	0.71	0.70
F Statistic	58.30***	31.60***	26.78***	21.77***	18.33***	15.15***	12.89***	11.20***	10.68***
Note:	Standard errors in parentheses. ***, **, * imply significance at 1, 5 and 10% respectively								

inhabitants to seek to leave the city. Yet at the same time, though individual welfare might increase, in general the pollution and congestion also increase (the profit of the «scale economy» decreases), and therefore social well-being decreases. Traditional economic theory fails to consider the positive and negative externalities arising from the interaction of three city spheres: economic, ecological and social. Externalities arise at interaction of economic and ecological, economic and social, and ecological and social components. Positive effects can be seen in the availability of social services (including education, health/medicine), and the increase in the probability of finding well-paid work. The economy of scale diminishes the negative impact on the environment, as energy and water use can decrease. The positive influence of the environmental sphere on the social is expressed in improvements in human health. Public welfare increases after a certain volume of vegetation is planted. For an investigation of the influence of external effects and a search for ways to internalize them, various indicators can be used. For example, many researchers have outlined a positive link between the existence of a park within walking distance, and urban real estate value (McCord et al. 2014; Kim et al. 2019). The authors' research for Moscow confirms this fact (Alekseeva et al. 2016).

Negative effects are expressed through emissions growth, congestion, and social tension. These factors can exert a negative impact on the economy by promoting conflicts, fluctuations in the labor market, bankruptcies, the withdrawal of companies from the city, and the outflow of investments. They can also breed interpersonal and intergenerational conflicts of interest.

Some researchers conclude that sometimes urban sprawl is even necessary to prevent overpopulation. Three factors cause inefficiency in terms of externalities: production, consumption and real income. With a decreasing city size (in terms of population), salaries increase with a shift in the labor supply. Companies must pay higher wages, as all local firms face higher salaries. Such an increase in costs is to some extent, albeit not entirely, offset by decreased land rent and rent for capital due to lower demand. Consumption changes according to the same logic, as local prices for goods and services increase with a decrease in the size of the city, due to the net effect of the processes described above. However, households pay less in rent for where they live. Both these externalities of distribution interact and affect the real income of households. Local households receive income from wages and rent from local land and capital. With a decrease in the size of the city, an increase in wages causes an increase in real income per household, yet lower rent for land and capital reduces real income. The latter phenomenon has a relatively greater impact on households with a larger share of local real estate and capital ownership. Generally speaking, this is understandable, since high-income households simultaneously own local businesses and require large buildings with large plots of land in comparison with families with lower incomes. Hence the real income of high-income households is reduced more than the income of lower-income households with a smaller share of local land and capital. Thus, with a decrease in the size of a city, high-income households migrate. Low-income households then find their income increasing with the continued decline in the size of the city, as increasing salaries begin to exceed their land and capital costs, which is the reason for their inflow into the city. This leads to a change in the structure of households within the city. With a decrease in the size of a city and the achievement of its «optimal» size, low-income households make up the greater part of this distribution.

Another way of interpreting these results is that the distribution of households is inefficiently shifted towards high-income households in overcrowded cities. The results show that there is a link between the optimal size of the city and the distribution of households: the first can be estimated using the second. It can be concluded that urban sprawl and the development of transport infrastructure can reduce the inefficiency from «overpopulation» in the city. Some retail activities (for example, shopping centers) can be «exported» out of the city. According to the results, cities with a relatively large share of retail and services have a larger «optimal» size than others. However, when production becomes R&D-oriented, the degree of «overpopulation» is reduced with the increase in the «optimal» size of a city. In general, production in large cities is more R&D-oriented than in small and medium-sized cities (Burnett 2016).

Problem of efficiency

We should notice here that results of our model are discussible and should give rise to more research. We have also discussed above some significant reasons for it.

According to the estimations of the model, «emissions per square kilometer» have a negative impact on the efficient city size, which is intuitively clear. The more polluted the air in the city is, the worse is to live in it. However, the created model states that «emissions per capita» have a positive impact on the «efficient city size». The way this can be explained is that the more emissions are made in the city, the more productive in terms of gross city product per capita the city is. The gross city product does not take into account ecological externalities and pollutions.

After that, the growth rate which is necessary to reach hypothetical efficiency was calculated for each city. This growth rate should provide efficiency for the city. The result for underpopulated cities can be seen on the Fig. 1. Naryan-Mar in the Russian Far North for example should be 8 times more populated in order to obtain the «hypothetical efficient size».

One can see that there is a significant gap between hypothetical efficient and actual city size for some Russian cities. It might be explained by very uneven size and economy structure of Russian cities. In other words, we should notice that cities of the Russian Far North such as Anadyr, Naryan-Mar and Salekhard are extremely underpopulated at present. This can also be explained by unfavorable climatic conditions in areas of northern and remote eastern regions in combination with high cost of living there (Zubarevich 2019). These conditions were not taken into account in this model and should be subject for future research. There is a problem with fresh water in Sevastopol but this fact was also not under consideration in our model.

Murom and Gorno-Altaysk are extremely underestimated with regard to benefits from living in them so new dwellers should be attracted in them by means of governmental programs of «area development». The support of historical heritage and favorable environmental situation should become drivers for economic development including tourism industry. There is a plenty of underpopulated cities all over the country and many of them are in its Western part where climate conditions are rather favorable (Fig. 2).

Russia has done little to support the development of its small and medium-sized cities. The resolutions «On Approval of the Federal Integrated Program for the Development of Small and Medium Cities of the Russian Federation under the Conditions of Economic Reform», June 28, 1996 № 762 and «Federal Integrated Program for the Development of Small and Medium Cities of the Russian Federation under the Conditions of Economic Reform» were adopted in 1996 but in 2002 this decree became invalid.

The Union of Small Cities of Russia developed a draft «Federal Target Program for Social and Economic Development of Small and Medium Cities of the Russian Federation for 2009–2012 and until 2017». Unfortunately, this document was not supported by the federal government.

Measures to support the development of small and medium-sized cities of the Russian Federation can be quite diverse. The principles of ‘Priority Social and Economic Development Areas’ (hereafter PSEDA) are defined by the Federal Law «On Creating Territories of Advancement of Socio-Economic Development» in 2014. They are justified with the support of single-industry towns (they include urban-type settlements with a population of more than 3,000 inhabitants, of which at least 20% work at enterprises of the same company. As a rule, this company provides 50% or more of the gross output of a city).

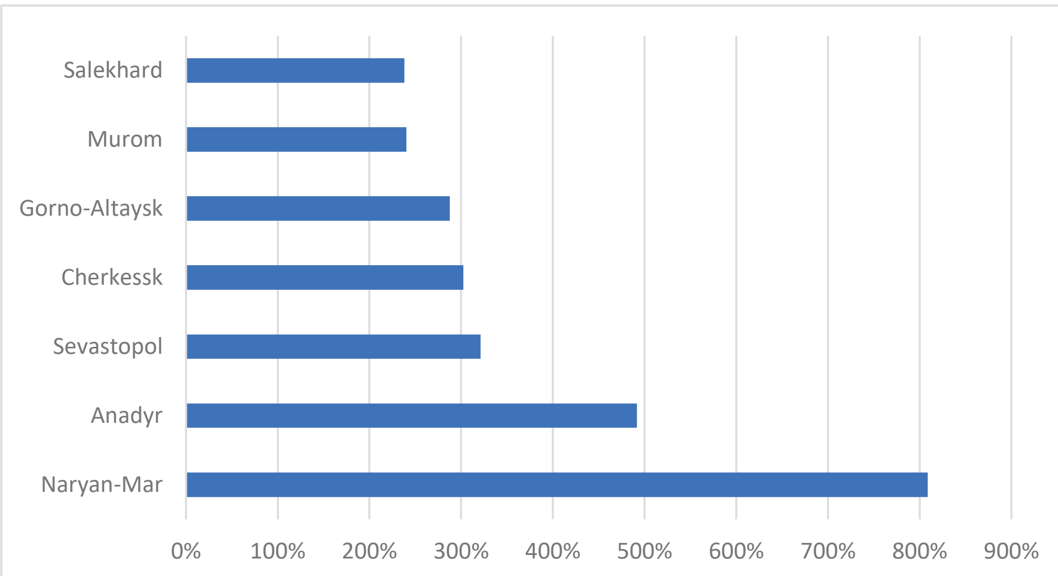

Fig. 1.City size growth rate (in%) to reach efficiency
Source: calculated by the authors using the data provided by Rosstat

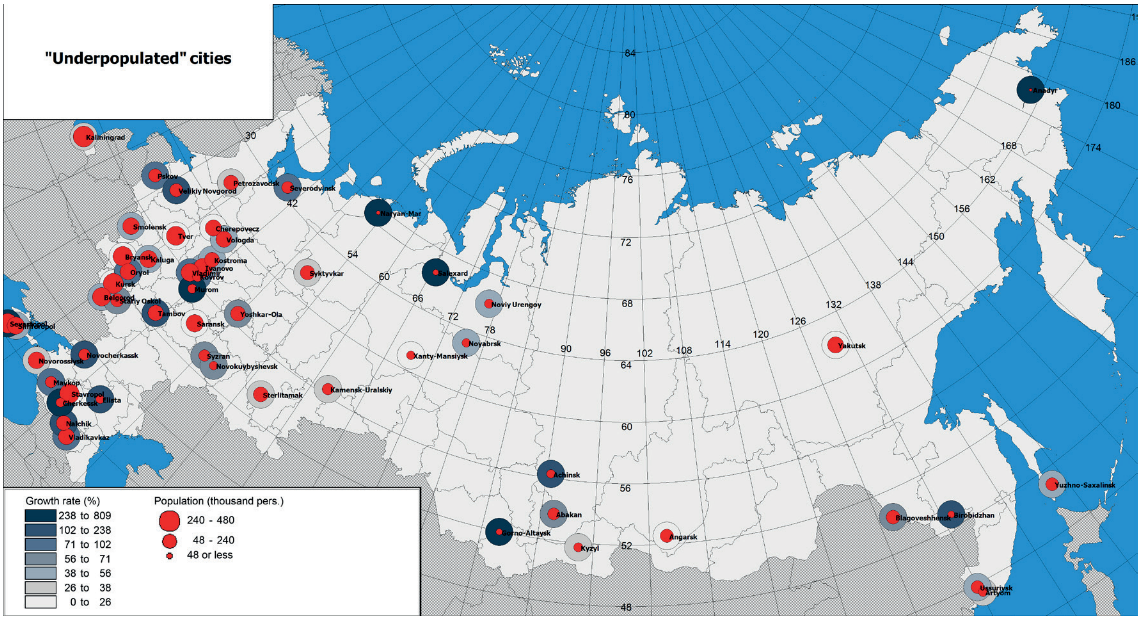

Fig. 2. Underpopulated Russian cities

Source: estimated by the authors using the data provided by Rosstat

Some monotowns (single industry towns, factory towns) of the Russian Federation have already received the status of PSEDA. Support to food and light industry, engineering is a very important measure for the development of small and medium-sized cities. Modernization of the municipal sector of small towns can play a big role. Energy efficiency programs in such cities are implemented. Stabilization of utility payments may be another effective measure (Pershina 2015).

The Resolution of the Government of the Russian Federation «On the All-Russian Competition for the Selection of the Best Projects in the Sphere of Creating a Comfortable Environment in Small Cities and Historical Settlements» prepared by the Ministry of Construction of Russia, was important. The competition was held in 2018 and in 2019. In 2019, 330 applications from 77 Russian regions were submitted to the competition. 80 winning projects were selected. These projects received financial support in the amount of 40 to 85 million rubles from the Federal Budget. The winners of the contest were announced on May 31, 2019. This decision was very important to support the development of small cities but this is not enough for a noticeable change in the situation.

There is also one additional significant and underestimated asset of small and medium-sized cities: historical real estate and the historical environment ensuring the uniqueness of the area. Unfortunately, this asset in many cities is rapidly deteriorating. One measure that can support the preservation of the historical environment and historical real estate could be the decrease of property tax for historical buildings, provided they retain their original appearance and satisfactory technical condition. All kinds of environmentally safe and economical feasible tourism should be developed attracting investments and providing new jobs. This could also help reaching SDG 11.4 «Protect the World's Cultural and Natural Heritage». This is also in accordance with the «New Urban Agenda» that was adopted at the United Nations Conference on Housing and Sustainable Urban Development (Habitat III) in Quito, Ecuador, on 20 October 2016: «We will support the leveraging of cultural heritage for sustainable urban development and recognize its role in stimulating participation and responsibility. We will promote innovative and sustainable use of architectural monuments and sites, with the intention of value creation, through respectful restoration and adaptation»[1].

On the contrary, Industrial centers of Russia, such as Norilsk, Chelyabinsk, Ekaterinburg, Perm, and Omsk are overpopulated in terms of hypothetical efficiency (Fig. 3). The ecological situation in most of them is very uncomfortable for living, i.e., they have very poor quality of life.

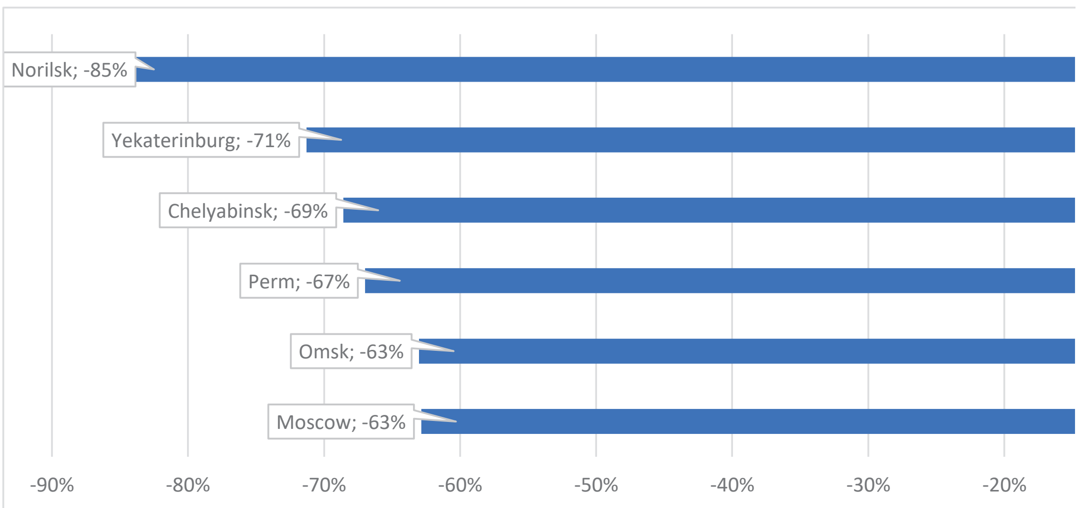

Fig. 3. City size decrease rate (in%) to reach efficiency

Source: calculated by the authors using the data provided by Rosstat

[1] https://uploads.habitat3.org/hb3/NUA-English

Some ways to reach efficiency

How the problem of inefficiency should be resolved? It is possible to achieve efficiency without changing the actual size of a city simply by changing the values of variables that affect the efficient city size. Two variables will be used to reach efficiency: «emissions per capita» and «emissions per square kilometer». There should be an ecological regulation. Given the gap between the actual and «efficient» city size and respective estimated elasticities of these two variables, the efficiency can be reached using a single equation.

$$\hat{\beta}_2 * R_{growth}^{Emis\_A} + \hat{\beta}_3 * R_{growth}^{Emis\_C} = \frac{size - \hat{size}}{\hat{size}} = x$$

Here, $R_{growth}^{Emis\_A}$ and $R_{growth}^{Emis\_A}$ are, respectively, growth rates of emissions per square kilometer and emissions per capita. This equation is linear with respect to growth rates of these variables. However, since the city size is assumed to be unchangeable, growth rates can be transformed into growth rates of gross emissions and city area.

$$\hat{\beta}_2 * \frac{R_{growth}^{Emissions} - R_{growth}^{Area}}{R_{growth}^{Area} + 1} + \hat{\beta}_3 * R_{growth}^{Emissions} = x$$

The set of feasible growth rates of emissions and area that allow the city to reach efficiency is a continuum. However, environmental constraints should be effective in terms of costs of its implementation. Thus, it is possible to specify a task where costs of reaching efficiency of the city are to be minimized under certain constraints. Obviously, there should be a constraint that allows to reach efficiency. Also, there should be upper and lower bounds of emissions and area growth rates.

$$\begin{cases} f_i\left(R_{growth}^{Emissions}, R_{growth}^{Area}\right) \rightarrow \min \\ \hat{\beta}_2 * \frac{R_{growth}^{Emissions} - R_{growth}^{Area}}{R_{growth}^{Area} + 1} + \hat{\beta}_3 * R_{growth}^{Emissions} = x \\ R_{growth}^{Emissions} \in \left[\varphi_{\min}^i, \varphi_{\max}^i\right] \\ R_{growth}^{Area} \in \left[\theta_{\min}^i, \theta_{\max}^i\right] \end{cases}$$

Here, f_i is the cost function of changing emissions and city area i. R^E_{growth} and R^A_{growth} are, respectively, growth rates of gross emissions and city area. $[\varphi^i_{min}, \varphi^i_{max}]$ and $[\theta^i_{min}, \theta^i_{max}]$ are the bound for emissions and are growth rates.

These findings should provide reaching SDG 11.3 «Inclusive and Sustainable Urbanization» taking into account the indicator «ratio of land consumption rate to population growth rate» as well as SDG 11.6

«Reduce the Environmental Impact of Cities and Urban air pollution»

However, it is essential to pay attention to the function of a city and its spatial organization. Environmental constraints are suitable for industrial centers such as Norilsk, Chelyabinsk, Ekaterinburg, Perm, and Omsk which according to results of our model are overpopulated in terms of hypothetical efficiency because of environmental degradation. The implementation of Best Available Techniques (BAT) and principles of circular economy should be helpful.

These findings are also in accordance with the «New Urban Agenda» mentioned above: «We encourage spatial development strategies that take into account, as appropriate, the need to guide urban extension, prioritizing urban renewal by planning for the provision of accessible and well-connected infrastructure and services, sustainable population densities and compact design and integration of new neighborhoods into the urban fabric, preventing urban sprawl and marginalization»[1]. One should also mention the «World Cities Report' (UN-Habitat 2020) according to which local governments should raise revenue simultaneously limiting urban sprawl and relieving overcrowded housing[2].

For underpopulated cities of the Russian Far North one should use other methods such as developing «Priority Social and Economic Development Areas» or PSEDA (Parfenova, Gurova 2020). Renewable energy sources should make living in smaller cities more economically viable. For Murom and Gorno-Altaysk, one should use programs of area development. The environmental situation, environmental and historical heritage make it possible, for example, to develop all kinds of tourism providing new jobs, attracting investments and strengthening local labor market.

CONCLUSIONS

The conclusion can be drawn that when attempting to find solutions for acute modern social problems such as urban development issues, it is necessary to carefully consider many externalities, both negative and positive. The existence of externalities makes impossible to measure social costs and social well-being by market means. Urban economy is crucial domain where externalities disrupt efficiency. Traditional economic theory fails to consider the externalities arising from the interaction of three city dimensions: economic, ecological and social. The results of the research give following recommendations for urban and regional policy for approach the achieving SDG 11 as well as some targets from the «New Urban Agenda» and the «World Cities Report» (UN-Habitat 2020). It is essential to pay attention to the function of a city and its spatial organization. There are different strategies to achieve hypothetical «efficiency» for different city types. Some of them were justified above. Despite of all discussible points of the model presented above, we have shown that under certain assumptions the environmental management may lead to the «efficiency» of the city without changing the city size.

It is important to consider possible external effects within the framework of urban planning; assessment of the flow of resources, income and pollution. The cost of restoring the health of residents of environmentally disadvantaged cities can be comparable to the economic benefits of living in such cities. The concentration of the population in large cities leads to a fatal decrease in fertility. The birth rate is the lowest among residents with a high level of education, living in an urban environment for several generations. It is necessary to develop other «points of growth» as an alternative of large cities.

New technologies and environmental factors will have an increasing impact on the quality of life of urban dwellers. Renewable energy makes living in smaller cities more economically viable. It is important to develop new technologies and adopt modern legislation for the development of renewable energy in order to achieve progress in this direction. It is necessary to adopt a law on microgeneration of electricity (small-scale generation with focus on renewables).

[1] https://uploads.habitat3.org/hb3/NUA-English
[2] https://unhabitat.org/World%20Cities%20Report%202020

It is desirable to adjust the urban and regional policy towards the harmonization of territorial development, smoothing disproportions in the development of cities and towns, and supporting the development of small and medium cities in Russia. In recent years, several legislative initiatives have been taken in this country to support the development of small cities. However, these actions are still not enough. More decisions need to be made to harmonize territorial and cities' development in accordance to Sustainable Development Goals, «New Urban Agenda» and «World Cities Report» (UN-Habitat 2020).

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RESEARCH PAPER

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CREATING REVENUE OUT OF GREEN WASTE: NEW PERSPECTIVES FOR MUNICIPAL ORGANIC WASTE HARVESTING IN GEELONG, AUSTRALIA

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ABSTRACT. The diversion and recovery of organic waste are one of the most significant opportunities and challenges for reducing the environmental impacts of waste disposal internationally, as recognised by the United Nations' SDG 12 that seeks to "ensure sustainable consumption and production patterns". This issue is particularly pertinent to developed countries, like Australia, who have a high propensity for waste removal arising from their industrial and domestic use of products, materials and organic consumables. Through the use of GIS technology, using modelling software developed by the Global Methane Initiative, a series of simulations were undertaken to determine the viability of an anaerobic digester for the City of Greater Geelong (COGG), located in the State of Victoria (Australia), where organic materials constitute over 25% of all waste land-filled. Using only municipal organic waste, the modelling concluded that the COGG would generate between AU$6M-AU$11M/annum from the sale of biogas/methane. In addition to this revenue stream, COGG would have an Annual Projected Net Emissions Reductions of 3797 Mt. This paper further considers the development of a geospatial database to identify and locate concentrated organic waste resources in COGG, the design and development of a software tool to help quantify the production of food waste, and the development of an economic model to value the organic waste stream of COGG arising from the implementation of this proposal.

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INTRODUCTION

Internationally we are drowning in a sea of waste, both on land and in our waters (Allam & Jones 2018). In 2018 the World Bank concluded, on current patterns, that global waste will increase by 70% by 2050. The Bank pointed to its escalation due to rapid urbanization and growing populations and projected that global annual waste generation is expected to increase to 3.4 billion tonnes over the next 30 years, up from 2.01 billion tonnes in 2016 (Kaza et al. 2018).

Portently, it was developed countries, despite only comprising 16% of the world's population, generated more than one-third (34%) of the world's waste. Frightening, it was the East Asia and Pacific region, including Australia, that was responsible for generating close to a quarter (23%) of all global waste. The World Bank concluded that 'solid waste management is critical for sustainable, healthy, and inclusive cities and communities, yet it is often overlooked, particularly in low-income countries' noted that 'while more than one-third of waste in high-income countries is recovered through recycling and composting, only 4% of waste in low-income countries is recycled' (Kaza et al. 2018). Of this, some 1.6 billion tonnes of carbon-dioxide-equivalent were generated in 2016 from the treatment and disposal of waste in 2016 comprising 5% of global emissions. The World Bank concluded that quality waste management systems are essential 'to building a circular economy, where products are designed and optimized for reuse and recycling'(Kaza et al. 2018). With local, national and or international acceptance of a circular economy, smart and sustainable ways to manage waste will thereupon help promote efficient economic growth while minimizing environmental impact.

Waste volume, particularly originating from developed countries, exponentially mirrors population and gross domestic product growth in these countries. Their historical approach has been to capture the majority of these wastes, and to hide them, often with due diligence and care but often with little regard to the environmental venue of 'disposal' and 'treatment'.

Hidden in all this is green waste, the organic wastes of food, garden, timber, textiles and paper all derived from our normal household and industrial processes, packaging, and fabrication processes. But more deeply hidden within 'green wastes' are the results of our scouring of the landscape to enable urbanisation and thereupon our aesthetic predilection to plant trees in these landscapes as well as clip, mow, and maintain these new landscapes as well as the established urban landscapes that we retrofit green into.

Sustainable development goals for organic waste

Turning to the United Nations' Sustainable Development Goals (SDGs). The SDGs comprise 17 global-based goals intended to offer a "blueprint to achieve a better and more sustainable future for all", and were adopted by the United Nations General Assembly in 2015 (United Nations 2020). Associated with each Goal is a set of targets, varying between 8-12 in total with 1-4 indicators each target, to enable performance measurement of the target achievement, that is intended to be achieved by the year 2030 (United Nations 2016).

In terms of organic waste, its scope is primarily contained within SDG Goal 12 that seeks to "Ensure sustainable consumption and production patterns" although, to a lesser extent, Goal 11 that states "Make cities and human settlements inclusive, safe, resilient and sustainable" is also relevant (United Nations 2016). These relevant goals, their targets and their indicators are quoted in Table 1.

Overall, SDG 12 seeks (i) a change of global activities towards using eco-friendly production methods and reducing the amount of waste; (ii) that by 2030 national recycling rates should increase, as measured in tons of material recycled; and (iii) that companies should adopt sustainable practices and publish sustainability reports. More importantly, Target 12.1 seeks the development and execution of the 10-Year Framework of Programmes on Sustainable Consumption and Production to scaffold avenues towards sustainable consumption and production in developed and developing countries (United Nations 2016).

Against this backdrop, this paper seeks to explore the potential of green waste as an avenue for additional revenue generation. The paper concentrates upon the City of Greater Geelong Council (COGG), a city in Australia, as a case study. It showcases, how, that instead of 'shrewdly hiding' the costs of wastes in municipal budgets, this could be exploited to allow municipals with an added revenue stream while helping in reducing emissions, creating employment opportunities and opening new avenues for the economic growth of the city. In this regard, this study outlines the development of databases that could be used, the tools (especially software) that could help in quantifying the production of the green waste and thereafter, develop an economic model that could guide the revenue creation from waste generated in COGG.

Materials: contemporary context and literature

Australia, as an exemplar of green waste 'production', has taken little forthright care in its policies and practices to creatively recycle, reuse or reconstitute green waste less except in plastics and paper. Domestic, commercial and industrial food wastes more often end up in rubbish bins, with only a small percentage being recycled or recirculated into poverty initiatives. Garden wastes, that include soil, lawns, trees, plants, etc., both their hard forms as well as clippings and masse removal to service urbanisation expansion or to service major excavations associated with infrastructure projects, is little discussed unless the soil is contaminated. Green waste includes are organic waste streams that predominately originate from our supermarkets, kitchens, dairies, vegetable, abattoirs and fisheries wastes, to grain and legume surpluses, and include our ordinary common domestic garden waste without even mentioning all the green waste generated by local municipalities in their day-to-day municipal maintenance operations. Timber waste is similarly hidden in landfill which is in stark contrast to the major commercial exotic and native species plantations in Australia that service the

Table 1. Sustainable Development Goals, Targets and Indicators pertinent to organic waste

Goal	Goals and targets (from the 2030 Agenda)	Indicators
Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable	11.6 By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management	11.6.1 Proportion of urban solid waste regularly collected and with adequate final discharge out of total urban solid waste generated, by cities
Goal 12. Ensure sustainable consumption and production patterns	12.3 By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses	12.3.1 Global food loss index
	12.4 By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment	12.4.1 Number of parties to international multilateral environmental agreements on hazardous waste, and other chemicals that meet their commitments and obligations in transmitting information as required by each relevant agreement
		12.4.2 Hazardous waste generated per capita and proportion of hazardous waste treated, by type of treatment
	12.5 By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse	12.5.1 National recycling rate, tons of material recycled

woodchipping industry (often being felled in Australia, shipped to Japan, and re-shipped back to Australia), or in their harvesting for commercial housing framing and associated domestic products (Frontier et al. 2018).

Waste is visibly hidden from the public arena, by both local municipal and state governments, as well as by private storage or recycling operations. So it is quite remarkable that: few in the community know about the numerous tip trucks from Sydney that thread their way north daily often into Queensland for dumping purposes carving their weight into nationally-paid for highway pavements; or, that hidden inside many derelict large warehouses in metropolitan Sydney or Melbourne are highly combustible venues of chemical, toxic, rubber, paper, plastic, etc., waste just waiting to ignite and cause major toxic fires and leakages into creek systems in conjunction with fire suppressant chemicals (Vedalgo et al.); or, that Melbourne's major new underground rail (Metro Tunnel 2019), and freeway tunnel (Victoria 2020a) projects are desperately seeking venues to host vast metric tons (Mt) of clean, clean/contaminated mix, and or contaminated soil within one-hour driving distance of their excavation sites.

Carey (2017) has written that, in Victoria,

Decaying food that emits greenhouse gases as it rots; shredded old cars and white goods that can't be recycled; vast quantities of construction spoil; discarded televisions and computers that if mishandled could leach harmful chemicals into the environment. … Victorians produced 12.8 million tonnes of rubbish in 2015-16, … [and that rubbish is] projected to generate more than 20 million tonnes of waste each year by 2043 … [that] will cost between $3.6 billion and $5 billion in the next 30 years to manage the increase in waste and improve the state's recycling regime so that less rubbish goes to landfill. About two-thirds of the 12.8 million tonnes of waste was recycled, … with the remaining third going to landfill. On that projection, the giant waste pile will grow by about 240,000 tonnes a year'.

In Victoria, organic materials (food, garden, timber, textiles and paper) typically constitute approximately 50% of household garbage by weight, some 25-30% of industrial waste, and comprise over 25% of all waste 'dumped' in landfill venues. What is additional hidden from the public, is the real and high financial and environmental costs of managing these wastes, and that this cost is predominantly borne by local municipalities and budget-translated to public quietly inside their local government rates. What was once the core functions of Australian local governance was 'roads, rates and rubbish' has now increasingly become 'roads, rates and Rubbish' with a capital P for 'Planning' that is little accepting responsibility to redress or innovate the latter.

While there is private and public sector research into this problem, and attempts to innovate, translating such recycling-related ideals into practice is slow and lacks vision. This is more so unless the private sector, like paper packaging, can see a $ return from their investment in human resources and hard infrastructure to enable recycling profitably. A corporation like Visy, in Australia (Visy 2020) and the United States (Stensholt 2015; Stensholt 2017) evidence this pattern, but it one of a few venturing into the arena. More still, it is the green or organic waste arena that has had little innovations and creative strategies that include 'P's' involvement.

An exception to this observation is the Global Methane Initiative (GMI) (GMI 2020). The GMI is a voluntary, international collaborative that is seeking to change values by bringing together national governments, private sector entities, development banks, non-government organisations (NGOs) and other interested stakeholders in a partnership initiative towards reducing global methane gas emissions and advancing methane recovery and its use as a clean energy source. Established in 2004, GMI is now an international-level public-private initiative that seeks to enable and encourage cost-effective, near-term methane abatement and recovery, and reconstitution of methane as a clean energy source in three sectors: biogas (including in agriculture, municipal solid waste, and wastewater), in coal mines, and in oil and gas systems. Partners in GMI include many countries, like Australia, as well as the United Nations Economic Commission for Europe (UNECE) and the Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants (CCAC) to reduce global methane emissions. At the crux of GMI's activities is a desire that promotes methane emission sources as an alternate and cost-effective approach to reducing global greenhouse gas (GHG) emissions and to increase global energy security, enhance economic growth, to improve air quality and to improve worker safety.

From 2015 through 2030, Global Non- CO_2 Greenhouse Gas Emission Projections are projected to decrease by about 6% to approximately 912 $MtCO_2e$ in 2030. Internationally, the top 5 emitting countries projected for 2030 are China (625 $MMTCO_2e$), Russia (57 $MMTCO_2e$), United States (45 $MMTCO_2e$), India (27 $MMTCO_2e$) and Australia (24 $MMTCO_2e$) with the rest of the world coming in at 133 $MMTCO_2e$. $MMTCO_2e$ in million metric tonnes of carbon dioxide equivalent (EPA 2015).

For Australia, the current and 2020-2050 projected methane emissions, set out in Table 2, presented in million metric tonnes carbon dioxide equivalent ($MMTCO_2e$), is quite staggering.

A key to green waste conversion is Anaerobic digestion. Anaerobic digestion is a process that converts commercial and industrial green waste into on-site electricity, heat and clean methane gas. The digestion involves a sequence of processes by which microorganisms break down biodegradable material in the absence of oxygen. This process is already used in our industrial or domestic activities as a strategy to manage waste or to produce fuels, of which the former involves the conventional fermentation strategy that used industrially to produce food and drink products, as well as home fermentation Matsakas et al. 2014). Additionally, anaerobic digestion occurs naturally in some soils and in lake and oceanic basin sediments, when earth scientists talk about "anaerobic activity".

Table 2. Australia's 2020 current and 2020-2050 projected methane emissions

Sector	2020	2035	2050
Oil & Gas	12.964	15.497	21.105
Coal Mines	23.960	23.960	22.463
Biogas	13.807	15.261	16.778
Totals	50.731	50.731	54.718

Source: EPA 2020; GMI 2020

Scientifically, the digestion process begins with bacterial hydrolysis of the input materials. Through hydrolysis, insoluble organic polymers, such as carbohydrates, are broken down into soluble derivatives that become available for other host bacteria. For example, Acidogenic bacteria will convert sugars and amino acids into carbon dioxide, hydrogen, ammonia, and organic acids. Thus, the hydrolysis process causes a chemical reaction whereby particulates are solubilized and large polymers converted into simpler monomers (Duan et al. 2018). In Acetogenesis, bacteria convert these resulting organic acids into acetic acid, along with additional ammonia, hydrogen, and carbon dioxide (Schuchmann and Müller 2016). Thus, Acetogenesis is a process by which acetate is produced either by the reduction of organic acids or by the reduction of CO_2. In the final digestion step, methanogens convert these products into methane and carbon dioxide. The methanogenic archaea populations, microorganisms that produce methane as a metabolic by-product in hypoxic conditions, perform a key role in anaerobic wastewater treatments. The latter is the normal way we treat and process biodegradable waste and sewage sludge on our sewerage 'farms' like the Melbourne Treatment Farm south-west of metropolitan Melbourne (Melbourne Water 2020). As part of its integrated waste management system, anaerobic digestion processes on this Farm naturally emit landfill gas emissions into the atmosphere.

Internationally, anaerobic digestion underpins our human desire to re-use waste as a resource aided by new technological approaches that have lowered capital costs. Thus, countries like United Kingdom, Germany, Denmark, and the United States, have shown increased commercial and non-commercial policy interest this realm but in terms of the 'green' act of recycling but more important in its potential as a renewable energy source. Because the anaerobic digestion process produces biogas, that consists of methane, carbon dioxide, and traces of other 'contaminant' gases, this biogas can be used directly as fuel in combined heat and power gas engines or reconstituted into natural gas-quality biomethane (Prussi et al. 2019). A lesser use, to date, is the use of the nutrient-rich digestate as a fertilizer for soil renewal and the cultivation of grain cereals and herbaceous species.

A further aspect to recognise is that there are waste hierarchy priorities:

1. Avoidance including action to reduce the amount of waste generated by households, industry, and all levels of government
2. Resource recovery including re-use, recycling, reprocessing, and energy recovery, consistent with the most efficient use of the recovered resources
3. Disposal including management of all disposal options in the most environmentally responsible manner.

STUDY AREA

To the south-west of metropolitan Melbourne, in Victoria, is the regional centre and region of Geelong and the Bellarine Peninsula presently hosting a growing community of over 500,000 permanent and transitory residents. Historically, Geelong was the heavy industrial corner-stone of Melbourne hosting numerous rust belt industries including Vterra, Ford, Alcoa, but global transformations have ceased much of these operations, and Geelong is increasingly engaging in health insurance, animal biosecurity, education, new carbon fibre technologies and digital innovation industries (Jones and Roös 2019). For this region, the Barwon South West Waste and Resource Recycling Group (BSWWRRG) (Barwon Waste Recovery) is responsible for facilitating an integrated approach to waste-related regional planning, and for the delivery of waste management and resource recovery services that align with state-wide waste and resource recovery planning for all municipalities located in the south-west region of Victoria that stretches from Geelong to Warrnambool to the South Australian state border (BSWWRRG 2017; BSWWRRG 2020).

The Barwon Waste Recovery works with nine municipal councils: (Figure 1): Borough of Queenscliffe, City of Greater Geelong, Colac Otway Shire Council, Corangamite Shire Council, Glenelg Shire Council, Moyne Shire Council, Southern Grampians Shire Council, Surf Coast Shire Council, and the Warrnambool City Council.

Fig. 1. Barwon South West Waste and Resource Recycling Group Area

Source: BSWWRRG 2017

The Barwon Waste Recovery was established in 2014 under the Environment Protection Act 1970 (Vic) (Victoria 1970), which sets out the objectives, functions and powers of a waste recovery group (BSWWRRG 2018). The statutory objectives of a Waste and Resource Recovery Group, under Clause 49G of the Act (Victoria 1970), are:

1. to undertake waste and resource recovery infrastructure planning to meet the future needs of its waste and resource recovery region while minimising the environmental and public health impacts of waste and resource recovery infrastructure;
2. to facilitate efficient procurement of waste and resource recovery infrastructure and services for its waste and resource recovery region through the collective procurement of waste management facilities and waste and resource recovery services in the region;
3. to integrate regional and local knowledge into statewide waste and resource recovery market development strategies;
4. to educate businesses and communities within its waste and resource recovery region to reduce waste going to landfill by using waste and resource recovery infrastructure and services efficiently; and
5. to ensure Regional Waste and Resource Recovery Implementation Plans and programs are informed by local government, business and community and inform statewide waste and resource recovery planning and programs.
6. In seeking to achieve its objectives, a Waste and Resource Recovery Group must collaborate with councils, Sustainability Victoria, the Authority, industry, business and the community.

The statutory functions of a Waste and Resource Recovery Group, defined under Clause 49H of the Act (Victoria 1970), are:

1. to plan for the future needs of waste and resource recovery infrastructure within its waste and resource recovery region consistently with the statewide Waste and Resource Recovery Infrastructure Plan;
2. to facilitate the provision of waste and resource recovery infrastructure and services by councils within its waste and resource recovery region;
3. to facilitate the development of contracts for the joint procurement of waste management facilities and waste and resource recovery services within its waste and resource recovery region;
4. to manage contracts in the performance of its objectives and functions;
5. to work with Sustainability Victoria, councils, businesses and communities to ensure statewide waste and resource recovery education programs are adapted to the needs of its waste and resource recovery region and to facilitate the delivery of those education programs;
6. to advise, with Sustainability Victoria, councils and businesses within its waste and resource recovery region on best practices for waste and resource recovery systems, facilities and services;
7. to support its waste and resource recovery region's Local Government Waste Forum to enable the Waste Forum to perform its functions; and
8. to undertake waste and resource recovery projects as funded by government, councils and other organisations.

Barwon Waste Recovery is one of seven statutory authorities in Victoria set up under the Environment Protection Act 1970 (Vic) to facilitate a coordinated approach to the planning and delivery of infrastructure and services for waste reduction and recycling (Victoria 1970). As a vision, Barwon Waste Recovery seeks to 'find innovative ways to reduce and recycle waste and plan for the future waste and recycling needs of the Barwon South West'. It does this by working closely with nine local municipalities as well as local businesses and the community to achieve its vision of being a leader in waste minimisation and resource recovery. It actions this vision by gathering knowledge and data about what is happening with recycling and waste; ensuring that there are enough facilities and processors to handle recycling and waste in Barwon South West; providing advice on recycling and waste issues; working with the community to reduce, reuse and recycle waste; working with local municipalities to improve recycling and waste services for their communities; supporting local municipalities to work together on recycling and waste initiatives; investigating new and interesting ways to turn waste from a problem material into a resource; connecting the makers of waste with processors to help them find new ways to reduce and recycle; and, assisting groups to obtain funding for waste reduction and recycling activities (Barwon Water 2020).

To enable this vision, the Barwon Waste Recovery has a Barwon South West Waste and Resource Recovery Implementation Plan 2017-2026 (BSWWRRG 2017). Consideration of the Victorian Guide to biological recovery of organics (Victoria 2018) and the Victorian Recycled Organics Market Analysis (Victoria 2013) are also applicable in this discussion.

In this paper we focus specifically on the City of Greater Geelong which is the largest local government area in the BSWWRRG. The municipality has jurisdiction for a land area of 1,248 km^2 and, in June 2018, had a population of 252,217. Between 2016 and 2041, the population for the City of Greater Geelong is forecast to increase by 153,685 persons (64.16% growth), at an average annual change of 2.00%.

Using available data, Table 3 provides based upon estimates of generation, recovery and landfilling of organics, based on the Barwon South West Waste and Resource Recovery Implementation Plan (BSWWRRG, 2017) and data sourced by Blue Environment (2020).

Table 3. Organics management in the Barwon Waste Recovery Region

Organics category	Generated	Landfilled	Recovered
Food	40,000-45,000	35,000-40,000	>5,000
Garden and garden and food	55,000-65,000	10,000-15,000	45,000-55,000
Wood/timber	30,000-40,000	15,000-20,000	10,000-20,000
Biosolids (to agriculture)	95,000 dried tonnes	nil	95,000 dried tonnes
Other biodegradable organics	20,000-25,000	500	20,000-25,000
Organics imported from outside the region	-	-	10,000-20,000 (mainly timber)
Organics exported out of the region	15,000-30,000	10,000-20,000	5,000-10,000

Source: Blue Environments 2020, 3.

Table 3 demonstrates that there are:
a) low levels (<13% by weight) of food waste recovery with a high proportion of food remaining in municipal and commercial putrescible waste;
b) that there are high levels of garden organics recovery, mainly due to the provision of kerbside garden organics (GO) and food organics and garden organics (FOGO) services across most of the region, and that this is expected to increase as partner municipalities implement FOGO services or promote on-site management of food organics; and,
c) that there are moderate levels of recovery of timber waste through formal waste management pathways recognising that unknown but significant amounts of timber are managed through informal pathways.

METHODS

To better understand the future residential, commercial and industrial growth patterns in the City of Greater Geelong area (COGG) and their corresponding impacts on the Geelong regional environment, a residential, commercial and industrial Build-Out was undertaken. A Build-Out projects the number, location and appearance of buildings based upon extant land use or urban planning zoning information. The build-out analysis was performed using CommunityViz (CommunityViz 2020), a geographic information systems (GIS) planning and simulation software package (Herron et al. 2015). The software allows the users to set density assumptions in dwelling units per ha, as well as minimum lot size or floor area ratio. In addition, while there are default values, users can also assign design assumptions, including layout efficiency, building offsets, development constraints, layout patterns and building types into the excel-based variables.

The results of the CommunityViz-derived build-outs include indicator charts that summarize the building counts or impacts, point shapefiles depicting building locations with attributes, and real-time visualizations of the buildings in 3D realistic models in context with the community (Herron et al. 2015). It also allows planners to factor in future scenarios since the build-out analysis provides an overview on the maximum number of buildings that a given area could comfortably accommodate, based on the existing zoning and land use regulations. In the case here, the adoption of the CommunityViz built-out analysis will also allow the determination of the remaining capacity in the City of Greater Geelong and this will help in estimating the expected future waste generation. Hence, the tools and economic model that could be adopted for turning green waste into a revenue-generating venture will manage to capture such future expected changes. This would be possible as the built-out analysis helps in the determination of other issues such as building offsets, layout efficiency, layout patterns and development constraints among other things.

To develop economic, demographic and planning scenarios the Community Viz software performs four functions. These functions are:
1) estimation, statistical counting and location modelling of new developments allowed in an area according to current or proposed zoning regulations;
2) a suitability evaluation of the new development to a prescribed area(s);
3) the allocation and direction of where urban/building growth is most likely to occur over a specific determined or flexible period; and finally,
4) the development of a series of environmental indicators that can graphically and numerically depict the impact of the new development upon the landscape (Walker 2011).

This process is graphically summarised in Figure 2. The build-out analysis (Figure 3) summarises the residential, industrial, and commercial potential from 2016 through 2050 for COGG.

The buildout indicators developed show the future impacts including:
- Annual carbon (CO) Auto Emissions
- Annual carbon dioxide (CO2) Auto Emissions
- Annual Hydrocarbon Auto Emissions
- Annual nitrogen oxides (NOx) Auto Emissions
- Solid Waste Generation
- Residential Energy Usage
- Residential Water Usage
- Residential Dwelling Units
- School Children

To better translate the detail of the COGG municipal waste profile three new waste indicators were developed. The indicators were split into 1) municipal solid waste, 2) organic waste, and 3) recyclable waste.

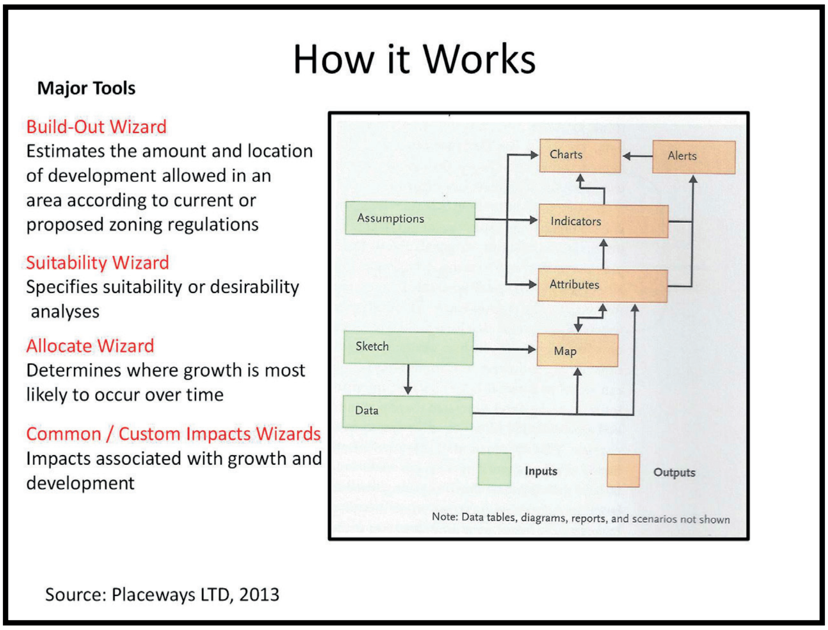

Fig. 2. CommunityViz: How it Works. Source: Walker 2011

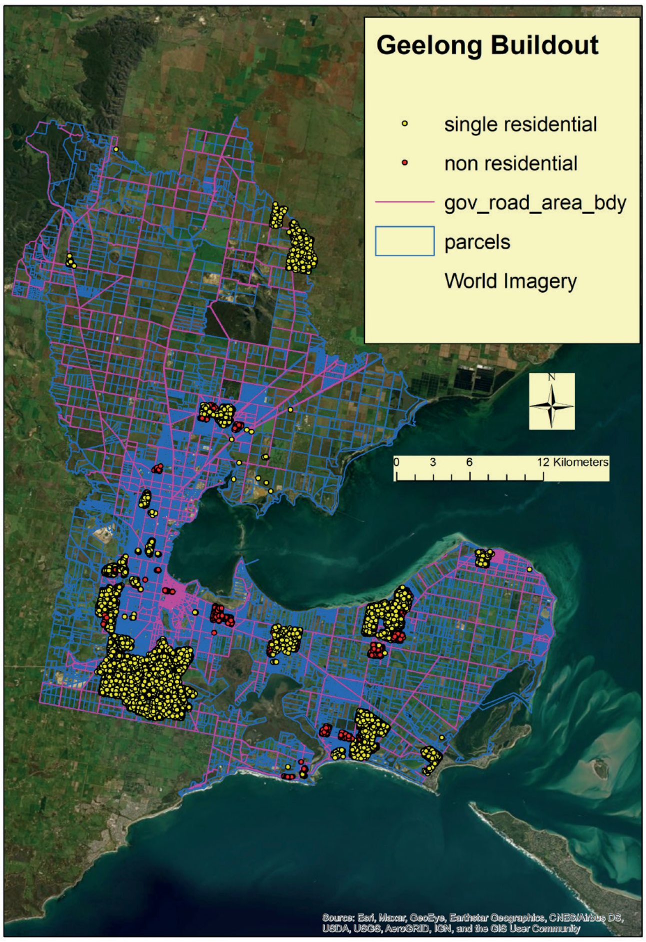

Fig. 3. Geelong Build-out Results.

The composition of municipal solid waste varies greatly from Australian municipality to municipality, and it changes significantly with time. In municipalities that have a well-developed waste recycling system, the municipal solid waste stream mainly consists of intractable wastes including plastic film and non-recyclable packaging materials. Organic waste consists of biodegradable waste: food and kitchen waste, green waste, paper (most can be recycled, although some difficult to compost plant material). Recyclable waste consists of recyclable materials: paper, cardboard, glass, bottles, jars, tin cans, aluminium cans, aluminium foil, metals, certain plastics, textiles, clothing, tires, batteries, etc.

In addition, the three waste indicators – 1) municipal solid waste, 2) organic waste, and 3) recyclable waste – were further segmented into daily, weekly, monthly and yearly results. This data, derived from this modelling and calculations based upon 2019 COGG waste data inventories, was individually reviewed and considered.

Initial benchmark data used for this GIS modelling was sourced from the Victorian government spatial data mart data website (Victoria 2020).

The detail statistics of the COGG waste profile and rubbish bin audit were developed by EC Sustainable of Sydney. EC Sustainable is a leading sustainability, waste and resource recovery consultancy operating across Australia that, in particular, have expertise in waste, sustainability and resource recovery strategies, waste plan development, and waste audits and recycling audits The rubbish bin audit included a visual bin survey/assessment and a physical audit of the municipal waste stream. Included in their audit are other forms of waste that can be similarly mapped and analysed. They include:

- Commercial waste consisting of waste from premises used mainly for the purposes of a trade or business or for sport, recreation, education or entertainment, but excluding household, agricultural or industrial waste.
- Industrial waste produced by industrial activity that includes any material that is rendered useless during a manufacturing process such as that of factories, industries, mills, and mining operations. Types of industrial waste include dirt and gravel, masonry concrete, scrap metal, oil, solvents, chemicals, scrap lumber, even vegetable matter from restaurants. Industrial waste may be solid, liquid or gaseous.
- Construction waste (including construction and demolition materials) that consists of unwanted material produced directly or incidentally by the construction or industries. Examples include building materials such as insulation, nails, electrical wiring, shingle, and roofing as well as waste originating from site preparation such as dredging materials, tree stumps, and rubble (EC Sustainability 2018).

RESULTS

The residential bin audit, depicted in Table 4, shows the nature and character of the waste stream, recycling stream, organic stream results for Geelong.

The residential waste profile for Geelong was segmented by volume per week and household. The segmentation took the form of eight classes of waste (i.e., i) paper, ii) organic, iii) glass, iv) plastic, v) metal, vi) hazardous, vii) building waste and viii) other). Tables 5 and 6 below depict the Geelong residual waste stream composition by volume.

Table 4. Waste Generation across Geelong. Source: Victoria (2018)

	Waste Stream - % by weight	Recycling Stream - % by weight	Organics Stream - % by weight
Paper	8.7	51.3	0.5
Glass	3.1	16.4	0.0
Plastics	13.6	9.9	0.1
Steel	1.4	2.5	0.0
Other non-ferrous	1.0	1.4	0.0
Food	34.0	0.7	0.2
Garden Organics	8.5	0.0	97.7
Other Organics	5.6	0.0	0.0
Hazardous	3.4	0.2	0.0
Other	20.6	15.3	1.5

Table 5. Residual waste (good, garden organics, hazardous and other) stream composition for COGG. Source: Abridged from EC Sustainability 2018, Tables 53, 84-85

Sorting Category		Weight (Kg/hh/wk)			Percentage (% by weight)		
		Waste	Recycling	Organics	Waste	Recycling	Organics
Food	Fruit and vegetables	2.149	0.012	0.011	22.84	0.22	0.13
	Meat and seafood	0.191	0.000	0.001	2.03	0.00	0.01
	Staples	0.434	0.021	0.002	4.61	0.39	0.02
	Tea and coffee grinds	0.041	0.000	0.000	0.43	0.00	0.00
	Eggshells	0.115	0.000	0.000	0.43	0.00	0.00
	Dairy	0.082	0.001	0.000	0.87	0.02	0.00
	Cooking oil	0.007	0.000	0.000	0.07	0.00	0.00
	Confectionery	0.017	0.000	0.001	0.18	0.00	0.01
	Meat meal leftovers	0.164	0.004	0.000	1.74	0.07	0.00
	Sub-total	3.199	0.038	0.014	34.00	0.70	0.17
Garden org.	Garden / vegetation	0.801	0.011	8.058	8.52	0.21	97.68
	Sub-total	0.801	0.011	8.058	8.52	0.21	97.68
Other org.	Compostable bag liners	0.000	0.000	0.000	0.00	0.00	0.00
	Other putrescible	0.525	0.000	0.000	5.58	0.00	0.00
	Sub-total	0.525	0.000	0.000	5.58	0.00	0.00
Hazardous	E-waste – ban applicable	0.176	0.001	0.002	1.87	0.02	0.02
	E-waste – other	0.037	0.007	0.000	0.40	0.13	0.00
	Asbestos	0.000	0.000	0.000	0.00	0.00	0.00
	Other hazardous material	0.110	0.003	0.000	1.16	0.06	0.00
	Sub-total	0.323	0.012	0.002	3.43	0.22	0.02
Other	Containerised food and liquid	0.174	0.008	0.000	1.85	0.14	0.00
	Wood / timber – treated	0.188	0.010	0.001	2.00	0.19	0.01
	Wood / timber – untreated	0.015	0.015	0.083	0.16	0.28	1.01
	Clothing / textiles	0.323	0.068	0.034	3.43	1.26	0.41
	C & D waste	0.464	0.005	0.000	4.93	0.008	0.00
	Nappies	0.569	0.051	0.001	6.05	0.94	0.01
	Other waste	0.203	0.028	0.001	2.16	0.52	0.01
	Bagged material	--	0.638	0.008	--	11.88	0.09
	Sub-total	1.938	0.822	0.127	20.60	15.30	1.54
Total		9.408	5.371	8.249	100.0	100.0	100.0

Table 6. Residual waste (paper, glass, plastic, and metal) stream composition for COGG.
Source: Abridged from EC Sustainability 2018, Tables 53, 84-85

Sorting Category		Weight (Kg/hh/wk)			Percentage (% by weight)		
		Waste	Recycling	Organics	Waste	Recycling	Organics
Paper	Newspaper	0.047	0.467	0.023	0.50	8.69	0.28
	Magazines / brochures	0.054	1.091	0.011	0.57	20.30	0.13
	Print / office	0.088	0.178	0.000	0.94	3.31	0.00
	Miscellaneous packaging	0.008	0.025	0.000	0.09	0.47	0.00
	Disposable paper product	0.132	0.048	0.001	1.40	0.85	0.01
	Shredded paper	0.006	0.006	0.000	0.06	0.12	0.00
	Other compostable paper	0.288	0.021	0.000	3.06	0.39	0.00
	Cardboard – pizza boxes	0.005	0.026	0.000	0.05	0.49	0.00
	Cardboard – other	0.175	0.732	0.003	1.86	13.64	0.04
	LPB containers - Tetrapak	0.004	0.021	0.000	0.04	0.38	0.00
	LPB containers – other	0.008	0.143	0.000	0.09	2.67	0.00
	Sub-total	0.814	2.756	0.038	8.65	51.51	0.46
Glass	Glass containers	0.257	0.653	0.001	2.73	12.16	0.01
	Glass fines (<12 mm)	0.035	0.334	0.000	0.37	6.23	0.00
	Sub-total	0.292	0.988	0.001	3.10	18.39	0.01
Plastics	Plastic containers (1-7)	0.340	0.431	0.002	3.62	8.02	0.02
	Other recyclable rigid plastics	0.021	0.027	0.000	0.22	0.51	0.00
	Plastic plates, cutlery	0.011	0.001	0.000	0.11	0.02	0.00
	Plastic toys, CD / DVD cases	0.016	0.016	0.000	0.17	0.31	0.00
	Plastic plant pots	0.008	0.003	0.000	0.09	0.06	0.00
	Plastic films	0.715	0.036	0.003	7.60	0.67	0.03
	Other rigid plastics – EPS	0.030	0.004	0.000	0.32	0.07	0.00
	Other ridge plastics – other	0.143	0.013	0.003	1.52	0.25	0.04
	Sub-total	1.284	0.55	0.008	13.65	9.82	0.09
Metal	Steel containers	0.083	0.100	0.000	0.88	0.86	0.00
	Steel pots and pans	0.009	0.005	0.000	0.10	0.09	0.00
	Aluminium containers	0.033	0.059	0.000	0.39	0.03	0.00
	Aluminium foil	0.037	0.002	0.000	0.39	0.03	0.00
	Other metal – steel	0.044	0.031	0.002	0.47	0.58	0.02
	Other metal – non-ferrous	0.027	0.016	0.000	0.28	0.30	0.00
	Sub-total	0.232	0.213	0.002	2.47	3.97	0.02

The waste profile results were further broken into a) recovered, and b) unrecovered resources, as shown below in Table 7 and Table 8.

COGG is currently hosting a total recovery rate of 74.62% on all wastes, as documented in Table 8.

One reason why COGG does not have a higher waste recovery rate is because of its contamination rate. The contamination rate is calculated using the following formula:

$$\text{The percentage of the recycling bin (or organics bins) contents not accepted,} \frac{\text{Weight of material not accepted in the recycling bins or (organics bins)} \times 100}{\text{Total weight of recycling bins (or organic bins) contents}}$$

The current COGG contamination rate is 18.80% of the total waste volume, as explained in Table 9.

A sample of the GIS output arising from this modelling is depicted below in Figure 4, that depicts the monthly totals per mesh block for existing buildings. Figure 5 shows the monthly municipal solid waste totals per mesh block. The totals range from 0 to 28,111 kgs of municipal solid waste per month for each mesh block.

Mesh Blocks (ABS 2020a) are the smallest geographical / statistical area defined and used by the Australian Bureau of Statistics (ABS). Mesh blocks form the building blocks for the larger regions of the Australian Statistical Geography Standard (ASGS) (ABS 2020b). All other statistical areas or regions are built up from, or approximate by whole Mesh Blocks. Mesh Blocks broadly identify land use, such as residential, commercial, primary production and parks, etc. (ABS 2020a).

The recycling activities for COGG are shown in Figure 6. As indicated up to 5,349 kilograms of waste in a Mesh block is being recycled.

Table 7. COGG: Unrecovered resources in the waste bin. Source: Abridged from EC Sustainability 2018, Tables 54, 86

Material Category	Percentage (% by weight)
Recyclable paper	5.53
Recyclable glass	2.73
Recyclable plastics	4.21
Recyclable steel packaging	0.98
Recyclable aluminium packaging	0.74
MGB recyclable	14.19
Other steel	0.47
Other non-ferrous	0.28
Potentially recyclable	0.75
Food	34.00
Garden organics	8.52
Other organic	5.74
Compostable	48.26
Non-recyclable paper	3.12
Non-recyclable glass	0.37
Non-recyclable plastics	9.44
Total other	23.87
MGB non-recyclable	36.80
Total	100.00

Table 8. Geelong Recycling resource recovery rates. Source: Abridged from EC Sustainability 2018

Material category	Resource recovery rate (% by weight)
Recyclable paper and cardboard	83.09
Recyclable glass	71.79
Recyclable plastic containers (1-7)	44.03
All recyclable plastic materials types	54.75
Recyclable steel	53.38
Recyclable aluminium	46.60
Total	74.63

Table 9. Geelong: Recycling stream contamination rate. Source: Abridged from EC Sustainability 2018, Table 55, 87

Material category		Percentage (% by weight)
Compliant	MGB recyclable	74.98
Containing – excluding glass fines	Potentially recyclable	0.88
	Compostable	1.18
	MGB non-recyclable	16.74
	Total contamination	18.80
Potential contamination	Glass fines	6.23

ORGANIC WASTE

The diversion and recovery of organic waste is one of the most significant opportunities and challenges for reducing the environmental impacts of waste disposal, generally and in COGG. Organic materials (food, garden, timber, textiles and paper) typically contribute around at least 50% of household garbage by weight, 25-30% of industrial waste, and make up over 25% of all waste landfill in Victoria. The financial and environmental costs of managing these wastes are high (Blue Environments 2020).

Landfill organics contribute to emissions of potent greenhouse gas methane, as well as producing toxic leachate that contaminates groundwater and releases odoriferous toxic gases at the landfill surface. To lessen these impacts and risks, landfills require expensive engineering and management controls and decades of monitoring and management after the landfill closes. The wastes in a landfill will continue to pose environmental risks for future generations, for many decades, and even for centuries. For most local municipalities, the greenhouse gas emissions from the waste they collect, and landfills, are by far the most significant source of emissions from all their municipal operations, including street lighting (Blue Environments 2020).

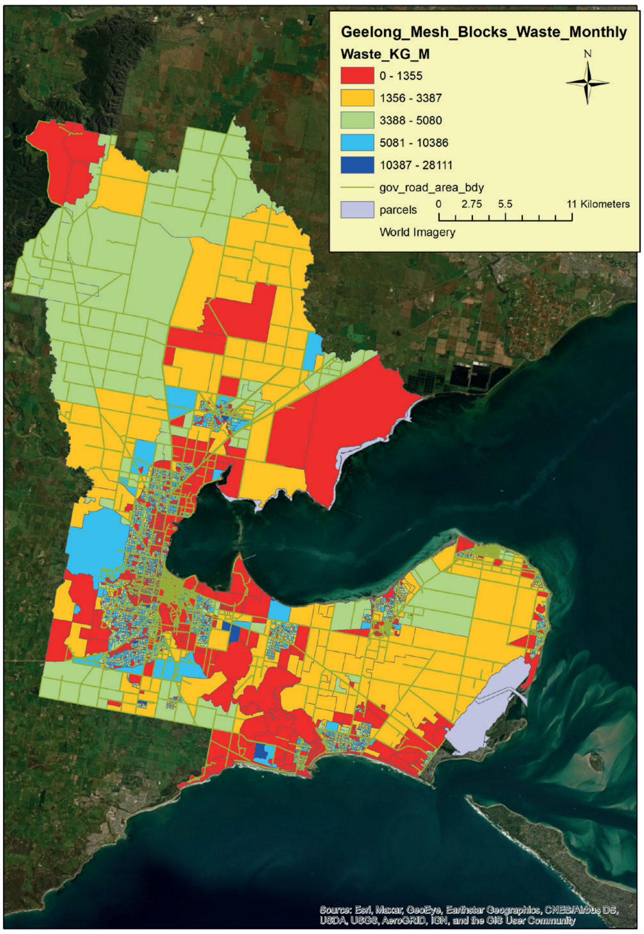

Fig. 4. COGG Monthly Residential Waste by Mesh block

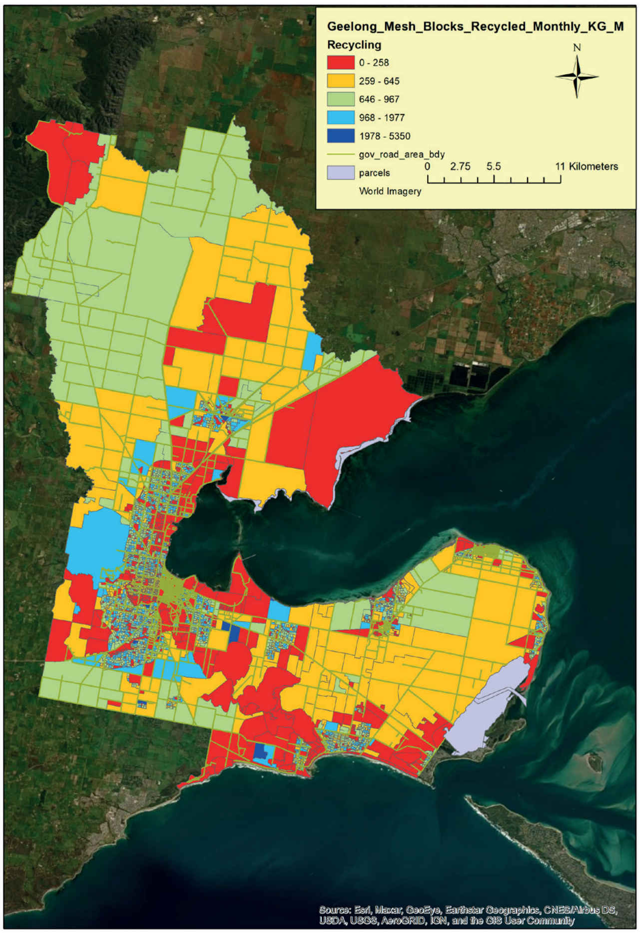

Fig. 5. COGG Monthly Recycling totals by Mesh blocks

Landfilled food and wet garden organics have the potential to release methane with a global warming potential equivalent to just under 2 tonnes CO_2 per tonne of organics. Although landfill gas management practices have improved compared to what they historically were in the past, even landfills with high levels of post cell closure gas management still do not capture all gas. Food organics and 'wet' green waste degrade rapidly and around 40-50% of the methane they generate in landfill can and are emitted in the first 2 to 3 years after such waste is buried or capped/covered. This means that generally, most emissions from a landfill site can be released to the atmosphere before effective gas recovery systems are in place. Thus, even a high performing landfill capturing 80% of gas generated after cell closure, can see around 700-900 kg of CO_2-equivaent methane released to the atmosphere per tonne of landfill food and wet garden organics. Composting facilities generate some greenhouses gases – on average, about 50-60 kg CO_2-e/tonne of organics processed. Transporting organics generates some greenhouse gas emissions – but at the low rate of around 65 grams/tonne/km (Blue Environments 2020).

Barwon Waste Recovery in 2020 undertook a market assessment as to the viability for recycled organic products within the region (Blue Environments 2020).

The assessment identified two options for organic waste:

1. Organic Renewable Option 1: using composting techniques on organic waste to produce a series of fertilizer products for commercial, agricultural and residential uses.
2. Organic Renewable Option 2: to develop an anaerobic digester that will convert organic wastes into biogas or methane that can be used as a renewable fuel source.

Organic Renewable Option 1

As stated in the Barwon Waste Recovery commissioned Organics End Markets Study (Blue Environments 2020), if COGG and the neighbouring (to the immediate south) Surf Coast Council introduced a food organic/garden organics (FOGO) service it was projected that organics recovery in those two municipalities would increase from the current 41,000 tonnes per year to over 80,000 tonnes by 2030. Across the larger Geelong / and Bellarine Peninsula region, the quantities of recovered municipal organics could be expected to increase from under 50,500 tonnes per year to over 90,000 tonnes per year by 2030 (Blue Environments 2020).

If all of these wastes were converted into compost, fertiliser, and mulch products, rather than energy, they could expect to yield in the order of:

- 70,000-75,000 tonnes of soil conditioner compost or organic fertiliser products (including some dried and composted biosolids from other areas);
- 45,000-50,000 tonnes of mulch (mainly timber mulches);
- around 5,000 tonnes of woody 'oversize' screening from composting facilities that currently has no market but may be suited to bioenergy and/or biochar production; and
- 115,000-120,000 tonnes of dried biosolids used as fertiliser or potentially bioenergy. Source: Blue Environments 2020).

At present, and in the foreseeable future, composting is the most likely option for the recovery of garden organics (GO), FOGO and commercial and industrial putrescible organics (Blue Environments 2020). This is likely to be supplemented by thermal energy recovery from timber and woody waste, and Anaerobic digestion of wet wastes. However, it is envisaged that the main market development needs will be for compost and related products.

Organic Renewable Option 2

This method proposes to develop anaerobic digestion that will convert organic wastes into biogas or methane that can be used as a renewable fuel source.

The Organics End Markets Study (Blue Environment 2020) outlined an argument for energy recovery from industrial organics via anaerobic digestion. Barwon Water's Colac facility creates an opportunity for some other industrial organics to be delivered to the facility. This is now occurring using food and other organics from meat processors from the Colac region. The facility, Renewable Organics Network, is being built in nearby Colac to use high-strength organic waste from the Australian Lamb Company (ALC) and the Bulla Dairy Foods factories for the production of electricity and hot water. The project is expected to create 17 construction jobs and 45 ongoing jobs.

Other benefits of the Renewable Organics Network Colac project include: the net production of 5.5 gigawatt hours of renewable electricity each year; approximately 50% of this renewable electricity will be used "behind-the-meter" to take the Colac Water Reclamation Plant off-grid electricity; the remaining renewable electricity generated will be exported into the grid; renewable hot water will also be generated by the project and supplied to ALC via an innovative hot water pipeline, which offsets ALC's natural gas consumption from the grid by 21.4 terajoules each year – equivalent to the gas usage of 350 households; and, overall, the generation of dispatchable renewable energy in the form of hot water and electricity results in carbon emissions being reduced by 6,300 tonnes each year (Barwon Water 2020). The report states that other food, dairy and meat processors in other parts of the region (Warrnambool, Geelong, and potentially Hamilton; all communities inside the Barwon Waste Recovery region) may also be able to develop comparable facilities.

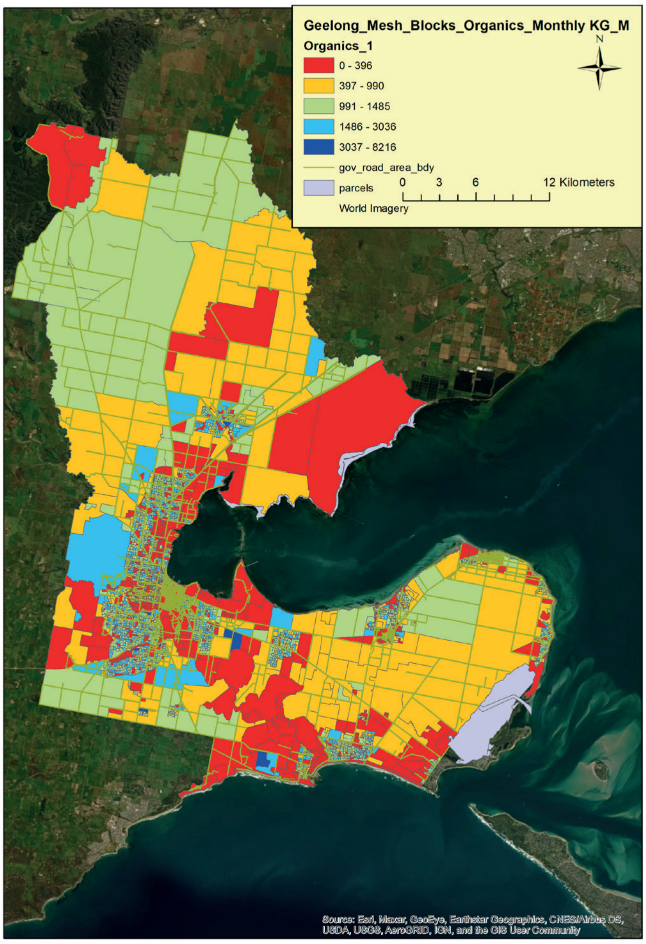

Fig. 6. COGG Monthly Organic Waste by Mesh Block

In terms of COGG, seven different biogas economic and financial models were selected to determine the economic viability of a biogas plant for Geelong. The analysis was based upon the Barwon Waste Recovery bin audit report of 2018 (University of South Wales 2020). The seven models ranged from very simple to use to highly detailed spreadsheets that were comprised several thousand lines of coded formulas and data entry points.

For this article two exemplar models were selected for further examination:

1. the Biogas Calculator from Ireland/Wales
2. the Anaerobic Project Screening model from the US EPA.

The Biogas Calculator document provides a guide to Irish Farmers to assess the feasibility of developing anaerobic digestion facilities on their farms, where manures (cattle, pig, poultry), organic municipal waste, food industry waste, animal by-products, catering waste and sewage sludge and specifically grown crops, such as maize, can be processed anaerobically (University of South Wales 2020).

The Biogas Calculator looks at seven potential biogas sources (households, agricultural industry waste, sludge, energy crops, catering waste, waste generated by industry and harvested biomass. For this paper we only used the household waste category (University of South Wales 2020). The Biogas Calculator required two inputs to calculate the potential biogas output for COGG, the population of COGG and the amount of organic waste per person per year.

The potential biogas production, when converted to kilowatt-hours, represents 24,419,241 potential kilowatt-hours. This number of kilowatts has a potential revenue value of AU$5.9 million per annum. The $ value was calculated by multiplying the kilowatt total by the average official electricity price per kWh by the Victorian state government reported by the CANSTAR energy reporting agency (GOGG 2020).

The Anaerobic Project Screening model tool uses a Mass-Balance Methodology to estimate biogas and digestate production. This is a commonly applied methodology that examines the products from the anaerobic digestion of solid wastes. Solid wastes entering the digester consist of organic material, inorganic constituents and water. During the digestion process a fraction of the volatile solids is converted into biogas consisting of primarily methane and carbon dioxide. Other compounds present in the biogas, such as hydrogen sulfide, are important but often considered negligible for this framework when calculating the production of biogas.

The program has eight major different categories of feedstock: fruit and vegetable, livestock excreted, other organic municipal, kitchen and food scrap, energy and cash crops garden, dairy and seafood). The major categories are further segmented into 80 subcategories. For the Geelong calculation nine subcategories were used (diverted municipal waste, grass, wood, textiles, newspaper, cardboard, magazines, folding cartons and paper bags).

The Anaerobic Project model program calculated the annual biogas production at 4,542,973 m^3 / year or the refined methane production to be 2,266,943 m^3 / year. The potential biogas production, when converted to kilowatt-hours, represented 47,928,365 potential kilowatt-hours. This number of kilowatts has a potential revenue value of AU$11.6 million per annum. The $ value was calculated by multiplying the kilowatt total by the average official

electricity price per kWh by the Victorian state government reported by the CANSTAR energy reporting agency [34].
In addition to this new revenue stream, COGG would reduce its carbon footprint by 3,798 metric tons.

DISCUSSION

The result of the two selected models showcases that COGG has a greater opportunity to derive sizeable benefits from using organic waste from households. With the option of creating Anaerobic digesters, as is demonstrated after simulating the two adopted calculation model (the Biogas Calculator model borrowed from Ireland / Wales, and the Anaerobic Project Screening model from the US EPA, it is now clear that the COGG can maximize its energy production. For instance, with the Biogas Calculator model, the simulation shows that there is a potential to produce over 2.3 million cubic metres of biogas which, when converted electric energy would equate to over 24.4 million kWh yielding local government with over AU$5.9 million yearly.

An almost similar output is viable with the Anaerobic Project Screening Model that is shown to promise over 21,788 mWh and a renewable natural gas capacity of 2,266,943 m^3 yearly. Calculations using this model also shows that organic waste generated in COGG could yield over 4.5 million m^3 yearly of biogas which when refined could translate to over 2.3 million m^3 of refined methane gas. Such would go a long way in reducing emissions as they could serve a sizeable number of households in the city.

Such figures obtained from these two models as very significant noting that the COGG has already pooled together with like-minded Victorian councils that are looking forward to transitioning to 100% use of renewable energy (COGG 2019). With such renewable energy programs, the councils are projecting to benefit from financial savings as well as guarantee long-term energy certainty, which is not obvious with relying on non-renewable sources.

Besides the revenue generation, the two models have been shown to rely on feedstock from obvious wastes that are generated in great capacity in COGG, and which have also not been given much attention when it comes to recycling and recovery. In particular, the organic materials from different sources have been reported to constitute more than 50% of the total waste that find their ways in landfills in the Victorian region, and these, as noted with the Biogas Calculator have potential to produce substantial biogas; thus, helping not only in reducing the emissions from those landfills but also help in contributing to environmental sustainability as well as economic growth.

With the option of composting the organic waste, COGG would have diverse options of boosting its agricultural sector through the various fertilizer products that could be derived from wastes. In addition, following the substantial amount of organic waste that COGG region is associated with, it is also probable that some of the fertilizer products could be sold to other regions; hence, contributing to revenue flow for the councils. This approach of composting the waste as has been noted by Blue Environments (2020) is not only viable for fertilizer production, but also has a potential to produce energy, especially from the 'oversize' woody wastes that cannot be used as fertilizers. This means that composting option also has the potential to contribute in the Victorian council's objective of using 100% clean energy (COGG 2019). The adoption of the composting initiative also impacts positively on businesses, especially as is noted after the pilot programs conducted in the Australian states of Queensland, Western Australia and South Australia. From the pilot studies, it was noted that besides reducing the amount of waste find its way into landfills, the businesses in the areas were also benefiting as this strategy allowed them to avert transportation costs and landfill fees. Additionally, these pilots also opened opportunities for stakeholders drawn from different sectors to propose programs and tools, like the Dynamic Resource Efficiency Calculation Tool developed by the Royal Melbourne Institute of Technology (Australia 2020), aimed at helping stakeholders in self-assessing their organic waste practices.

In the context of utilizing organic waste as a source of revenue generation, as has been focused in this paper, the adoption of a composting model would serve COGG well. This is because, as shown above, organic wastes are the least recycled and/or recovered waste categories in the Victorian region. However, this option would face challenges since the cost of landfills in Australia are relatively cheaper (Australia 2020), and it would require councils to come up with proactive and innovative ways of incentivising the public to encourage them to divert their wastes from landfills. It would also be less effective as other wastes would not be composted; hence, requiring additional methods of management. In this case, the anaerobic digester may seem much appropriate as it has the potential to allow management of a wide range of organic wastes. It also produces a higher annual biogas output; hence, ensuring that local councils can earn higher revenue values as well as reduce substantial amounts of emissions. While this study focusses on a specific case study, the methods developed in the present paper can be applied to other urban contexts in varying geographical locations, leading to a better understanding of waste management options for more informed decisions; hence aiding at governance levels regarding urban waste management and disposal.

CONCLUSIONS

Through this paper exploring the organic waste of the City of Greater Geelong (COGG) through two scenarios -with the use of GIS systems, the current and future waste profiles for the COGG were outlined. This demonstrated positive results and the underlined the potential for GIS-based system in modelling and evaluating prospective energy derived from green waste. The system showcased that there is potential to visualize commercial, industrial, construction and demolition waste streams. This visualization feature, coupled with the build-out provisions, could conceptualize future waste streams and assist in the understanding and estimating quality implementations of a more efficient and innovative waste hierarchy; comprised of three guiding principles: avoidance, resource recovery, and disposal.

Table 10. Forecast COGG BioGas Production Calculated by the BioGas Calculator. Source: University of South Wales 2020

Energy Potential of Organic Waste Generated by households				
Region	Population	Organics waste / person / year (kg)	Average BioGas per ton of treated waste (m^3)	Potential BioGas production (m^3)
COGG	257,180	60	150	2,314,620

The literature underlined that the concept and application of GIS focusing on waste in Australia is still in its early stages, but this is expected to develop rapidly noting the challenges of scale coupled with the rapid urbanisation rate. Indeed, as the volumes of waste continue to grow, the pressure on society and cities to control that growth will continue to escalate, demanding urgent and efficient models for waste management. The approach for this paper is thus topical and can be replicated to varying contexts, where we showcase that waste information calibrated into a GIS, with associated modelling, offers an important possible new tool that can assist to inform and manage the growing amounts of municipal waste.

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RESEARCH PAPER

GROUNDWATER POTENTIAL ZONE DELINEATION IN HARD ROCK TERRAIN FOR SUSTAINABLE GROUNDWATER DEVELOPMENT AND MANAGEMENT IN SOUTH MADHYA PRADESH, INDIA

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ABSTRACT. In view of the vital significance of water resources and issues emerging from their temporal and spatial distribution and utilization posing serious problems to the land resources and to the society United Nations has identified sustainable management of water resources (SDG 6) as one of the seventeen major Sustainable Development Goals (SDGs). In this perspective, the purpose of the study is to identify the groundwater potential zones in the hard rock terrain of Betul-Chhindwara Region, Madhya Pradesh, India, using AHP technique. The study area comprises the sub-watersheds of Tawa river (Narmada basin), Tapi river (Tapi basin), Kanhan and Pench rivers (Godavari basin). Various thematic layers such as geomorphology, geology, physiography, rainfall, soil, slope, lineament, drainage density, groundwater depth, and land use/land cover were developed. The analytical hierarchy process helps to delineate groundwater prospect zones, which are categorized into five classes, i.e. very poor, poor, moderate, good, and very good based on objective, criteria, and preference. The good, moderate, and poor groundwater potential zones cover 4815 sq. km., 6423 sq. km, and 4857 sq. km, respectively, comprising 22.46%, 29.96%, and 22.65% of the entire region under study. The result indicates that 15.22% of the area comprising 3262.10 sq. km have very good groundwater potential whereas 9.71% (2080 sq. km) has very poor groundwater potential. The obtained result has been verified through field check based on the yield data collected from 16 bore wells in the study area. The accuracy of the results was 75% that proves the efficiency of the adopted techniques. Thus, this study will be efficient for the sustainable development and management of groundwater in the study area.

KEY WORDS: SDGs, Groundwater Potential Zones, Geographical Information System, Analytic Hierarchy Process, Betul-Chhindwara region

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INTRODUCTION

The concept of sustainable development connotes the utilization and management of resources to meet the needs of humanity at present without compromising the potentiality for the future generation. As such, sustainable development planning entails inventory, evaluation, and physical planning of development. Resource inventory, entailing survey, mapping, and assessment of quantity and quality of resources, is a prerequisite for sustainable development planning. Water resources occupy a unique place in the array of natural resources. Their temporal and spatial distribution and utilization also have posed serious problems to the land resources and the society. These problems include land degradation, salinization, waterlogging and lowering of the water table, and depletion of groundwater resources. Because of the vital significance of water resources, one of the seventeen Sustainable Development Goals (SDGs) of the United Nations is to ensure availability and sustainable management of water and sanitation.

Sustainable development of water resources is impossible until we study the fast deteriorating groundwater potential and address the issue practically and scientifically. Groundwater is vital resource and significant factor in meeting the water prerequisites of different segments, including their real users in agricultural, industrial, and domestic sectors. The manageable improvement of groundwater requires exact quantitative evaluation depending upon technically legal standards. The escalated use of groundwater in some areas of India has caused a rapid decrease in groundwater level. The estimated groundwater potential in India is 399 billion cubic meters (MOWR 2009). Therefore, significant steps for the tapping of potential groundwater sites need to be assessed at the utmost to fulfill the ever increasing demands of freshwater.

The groundwater availability and movement depend on different factors such as the density of lineament, Land Use Land Cover (LULC), geomorphology, geology, soil type, drainage density, slope etc. (Jaiswal et al. 2003; Shankar and Mohan 2005; Dwivedi 2007; Shekhar et al. 2014; Tirkey et al. 2016). Several researchers globally used geospatial technique to map groundwater prospect zone by incorporating the above mentioned layers of hard rock terrains (Gupta and Srivastava 2010; Jha et al. 2010; Mukherjee P. et al 2012; Fashae et al. 2014; Tirkey et al. 2016; Das 2017; Dwivedi et al. 2017). The emerging geospatial techniques are an inevitable and reliable tool in hydrogeological studies, especially for modelling and monitoring groundwater resources (Krishnamurthy et al. 1996; Chowdhury et al. 2009; Machiwal et al. 2011).

Groundwater prospect zones delineation through appropriate analytic methods becomes essential to manage, monitor, and balance the use of groundwater resources. The multi-criteria decision-making technique (MCDM) supports the proper sustainable management of groundwater resources of the region. MCDM involves many complex criteria for handling the problem and gives a realistic solution based on field investigation, pilot studies, and experienced consultancies (Dunning et al. 2000; Flug et al. 2000; Joubert et al. 2003). There are numerous MCDM techniques such as Analytical Hierarchy Process (AHP), Fuzzy AHP, and Multiple Attribute Utility Theory (MAUT). Among them AHP technique developed by Saaty (1980) is more reliable to manage the real-world problem and the natural resource-related problems such as structuring, prioritizing, distributing, and selecting resources, , and thematic ranking. (Saaty 1980; Malczewski 2006; Malczewski and Rinner 2015).

Numerous investigators have successfully applied the concept of Saaty's Analytical Hierarchy Process in GIS techniques for evaluating the probable zones of groundwater resources in various regions (Jha et al. 2010; Machiwal et al. 2011; Shekhar and Pandey 2015; Machiwal et al. 2015; Jhariya et al. 2016; Chowdhury et al. 2009). They found that the GIS technique and AHP are advantageous to plan sustainable utilization of groundwater resources in hard rock areas.

Groundwater is a vital component of the environment being a major source of supply throughout the world. Groundwater occurrence depends on geology, topography, drainage, land use, land cover, lineament, etc. We revealed rapidly increasing reliance on groundwater to meet the increasing water demands. This leads to water exhaustion and groundwater overconsumption causing ecological problems such as decreased water levels and water pollution. Therefore, there is a strong need to investigate groundwater occurrence using advanced techniques for sustainable development and management of this precious resource.

The Betul-Chhindwara region of Madhya Pradesh, India, faces water-related issues such as water scarcity, intermittent droughts, and groundwater depletion. The study area witnessed drinking water shortage and water deficiency during summer. The crop yield reduction observed in the study area is due to water shortage (Galkate et. al. 2008). The major part of the study area covering hard rocks gives less scope for groundwater occurrence due to poor aquifer conditions and high runoff. These precondition impose droughts therefore groundwater potential sites in the region need to be delineated using advanced techniques for sustainable development and management.

This study aims to investigate groundwater potential zones in the Betul-Chhindwara region using the AHP-based geospatial techniques for proper development and management of groundwater resources.

STUDY REGION

The Betul-Chhindwara region is positioned in the southern part of Madhya Pradesh, India, between 21° 28′ N and 21° 54′ 40.3092″ N latitudes and between77° 54′14.2308″ E and 79°24′E longitudes covering an area of 21440.8 km2. The location map of the study area is given in Figure 1.

The Betul-Chhindwara region is a part of the Middle Satpura Region. Geologically the whole area is covered by hard-rock

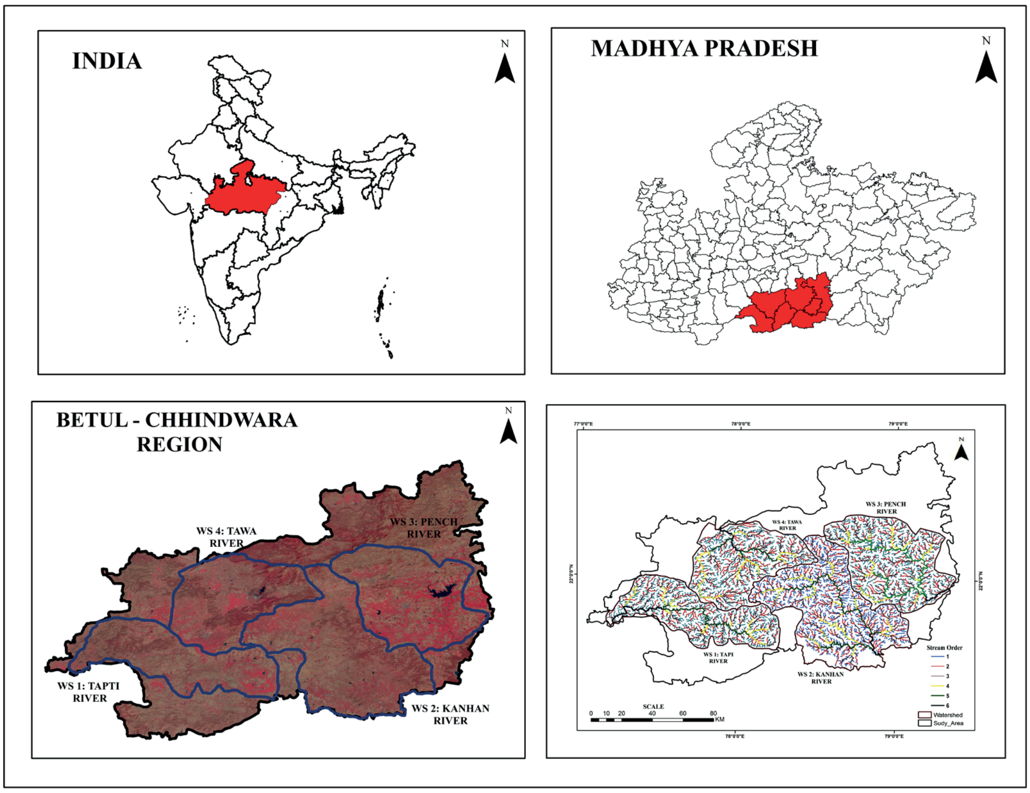

Fig. 1. Study area location with delineated watersheds

formations (CGWB 2009). This area is drained by seasonal rivers such as Pench, Tawa, Kanhan, and Tapi. Topographically entire region is undulating and dissected; many elongated hillocks are elevated to an altitude of from300 meters to 900 meters above MSL (Dehriya, 2014). The climate of the region is tropical with three main periods such as winter, summer, and monsoon. In May the temperature rises to 44ºC while January is considered the coldest month, in which the temperature lowers up to 12ºC. The study region receives maximum rainfall in July. The reported average annual rainfall of the region is 1,130 mm while spatial distribution is very uneven. The annual rainfall in most of the area (approx. 89 % of total area) is less than 850 mm, which is a scanty amount.

MATERIALS AND METHODS

To delineate groundwater prospect zone in the study using ten thematic layers such as geomorphology, geology, rainfall, physiography, soil, slope, lineament, drainage density, land use/land cover, and groundwater depth we used the multi-criteria decision method based on the Analytical Hierarchy Process (AHP).

The comprehensive flowchart representing the adopted methodology is illustrated in Figure 2.

Sentinel-2 satellite data was downloaded from the USGS website and thereby rectified and geo-referenced to prepare LULC and the investigated area's lineament map using ERDAS 9.3 ArcGIS 10.4 software. LULC map was generated using supervised classification with maximum likelihood classifier in ERDAS Imagine 9.3. The drainage map was digitized from the Survey of India's toposheet and rationalized with Sentinel-2 imagery for mapping recent stream networks. ASTER DEM data was used to develop a slope map of the area. The geology and geomorphology map of the investigated area was made using published data procured from GSI. The soil map was prepared from the existing data sets of the National Bureau of Soil Survey and Land-Use Planning (NBSS and LUP). Groundwater level data for 2018 were provided by the Central Groundwater Board and were subsequently imported in the GIS environment and spatially interpolated to prepare the groundwater level map of the study area. Rainfall data for 2018 collected from the Tropical Rainfall Measuring Mission (TRMM), NASA, were sorted with the purpose of development of rainfall map.

All thematic layers were selected for evaluation and assignment of weights with the help of Saaty's AHP keeping in view the comparative significance of each segment in the occurrence of groundwater.

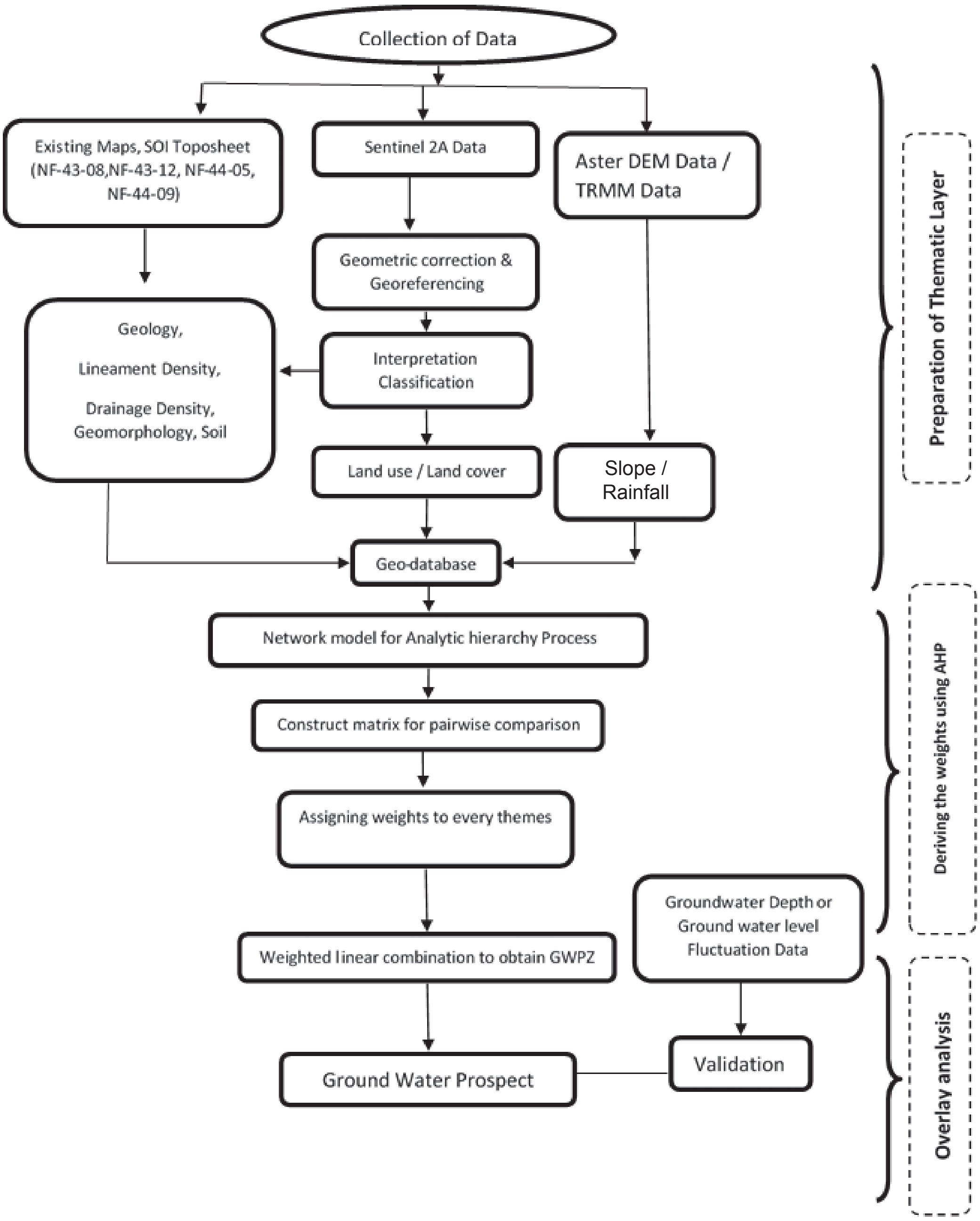

Fig. 2. Study area location with delineated watersheds

Thematic Layers Development Geomorphology

Geomorphology of the region provides evidence of structural evolution and geomorphic process in the geological past (King 1962). The spatial occurrence and movement of groundwater depend on geomorphological features and its genesis (Dwivedi,2007). Based on landforms origin, the area under investigation was classified into seven distinct geomorphological units viz. pediment and pediplain complex, vertically dissected plateau, dissected hills and valleys, alluvial plain, dam, and reservoir (Fig. 3).

Pediment-Pediplain Complex unit is of denudational origin. It covers the major part of the study region occupying approximately 9542.65 sq. km (43.58% of the area). Pediment has an erosional and undulating surface at the foot of hills while pediplain is an extended part of pediment with slopes varying from moderate to gentle (below 10 degrees) and formed by deep weathering and stream erosion. Pediment-pediplain complex unit are dispersed over the large area of Chhindwara, Betul, and Morabd plateau. Its groundwater potential varies from moderate to good . It is based on the underlying geological structure, lineament density, and weathering conditions of the region.

The dissected plateau is flat-topped, uneven with eroded structures, which are represented in the study region in a large quantity. We classified them into three classes: highly dissected, moderately dissected, and low dissected plateau. The second-largest geomorphological unit of the region is a moderately dissected plateau, which covers an area of 7742.83 sq. km. (35.36% of the area). It is spread over the basaltic terrain of the region and has medium groundwater prospect due to vesicular, fracture porosity, and moderate runoff.

A highly dissected plateau is steep-sloped structures, which occupy approximately 9.6% of the area (2121.95 sq. km) of the region. It indicates poor groundwater prospects due to high runoff while steep escarpments with high relief features are recognized as dissected hills and valleys formed due to an intense erosional process and reflects that the region has low groundwater prospects.

All these landforms, on the basis of their origin can be classified under two broad categories viz. denudational and structural landforms. Denudational landform includes pediment, pediplain, dissected plateau etc. extended over upper and lower Gondwana sandstones. Groundwater potential of gneiss/granite rocks varies from moderate to good due to primary and secondary porosity (CGWB 2013). While structural landforms comprise dissected hills, valleys, escarpment, etc. capped with the Deccan trap with a thickness varying from 7 m to 21 m (CGWB 2013) they have a low groundwater potential due to steep slopes. Weightage was assigned as per the groundwater occurrence response of different geomorphic units of the study area.

Rainfall

Rainfall is considered an essential factor in hydrological studies. The groundwater level is directly dependent on the received rainfall amount in a particular area; therefore, spatial variability of rainfall often affects the aquifer's recharging rate (Guhathakurta and Rajeevan 2007).

High rainfall zone is characterized by a high weight while low rainfall zones are characterized by a low weight. The study region receives maximum rainfall from the southwest monsoon – 1130 mm annually. However, the study area is characterized by a high spatial variability as Amarwada and Chhindwara plateaus are receiving a large amount of rainfall (above 950 mm) while Betul plateau and Gwaligarh hills receive very small amount of rainfall (less than 600 mm). The rainfall of the region was categorized into nine classes (Fig. 4).

Geology

The study area consists of Archaens and recent geological formation (CGWB 2009). The main geological units are metamorphic crystalline complex, Gondwana Supergroup, and Deccan Trap.

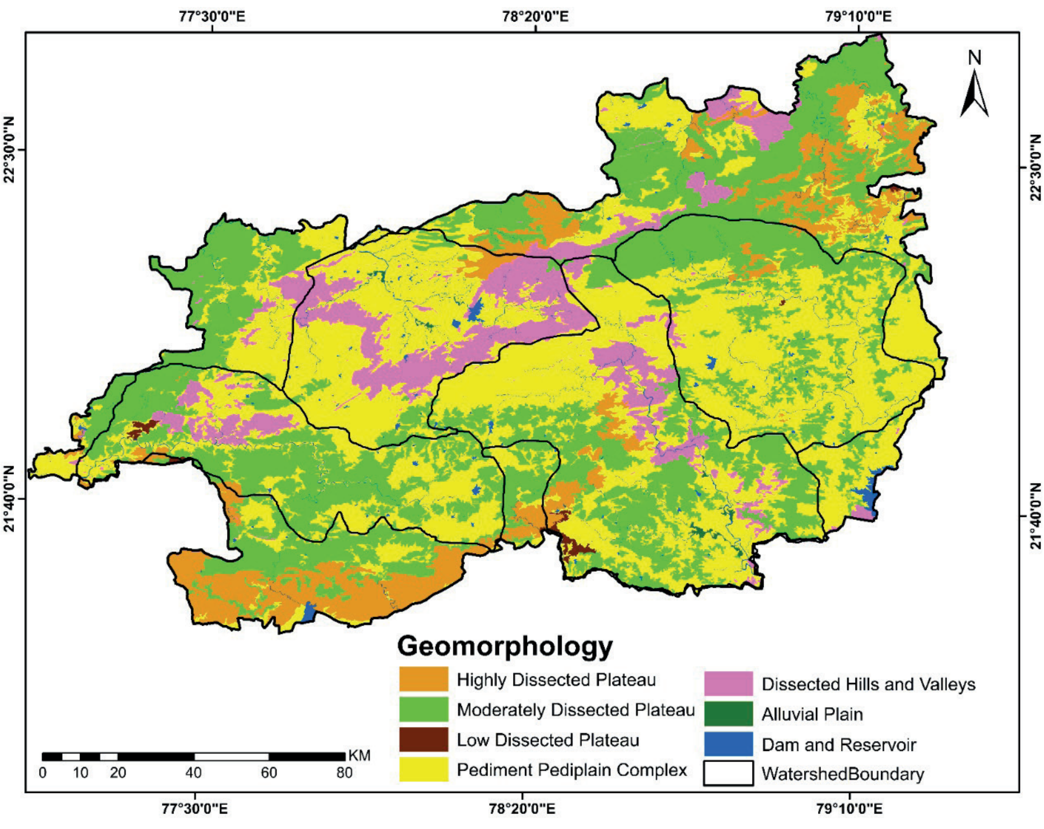

Fig. 3. Geomorphological setting of the selected study area

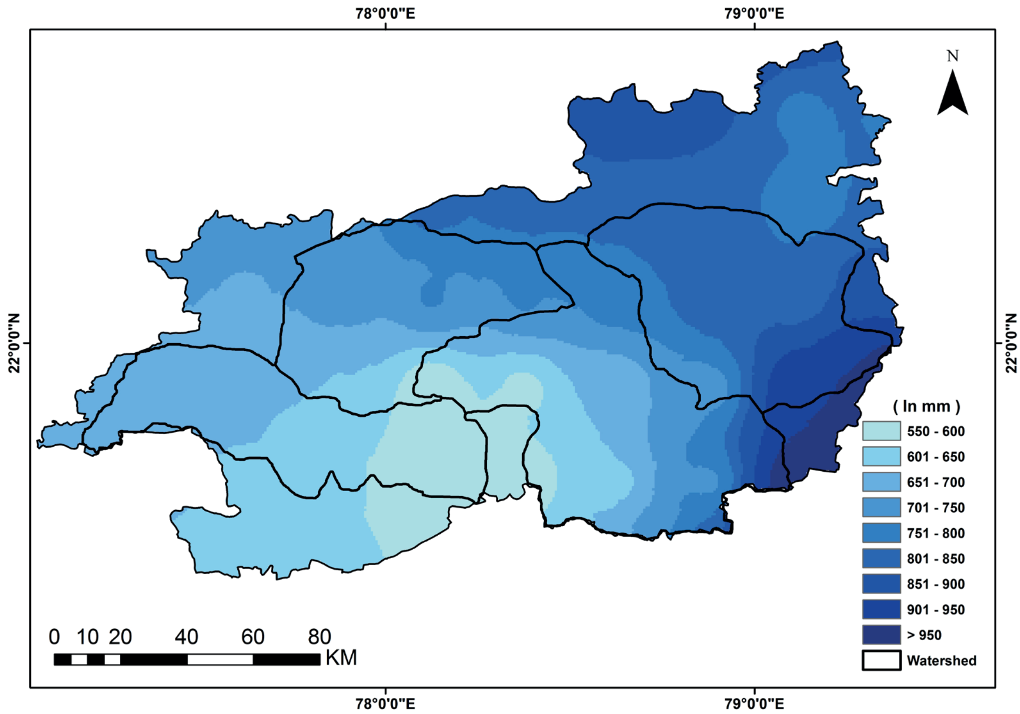

Fig. 4. Rainfall pattern in the selected study area

Low grade metamorphosed crystalline rocks are the basement rocks, including Sausar Series, granite, and gneiss rocks (Rajeeva et al. 2012). They are well exposed in the Sausar plateau and along the valley of the Kanhan river. Conditions in the lower and upper Gondwana sandstones are favourable for groundwater storage, which overlies the basement rock and Gondwana rock overlain by the Deccan trap (Murkute and Joshi 2015). The Deccan Trap covers the maximum portion of the study area, approximately 65% (14309 sq. km.) of the whole region (Fig. 5). It is observed that lower and upper Gondwana rocks have high groundwater potential due to their intergranular porosity, while the granitic, basaltic, and gneissic rocks are characterized by a lower porosity due to their impermeable nature. In hard rock terrain, groundwater is mainly found in secondary porosity structures like fractures, joints, cleavage, and weathered surfaces. Therefore, these parameters have been assigned with corresponding weightage values due to their greater inclination to determine the groundwater potential.

Physiographic division

The study area is categorized into eight dominant physiographic units (Fig. 6). The Betul and Chhindwara plateaus are characterized by good groundwater conditions, followed by the Amarwara plateau.

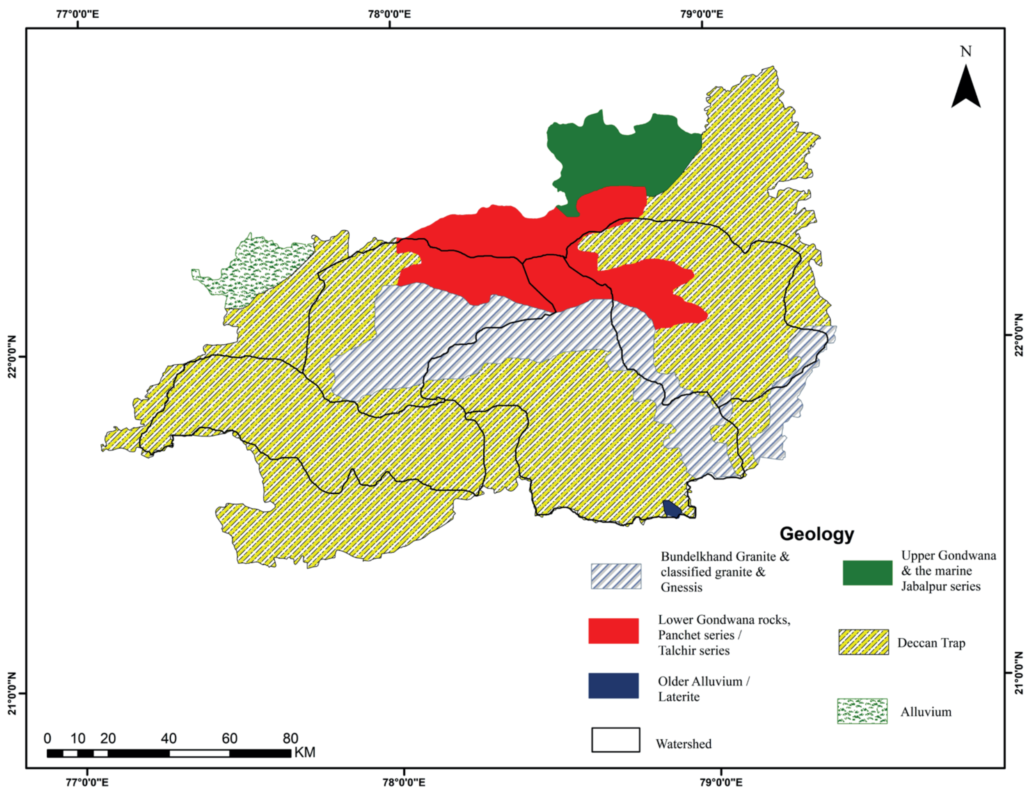

Fig. 5. Geology map of the selected study area

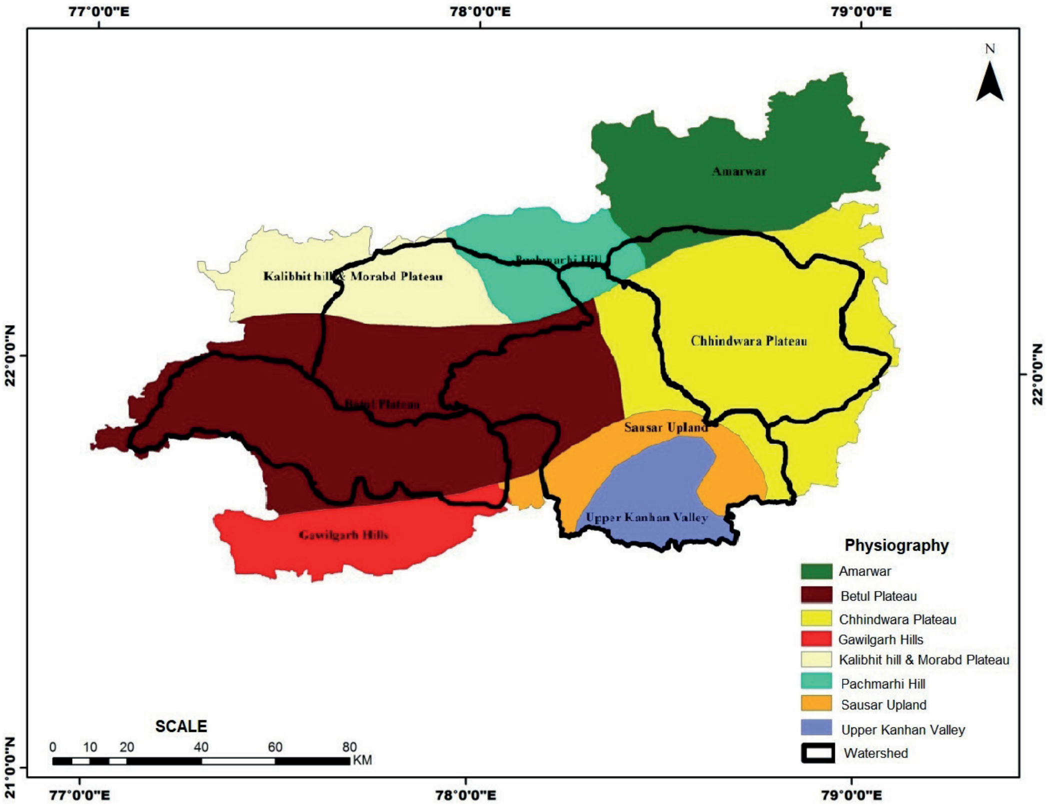

Fig. 6. Physiographic map of the selected study are

The Upper Kanhan valley has a moderate groundwater occurrence whereas Sausar upland and hills have a poor groundwater condition; the weightage values to these features was assigned accordingly.

Soil

Four dominant soil textures – sandy, silt, clay, and loamy – are observed in the study region (Fig. 7).

The soil rich in sand is usually characterized by a comparatively high rate of infiltration. Therefore, it is given higher priority; on the other hand, the soil with high clay material is characterized by a minimum infiltration rate; hence, its priority is the least. Weightage to soil layers was assigned as per their infiltration rate and transmission capacity, which allows for groundwater recharge.

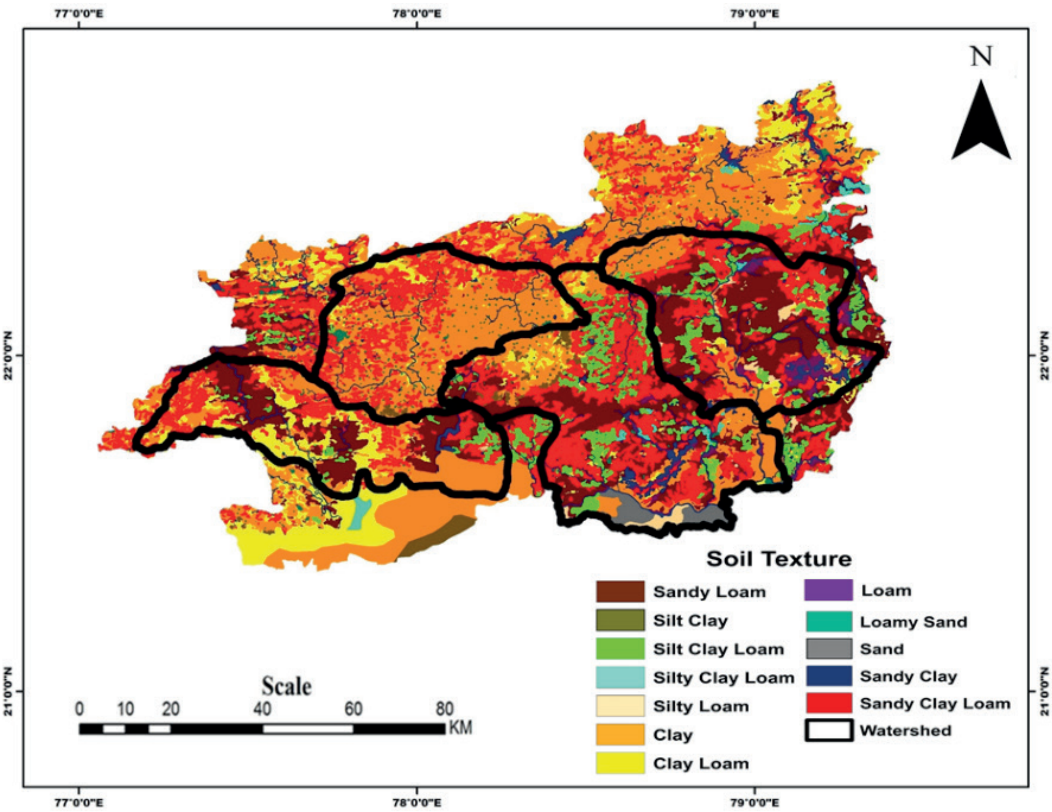

Fig. 7. Distribution of soil in the selected study area

Drainage density

In hydrological studies, drainage density is an important parameter because of its direct relation to the slope and an inverse relationship with permeability (Ghosh and Jana 2017). Drainage density represents the ratio between stream length and unit area of the basin (Strahler 1952). It indicates the total volume of streams in a watershed. Drainage density is heterogeneous because of variation in lithology, relief, slope, and precipitation from one region to another. In this paper, drainage density has been categorized into five classes (Fig. 8). Areas with higher drainage density indicate a favourable condition for the surface runoff; therefore, it is deemed a low-potential groundwater zone. Thus, regions with low drainage density are given high weightage and vice versa.

Lineament density

As detected in satellite images simple or complex properties of a linear geological structure such as faults, joints, fractures, or any other discontinuities on the surface are considered lineaments. Lineaments in the study area have aligned into NW-SE, NE-SW, NNE-SSE, and ENE-WSW direction. Lineament density, intersection point, and lineaments along the drainage lines are essential factors for determining groundwater potential in any area, as they are used as a tool to understand the occurrence and movement of the groundwater in hard rock terrain.

The lineament density of the study area was grouped into five classes (Fig. 9). The high lineament density areas (from 0.69 km/sq. km to 1.29 km/sq. km) are thereby assigned the highest weightage values in assessing the groundwater prospect zones of the Betul-Chhindwara region whereas the low weight is assigned to low-density areas (0 km/sq. km to 0.17 km/sq. km) (Table 4).

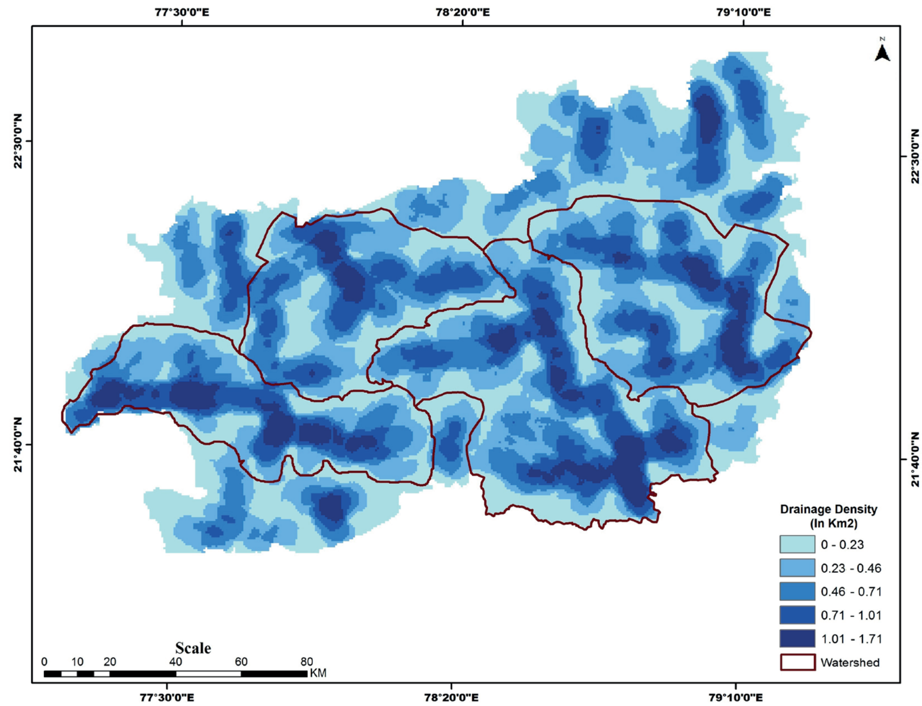

Fig. 8. Drainage density map of the selected study area

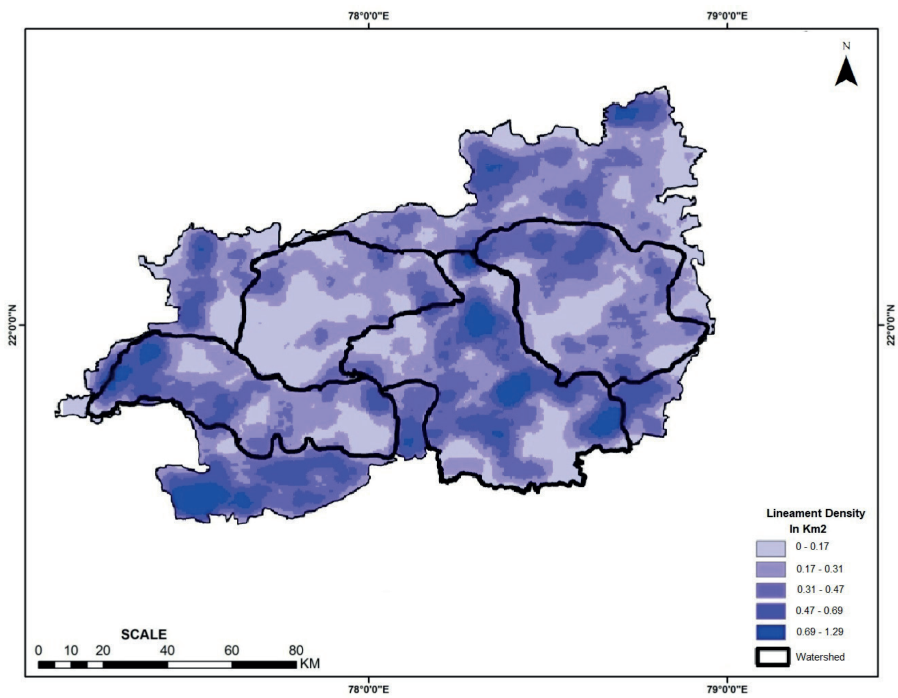

Fig. 9. Lineament density map of the selected study area

Slope

The study area's slope ranges from 0 degrees to 65 degrees and has been categorized into five classes (Fig.10). Most of the region (72.87% of total area of the region) comes under a 10-degree slope. An area with a gentle slope (0–5 degrees) could be useful for groundwater potential because the slope directly relates to runoff while we established an inverse relationship with the infiltration rate. The high slope class is assigned low weight whereas the low slope is given high weightage as per its responses on groundwater occurrence.

Land use and land cover (LULC)

LULC influences hydrological cycle and fluctuation of the water table and groundwater occurrence (Cook et al. 1989; Phillips 1994; Tyler et al. 1996; Pandey and Dwivedi 2014). Many investigations related to groundwater recharge and its impact on LULC have been conducted to understand the hydrological behaviour (Roark and Healy, 1998). Land use/land cover is directly associated with factors controlling the groundwater recharge, such as soil, vegetation, slope, rainfall, etc. Seven land use/ land cover classes were recognized as sparse forest, dense forest, cropland, waterbody, fallow land, settlement, and barren land (Fig.11). Waterbody, dense forest, sparse forest, and cropland area have good groundwater potential. Therefore, maximum weightage is given these classes while barren land, settlement, and fallow land have an inadequate response to groundwater recharge to assign low weightage to these features.

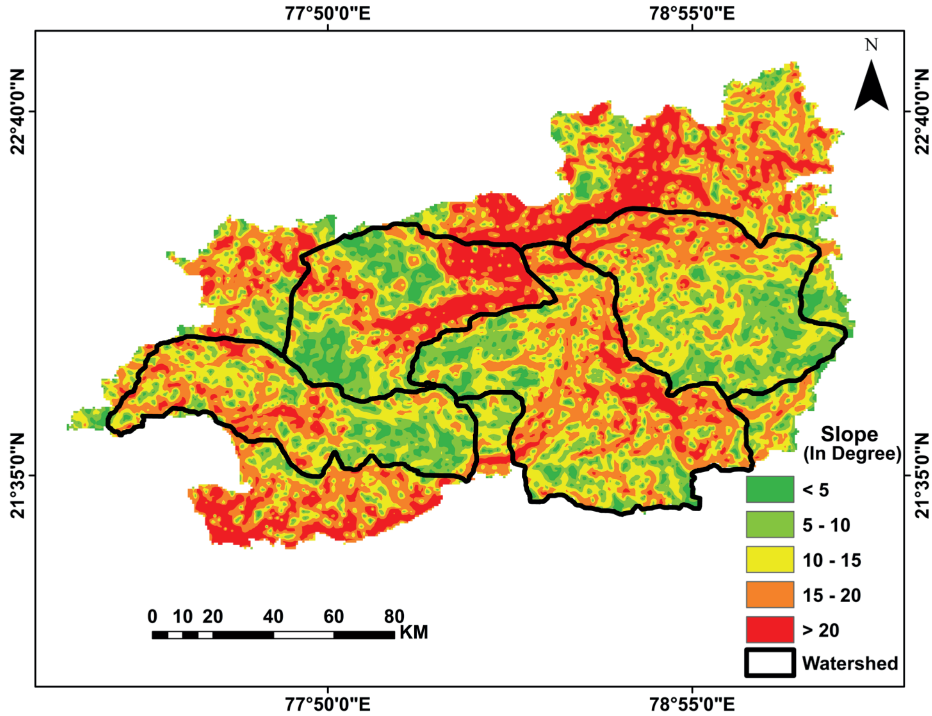

Fig.10. Variation of slope in the selected study are

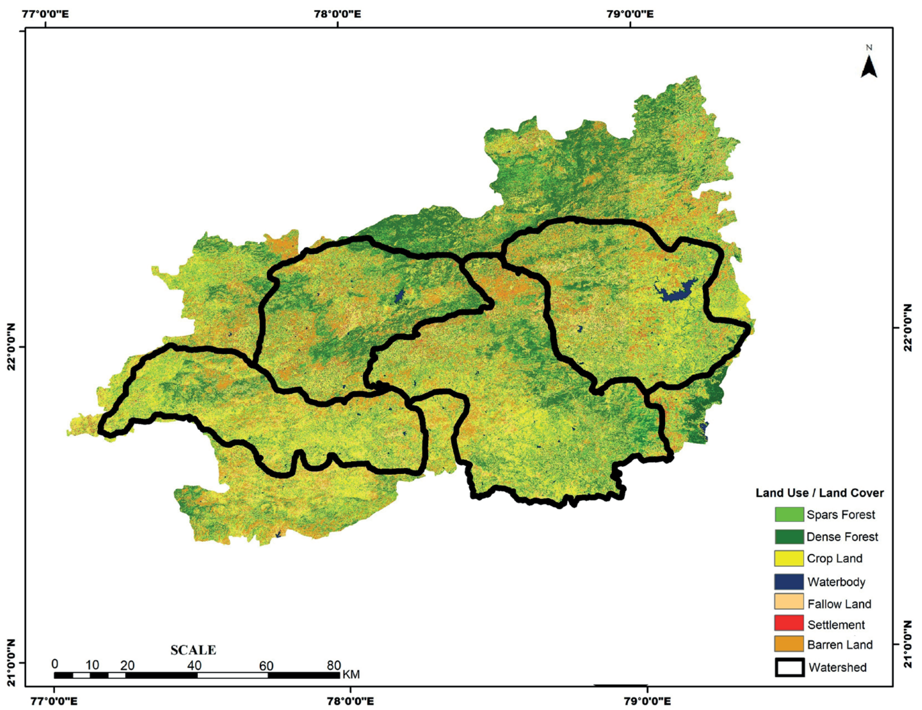

Fig. 11. Land use / land cover map of the selected study area

Groundwater depth

The map showing the groundwater level of the pre-monsoon season was developed using the groundwater level data.

Fig. 12: Groundwater depth map of the selected study area During the pre-monsoon season, the average depth of the water level varies from <5 m to >35 m. The northern part of the study area is characterized by a good water level in comparison to other regions. On the obtained groundwater level map the study area is divided into eight sub-classes (Fig. 12).

Weights assignment using AHP

A three-level hierarchy of goals, criteria attributes, and alternatives was considered to demonstrate the spatial AHP procedure and to evaluate potential groundwater zones. Ten thematic layers such as geomorphology, geology, rainfall, lineament, drainage density, physiography, soil, slope, groundwater level, and LULC were selected for assessing the status of groundwater availability in the study region. The weightage assigned to these layers is based on their role in the occurrence of potential zones of groundwater in the study region.

The methodology, which was adopted to execute AHP, mainly consists of (a) development of a GIS digital database, which included all spatial information (b) determination of the criteria of evaluation and hierarchical structure formation and criteria of multiple formations (c) implementation of the AHP method in the calculation of the criteria relative importance weights; and (d) implementation of the weight – sum method (WSM) in the estimation of potential groundwater zones.

Generation of comparison matrix

The (1–9) Scale of Thomas L. Saaty determines the relative importance values.

(a) Indication of the score as one (1) means that both the themes are equal in importance whereas the indication of the score as nine (9) means that one theme is more significant in comparison to the other (Saaty, 1980)

(b) Matrix is constructed by assigning the values from 1 to 9 to each layer's relative importance. The basic concept is that if the 'x' layer is more important than the 'Y' layer, then the assigned value will be 9. Meanwhile, 'Y' will be less important than 'x', then the value assigned will be 1/9 (Saaty 1980). The matrix is shown in Table 2.

(c) After assigning relative weight, the vector of weight (Eigen value) was calculated on a judgment base (Saaty, 1980)

(d) Finally, the Consistency Index (CI) is derived using the Equation-1 S (Saaty 1980) –

$$CI = (\lambda\max - n)/(n-1) \quad (1)$$

'λmax' indicates the largest Eigenvalue of matrix and 'n' indicates the total classes. After calculating the Eigen value of the matrix the largest value was 11.21, which represents λmax. Consistency Ratio (CR) was calculated using Equation 2.

$$CR = (CI)/(RI) \quad (2)$$

Consistency Index (CI) computed by equation (1) = (11.21-10) / (10-1) = 0.134

Consistency Ratio (CR) = (0.134) / (1.49) = 0.0835

RI indicates the Random Consistency Index, which varies upon the order of the matrix (Table 3). Saaty (1980) suggests that if the 'CR' value is lesser or equivalent to 0.1, the inconsistency is reliable. The consistency of the matrix in the present study was tested to confirm the consistency of decisions in the pair-wise comparison, wherein the value of CR was computed to be 0.083, which is less than 0.1.

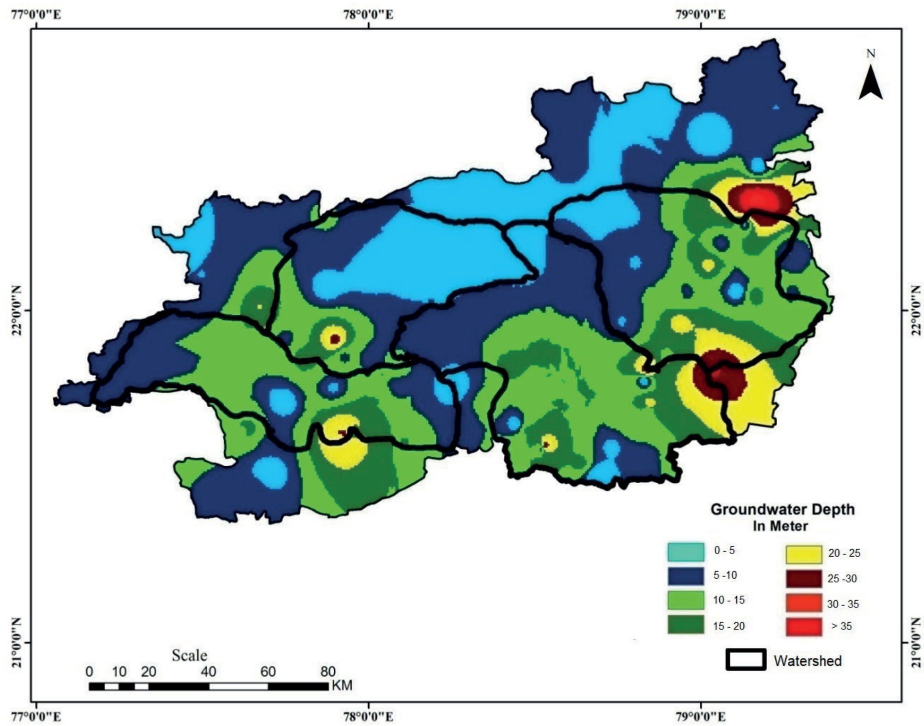

Fig. 12. Groundwater depth map of the selected study area

Table 1. Scale of Saaty (1–9)

Scale	1	2	3	4	5	6	7	8	9
Importance	Equal importance	Weak	Moderate importance	Moderate plus	Strong importance	Strong plus	Very strong importance	Very, very strong	Extreme importance

When obtaining the pair-wise comparison matrix according to the preference values (Table 2), the matrix was analyzed to find each criterion's performance ratings in achieving the related weights. The normalized weights are obtained by using the Weight Sum Model (WSM), which computes the Groundwater Potential Index (GWPI) by multiplying AHP weights with the corresponding ratings (Equation 3).

Overlay analysis

The groundwater potential index (GWPI) in this study is computed using the WSM method (Malczewski 1999; Machiwalet al.2011) and is shown in Equation 3.

$$GWPI = \sum_{i=1}^{n}\sum_{j=1}^{m}\left[a_i\left(\beta_{ij}x_{ij}\right)\right] \quad (3)$$

β_{ij} indicates the weight of j^{th} class of i^{th} theme taken by AHP and αi shows the weight of ith theme, while 'n' and 'm' denotes the total number of thematic layers classes in the thematic layer and x_{ij} represent the value of a pixel of j^{th} class of i^{th} theme.

Table 2. Pair-wise comparison matrix of thematic layers, weight sum, and consistency ratio

Parameter	Geomorphology	Rainfall	Geology	Physiography	Soil	Drainage density	Lineament density	Slope	LU/LC	Groundwater depth	Weighted sum	Consistency ratio
Geomorphology	1	1.125	1.285	1.384	1.5	1.636	1.8	2.25	2.571	3	17.55	6.38
Rainfall	0.888	1	1.142	1.230	1.333	1.454	1.6	2	2.285	2.666	15.60	7.18
Geology	0.777	0.875	1	1.076	1.166	1.272	1.4	1.75	2	2.333	13.65	8.21
Physiography	0.722	0.812	0.928	1	1.083	1.181	1.3	1.625	1.857	2.166	12.67	8.84
Soil	0.666	0.75	0.857	0.923	1	1.090	1.2	1.5	1.714	2	11.70	9.58
Drainage density	0.611	0.687	0.785	0.846	0.916	1	1.1	1.375	1.571	1.833	10.72	10.45
Lineament density	0.555	0.625	0.714	0.769	0.833	0.909	1	1.25	1.428	1.666	9.75	11.5
Slope	0.444	0.5	0.571	0.615	0.666	0.727	0.8	1	1.142	1.333	7.80	14.37
LU/LC	0.388	0.437	0.5	0.538	0.583	0.636	0.7	0.875	1	1.166	6.82	16.42
Groundwater depth	0.333	0.375	0.428	0.461	0.5	0.545	0.6	0.75	0.857	1	5.85	19.16

Table 3. Saaty's Ratio Index for Different Values of 'n'

n	1	2	3	4	5	6	7	8	9	10
Ratio Index	0	0	0.58	0.89	1.12	1.24	1.32	1.41	1.45	1.49

Table 4. Assigned weightages of thematic layers and normalized weights and rank

Thematic parameters	Sub-classes	Weight	Normalized weight	Rank	Area (km^2)	Area (%)
Geomorphology	Highly dissected plateau	1	0.047	0.156	2121.95	9.69
	Moderately dissected plateau	2	0.09		7742.83	35.36
	Lowly dissected plateau	3	0.14		72.06	0.32
	Pediment pediplain complex	4	0.19		9542.65	43.58
	Dissected hills and valleys	1	0.047		2044.05	9.33
	Alluvial plain	5	0.23		31.69	0.14
	Dam and reservoir	5	0.23		341.41	1.55
Rainfall (mm)	550–600	4	0.06	0.139	1965.9	8.96
	601– 650	5	0.07		3545.8	16.17
	651–700	6	0.09		3939.4	17.96
	701–750	7	0.10		3279.7	14.95
	751–800	8	0.12		2268.7	10.34
	801–850	8	0.12		4524.3	20.63
	851–900	8	0.12		556.0	2.53
	900–950	9	0.14		567.3	2.58
	.>950	9	0.14		1276.9	5.82
Geology	Upper Gondwana	3	0.14	0.121	1309.94	5.98
	Lower Gondwana	4	0.19		2481.22	11.33
	Recent alluvium	6	0.28		490.945	2.24
	Deccan trap	2	0.095		14309.9	65.35
	Older alluvium / Laterite	5	0.24		18.2458	0.08

	bundelkhand granite / gneiss	1	0.047		3285.89	15.0
Physiography	Betul plateau	6	0.214	0.113	6679.6	30.50
	Chhindwara plateau	6	0.214		5185.93	23.68
	Amarwara	5	0.178		2964.19	13.54
	Gawilgarh hill	1	0.035		1506.36	6.87
	Kalibhit hill and Marabdi plateau	2	0.071		1947.48	8.89
	Pachmari hill	1	0.035		1391.14	6.35
	Sausar upland	3	0.107		1176.04	5.39
	Upper Kanhan valley	4	0.143		1048.05	4.78
Soil	Clay loam	1	0.017	0.104	2856.83	12.95
	Sandy loam	9	0.157		4515.53	20.48
	Loam	6	0.105		423.479	1.92
	Clay	1	0.017		7157.8	32.46
	Sandy clay loam	4	0.701		4712.13	21.37
	Silt clay loam	3	0.052		1014.85	4.60
	Silty loam	5	0.087		144.43	0.65
	Silt loam clay	2	0.035		111.19	0.50
	Loamy sand	8	0.140		179.168	0.81
	Sand	10	0.175		209.839	0.95
	Sandy clay	7	0.122		537.747	2.43
	Silt clay	1	0.017		182.272	0.82
Drainage density	0–0.234	5	0.333	0.095	6324.03	29.09
	0.234–0.469	4	0.266		6392.194	29.41
	0.469–0.717	3	0.200		4445.615	20.45
	0.717–1.012	2	0.133		3182.322	14.64
	1.012–1.710	1	0.066		1389.074	06.39
	0–0.177	1	0.066		5169.97	23.63
Lineament density	0.177–0.314	2	0.133	0.086	7789.42	35.61
	0.314–0.471	3	0.200		5601.32	25.64
	0.471–0.699	4	0.266		2614.43	11.95
	0.699–1.292	5	0.333	0.069	695.14	3.17
Slope	<5	5	0.416		8669.27	39.59
	5–10	3	0.250		7287.64	33.28
	10–15	2	0.166		3717.64	16.97
	15–20	1	0.083		1669.73	7.62
	>20	1	0.083		552.18	2.54
LU/LC	Dense forest	6	0.272	0.060	5129.75	23.41
	Sparse forest	5	0.227		2705.55	12.34
	Crop land	4	0.181		5023.48	22.93
	Fallow land	3	0.136		4214.59	19.23
	Water body	7	0.31		160.248	0.73
	Settlement	1	0.045		308.236	1.40
	Barren land	1	0.045		4365.79	19.92
Groundwater depth	0–5	8	0.22	0.052	3864.47	17.65
	5–10	7	0.19		8226.77	37.58
	10–15	6	0.16		5552.11	25.36
	15–20	5	0.14		2667.75	12.18
	20–25	4	0.11		1114.61	05.09
	25–30	3	0.08		373.588	01.71
	30–35	2	0.05		75.5539	0.35
	35>	1	0.02		18.4908	0.08

Finally, the themes were rasterized based on their evaluated normalized weights in the GIS platform for measuring the prospective groundwater area of the Betul-Chhindwara region. The layers were overlaid using a spatial analysis tool in ArcGIS software to appraise the potential groundwater zones. The obtained potential areas have been categorized into five zones: very good, good, moderate, poor, and very poor prospect zone (Fig. 13).

Validation with actual yield data

The result was validated by evaluating the relationship between the obtained result and the actual yield data collected from 16 wells from various locations of the study area. The location of wells with yield information is shown on the map (Fig.14). Actual yield has been classified into five classes: below 5 m.bgl. (very good), from 5 m.bgl. to 10 m.bgl. (good), from 10 m.bgl. to 15m.bgl. (moderate), from15 m.bgl. to 20 m.bgl. (poor), and above 20 m.bgl. (very poor). The classification is based on the shared information collected from the field hydrogeologist working in the study area. Validation was completed through the successful evaluation of prospect zone maps and actual yield data of wells (details are shown in Table 5).

Expected accuracy indicators are as follows

Claimed total well location of yield for accuracy estimation = 16

Satisfied well location on the reference map (groundwater prospect map) = 12

Unsatisfied well location on the reference map = 04

Predicted accuracy = (satisfied well location) / (claimed total well location) * 100

Predicted accuracy = 12/16*100 = 75%

Predicted accuracy reflects that the AHP method is suitable for the identification of groundwater potential zone mapping.

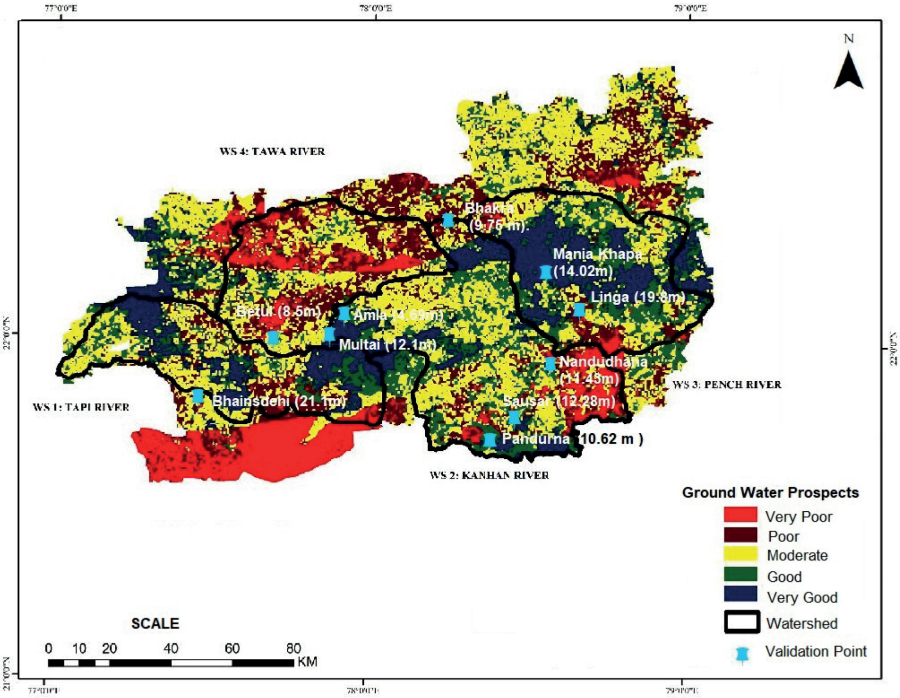

Fig. 13. Groundwater prospect zones of the region and field validation point

Table 5. Actual yield from observation well point during the Field Visit

S.N.	Lat (N)	Long (E)	Area	Actual yield (mbgl)	Description of yield data	Expected yield description for prospect map	Validation between actual yield and expected yield
1	21.964827	78.92926	Linga	19.8	Low	Low	Satisfied
2	21.538921	78.643784	Pandurna	10.62	Good	Moderate	Dissatisfied
3	21.572483	78.707146	Gangatwara	10.66	Good	Good	Satisfied
4	21.599154	78.74572	Sausar	18.28	Poor	Poor	Satisfied
5	21.767147	78.828255	Nandudhana	11.43	Moderate	Moderate	Satisfied
6	22.081533	78.853058	Mania Khapa	14.02	Moderate	Moderate	Satisfied
7	22.219461	78.477982	Bhakra	9.75	Good	Moderate	Dissatisfied
8	21.64444	77.63667	Bhainsdehi	21.1	very poor	very poor	Satisfied
9	21.92361	78.12417	Amla	5.69	Very good	very good	Satisfied
10	21.84667	78.09194	Multai	12.1	Moderate	very Good	Dissatisfied
11	21.76861	77.89389	Betul	8.5	Good	Moderate	Dissatisfied
12	22.348139	78.662231	Tamia	11.8	Moderate	Moderate	Satisfied
13	22.386095	78.777107	Sidauli	18.3	Poor	Poor	Satisfied
14	22.192768	78.598717	Junnardeo	14.5	Moderate	Moderate	Satisfied
15	22.014781	77.672993	Chicholi	12.6	Moderate	Moderate	Satisfied
16	22.289212	79.170394	Amarwada	13.2	Moderate	Moderate	Satisfied

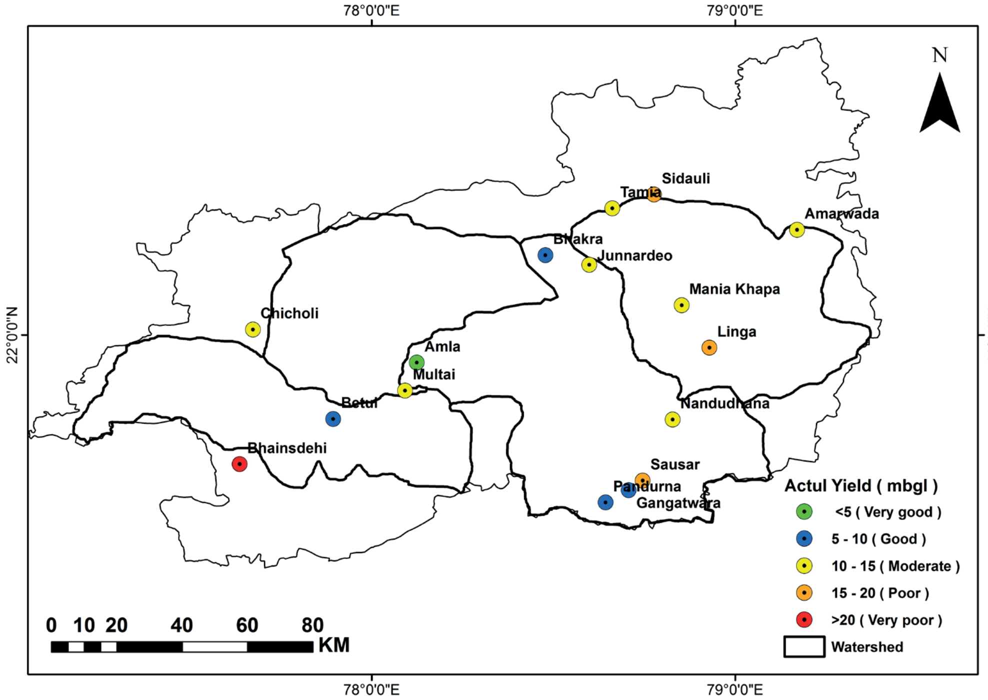

Fig. 14. Field observation points

Results and discussion

The results show that groundwater potential on two-thirds of the study area varies from moderate to very good. Among them very good potential zone covers 15.22% (3262.191 sq.km), good potential zone covers 22.46% (4815.35 sq. km), and moderate groundwater potential zone covers 29.96% (6423.02 sq.km) of the study area whereas approximately one-third of the study area has poor (22.65% or 4857.26 sq.km) and very poor (09.71%, 2082.975 sq.km) groundwater potential. Figure13 shows that out of the four watersheds in the Betul-Chhindwara region, the WS 1 (watershed of the Tapi river) was ranked the second that corresponds to a very good groundwater potential zone. It was noted that groundwater potential zone in the maximum areas of the Tapi river watershed varies from a very good to good. On the other hand, the maximum regions of WS 2 (the Kanhan river watershed) belong to moderate groundwater potential zones. The WS 3 is the Pench river watershed, which has a considerable extent of very good groundwater potential zones; however, groundwater prospect zones in the lower watershed regions vary from low to very low. The groundwater potential zones of the Tawa river watershed (WS 4) mostly vary from moderate to very low. Therefore, to establish a balance between high and low potential zones concerning water resource utilization is an urgent task.

The results reveal that low and medium groundwater potential areas are suffering from the severe scarcity of water and fail to meet the demand for freshwater in the region. The water resource of these regions needs to be urgently and properly managed. The outcome of the present inventory study can be used as the basis for further planning of the sustainable development and management of water resources and solving issues related to water resources.

The study focuses on hard rock, which is characterized by low porosity and permeability hence the study area faces water scarcity due to high runoff, less annual rainfall, etc. There is a strong need to adopt different rainwater harvesting structures and artificial recharge structures such as Check Dams, Nala Bunds, Percolation Tanks, Injection Wells, Induced Recharge, Contour Bunding, Contour Trenching, and Gully Plugging as per geological and topographical conditions to improve the groundwater conditions of the study area. The structures mentioned above need to be developed in the places where groundwater potential is low, whereas high potential zones can be used for extraction, drinking, and irrigation purposes (Table 6).

Table 6. Actual yield from observation well point during the field visit

No.	Groundwater potential zone			Suitable zone and critical zone for groundwater development and management
	Zone	Area covered	Area percentage	
1.	Very good	3262.191 sq.km	15.22%	Suitable for goundwater extraction
2.	Good	4815.35 sq.km	22.46%	Suitable for goundwater extraction
3.	Moderate	6423.02 sq.km	29.96%	Suitable for groundwater extraction and recharge as per the needs of the area
4.	Poor	4857.26 sq.km	22.65%	Critical zone and an urgent need for groundwater recharge through harvesting structures
5.	Very poor	2082.975 sq.km	09.71%	Critical zone and an urgent need for groundwater recharge through harvesting structures
	Total	21440.8 sq.km	100.00%	

Agriculture is the main economic activity in the Betul-Chhindwara region therefore there is high water demand for irrigation. Because of easy and timely accessibility, ubiquitous availability, and cheap drafting technology, groundwater is a significant source of water supply not only for drinking and domestic purposes but also for irrigation. Since water is a vital resource for the use and maintenance of other resources, it can only be developed to a certain extent without affecting other resources and ecological conditions. It is also highly variable across the study area. Therefore, it is crucially essential that this resource is developed and managed sustainably.

This study found that a gentle slope with low drainage density gives more scope for high groundwater development. There is a need to adopt proper artificial recharge practice with geological and topographical consideration in the region as most of the area possesses adequate groundwater recharge capacity.

CONCLUSIONS

The groundwater potential zones mapping is beneficial for sustainable groundwater development and management planning. The present study fulfils these necessities. The need for groundwater resources is high, but due to rocky terrain, their availability is limited. In this study, favourable zones for groundwater occurrence and storage were delineated based on various thematic layers such as geomorphology, geology, physiography, rainfall, soil, slope, lineament, drainage density, and groundwater depth and land use/land cover of this region. This study expressed the competences of remote sensing and GIS and the integration of analytical hierarchy process techniques to identify potential groundwater zones in the Betul-Chhindwara region. The obtained result is validated with groundwater well yield data to ensure that the obtained result is accurate.

There is wide spatial variation in groundwater resources in the region. Only one-third of the area possesses high and very high potential, and hence it is safe to plan sustainable use of water in those areas. The high groundwater potential areas may be used with the help of modern technology to optimize the use and to reduce the wastage and misuse of water while the needs of the low groundwater potential areas can be met with conjunctive use of groundwater with surface water for reducing pressure on groundwater resource. At the same time, measures to improve groundwater potential must be taken in these areas. Possibilities of transfer of water from high potential areas to low potential areas can also be explored. Thus, the outcome of the present inventory study may be used as the basis for further planning of the sustainable development and management of water resources and solving issues related to water resources.

Because of the nature of the distribution and degree of the potentiality of groundwater in the region, it is evident that there is a strong need for sustainable groundwater development and management planning to effectively manage and develop available resources to ensure freshwater supply as SDGs target 6.4 for the present and the future without making undesired impacts on the study area's environment. The findings of the present study provide an authentic assessment of the potential groundwater zones of the Betul-Chhindwara region, which can be used for planning sustainable development and management of groundwater resources. The results of this study will be helpful for government officials and decision-makers in articulating an effective groundwater utilization plan in the study area. ■

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RESEARCH PAPER

TRAFFIC CONGESTION IN AZADPUR MANDI: A STUDY ON THE LARGEST VEGETABLES AND FRUITS MARKET OF ASIA

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ABSTRACT. India's intended nationally determined contribution emission which is safe, smart and sustainable green transportation network. Azadpur Mandi which is known for the biggest selling place of fruits and vegetable in Delhi is becoming a place of very heavy traffic area zone. People who are living nearby and the people coming to Azadpur Mandi facing a lot of traffic and also because of no proper direction hinted there people are not able to reach their destination on time. This paper assesses urban traffic congestions and its impact on the daily life of stakeholders and also advocates some possible solutions. In this research found results the number of vehicles has increased in the last ten to fifteen years. The total number of categorised vehicle has also increased. Azadpur Mandi has impacted the land value of the surroundings. The road infrastructure is not sufficient to cater to the traffic volume of this area. The number of lanes in this area is less. This paper outlines the problems of traffic congestion in Asia's largest sabji (Vegetable) Mandi by using statistical tools. There are very few parking lots inside and outside of the Mandi. This paper investigates the goal 11 of Sustainable Development Goals (SDGs). Goal 11 says to make cities safe, resilience, sustainable. According to the Delhi Traffic police, Azadpur is one of the most accident-prone hotspots of Delhi.

KEY WORDS: Traffic, Road, Infrastructure, Transport, Congestion, Azadpur Mandi

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INTRODUCTION

The vehicular road traffic and traffic jam have the liability of vehicular air pollution, noise impacts and accidents, which causes the impairment of many health issues. And all these issues are discussed in the United Nation's Sustainable Development Goals. Out of 17 Sustainable Development Goals, there are two goals which are directly related to the transportation. The present paper has been prepared and analyzed keeping in mind United Nations's Sustainable Development Goal 11, which discusses way to make cities safe, resilient and sustainable (UN 2019). This goal can be divided into sub-objectives, such as reducing the number of traffic accidents and the severity of accidents (Ghate and Sundar 2010). Lack of mass transportation systems, illegal encroachments on roads, lack of pedestrian facilities, and weak traffic management systems are the major issues of concern in the Azadpur Mandi area. Increasing vehicle traffic is creating many parking issues in the Mandi. The Mandi is served with two main roads to connect and facilitate the traffic to supply Mandi goods and services, but there is inadequate parking space allocated for Slow Moving Vehicles (SMV) and cargo vehicles and other modes of transit on the market (Weinberger, John and Mathew 2010). Transport is a vital component of urban existence. Sustainability in freight transportation demands for a balance among economic, environmental, and social aspects in shipping commodities throughout a supply chain (Pathak et al. 2019). Transport facilities are important framework in the economy of any nation, especially in developing nation like India (Awasthi and Omrani 2018). Traffic rotaries are the notable widespread highlight of traffic guidelines and the traffic board (Rao et al. 2011). Although the expression «sustainability» didn't pick up footing in India until the 1980s, worries about the outcomes of transportation innovation had begun some time before that (Sultana et al. 2017).

Sustainable development is a development which fulfils the needs of the present without compromising the ability of future generations to meet their own needs. (Brundtland Report 1987). A vehicle framework is the place where each individual or traveller can satisfy their versatility needs. It is in a fast, reasonable, sheltered, dependable, and ecologically generous way (Kumar 2014). Transportation systems are complex evolving systems. The presence of multiple, correlated, dynamically changing elements in the system with dependence and feedback add further complexity to the problem (Sayyadi and Awasthi 2018). A sustainable transport system defined by the European Council of Transport Ministers allows the primary access and development needs of individuals, companies and societies to be satisfied in a safe and compatible manner with an understanding of the human and ecosystem health (TERI 2013). Acharya (2005) Channelization has to be done in order to decrease the pace of the vehicles as they enter the crossing points from the carriageways Channelization has to be done in order to decrease the pace of the vehicles as they enter the crossing points from the carriageways, Channelization will likewise go about as a wellbeing boundary for pedestrians and vehicle proprietors to comprehend the rules of traffic guidelines first and serve their best to maintain a strategic distance from the mishaps occurring in the Mandi, which furthermore makes the passerby crossing safe. Basu (2014) has explained that traffic congestion is an alarming problem on a global scale, and has exponentially increased.

The parking problem is a significant contributor to the question, as well as a substantial problem, such as the increase in the number of vehicles, not a segment of parking spaces and confined spaces in urban areas. Dawra and Kulshreshtha (2017) discussed that Indian cities are witnessing a spurt in urban growth. The growth in private vehicle ownership accompanies this increase in urban growth. Kumar and Ganguly (2018) explained that public transport sent have improved in both developed and developing countries, and various types of traffic have increased.There is an exponential growth in the number of vehicles on Delhi roads, which has risen from the 2.15 millions in 1971 to 6.33 millions in 1981, 18.68 millions in 1991, 34.55 millions in 2001 and to 76.11 millions in the year 2016 and further up (RITES 2016). The construction and maintenance of national highways is the responsibility of the central government, while the other roads fall within the jurisdiction of state governments or local bodies. The union territory of Delhi covers 0.04 percent geographical area of India (Anand 2010). Azadpur Mandi is Asia's biggest one of the most famous fruit and vegetable markets of India producing Mandi and thousands of commercial vehicles load and unload their vegetables and fruits daily here (Rao 2015; Upadhya 2016). It is located along the Grand Trunk (G.T.) Karnal road which connects inner Delhi to outer Delhi. This G.T. road is often reported as congested due to presence of heavy freight vehicles coming to Azadpur Mandi for transferring the goods (Singh 2018). Trucks in the Mandi coming from all the states of India use the entire national highway which connects to the Mandi. According to the Delhi traffic police, Azadpur is one of the most accident-prone hotspots in Delhi. India intends to implement nationally determined regulations for traffic emissions with a safe, smart and sustainable green transportation network. Four-arm channelization intersection can provide more efficiency and safety to the road users (Martin and Shaheen 2010).

In Azadpur Mandi, more than 5000 trucks bring fresh produce from all over the country everyday (from places such as Himachal Pradesh, Jammu & Kashmir, Madhya Pradesh, Punjab, and Uttar Pradesh), and the annual arrivals amount to millions of tones (APMC 2018). It is the most critical link in Delhi's food supply chain. Earlier the Mandi was situated in old subzi Mandi area. In 1968, a fire broke out there and it got completely burnt.

In the same year, the govt decided to shift the market and selected the present location for it. The allotment process of this new Mandi started in 1969, but it was ultimately completed by July 1976 (APMC 2018). In central business areas of the city, because of less space, demand for parking spaces has grown by a large amount in recent times. Sustainable portability is fundamental to guarantee financial practicality, ecological well-being and improve personal satisfaction in present day urban communities (Awasthi and Omrani 2019). Due to lack of parking space in Azadpur Mandi, people are used to parking their vehicle on the road. This narrows down the road width and causes traffic congestion problem. Due to this people tend to waste a lot of their time and energy near Azadpur Mandi and have various urban issues, for example, clog, air contamination, unending urban spreads and improper land improvement with low urban thickness (Way and Ming 2019).

Research Question

What is the growth of vehicles in Azadpur Mandi?

What are the types of motor vehicles in Azadpur Mandi?

What is the traffic flow pattern of Azadpur Mandi?

What are the major problems occurs from the traffic Congestion?

To justify this paper, three objectives have been designed which gives the holistic view and describe the causes to understand the traffic congestion of Azadpur Mandi. These objectives are as follow;

To analyse the growth of vehicles and its footfall in Azadpur Mandi.

To understand the traffic flow of vehicles and their characteristic in the study area.

To study the travel characteristics and people perception about traffic congestion in Azadpur Mandi.

MATERIALS AND METHODS

In this study both primary and secondary data sets have been used to fulfil the requirements of the study. Two hundred respondents have been selected through random sampling technique and Purposive sampling technique. Questionnaire has been organised to fulfil the objective of study with proofed out to be ideal for this purpose. The selected sample of people included all the working-class section of the Azadpur Mandi, i.e. from the wealthy class to poor class. People's perception about traffic issues was collected from Azadpur Mandi .The secondary data such as the registered number of vehicles is collected from Transport Department Government of Delhi. The analysis of collected data Quantitative methods have been used and presented with the help of descriptive statistical technique, using of SPSS software, MS office. All stakeholders including residents, labours, transport service providers, costumers and shopkeepers have been taken into consideration during the survey to achieve the required metadata amount to fulfil the objective requirement. Authorities concerned and other service providers/controllers such as

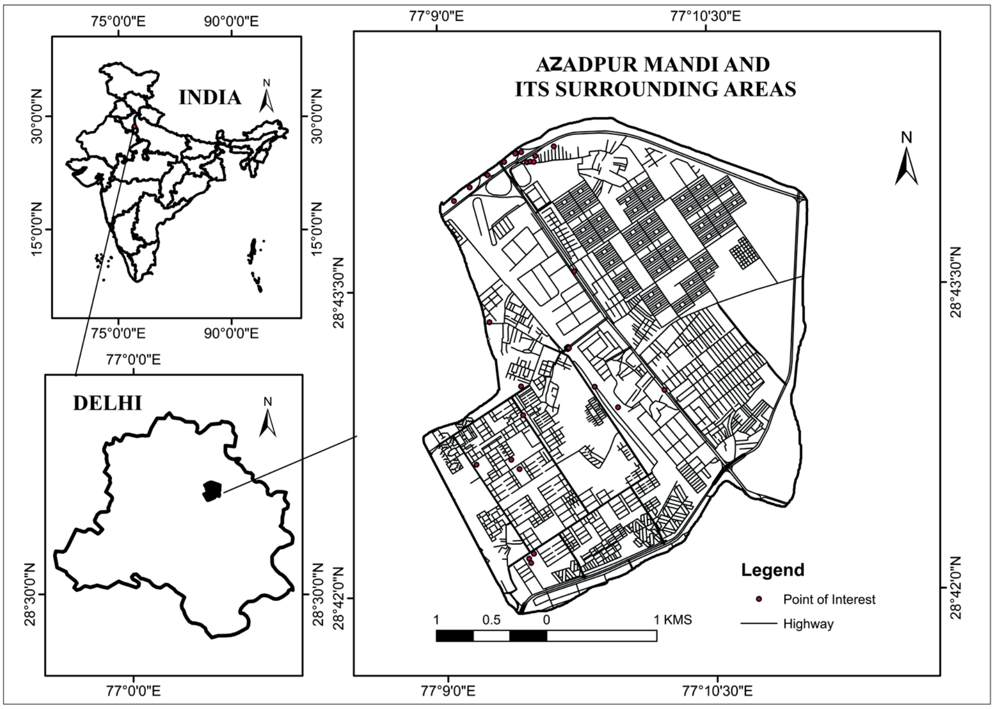

Fig. 1. Location of Azadpur Mandi

Source: Census of India, 2011

Delhi Transportation Corporation (DTC), Central Pollution Control Board (CPCB), Municipal Corporation of Delhi (MCD), Delhi Development Authority (DDA), Centre for Science and Environment (CSE), Delhi police and the School of Planning and Architecture (SPA) have also been taken into consideration during preparation of impact related metadata. Other archive sources like journal, books, newspaper and reports are also have been consulted and analysed for the completion of study.

The area of Azadpur Mandi is at 28.71° 28″N, 77.17°08″ E. Azadpur Mandi comes under the northwest district of Delhi. As per the Census of India 2011 figure, the population of this district is 883,418. Population density is at 14, 973 inhabitants per square kilometres. Azadpur Mandi has a total of seven gates; the people of the area commute from this route and face many environmental and social problems due to unavailability of parking for the vehicles. Azadpur Mandi is essential for Delhi as it provides the nutritious vegetables and fruits to the Delhi residents. The livelihoods of millions of peoples are dependent on Azadpur Mandi. However, lack of proper parking facility is now creating severe environmental issues (CPCB 2010) in the Mandi.

RESULTS

The networks of roads in Delhi are maintained by the National Highway Authority of India (NHAI), Delhi Development Authority (DDA), Public Work Department (PWD), North Delhi Municipal Corporation (NDMC) and Delhi Cantonment Board (Singh et al. 2016). The road networks of Delhi have been categorized into four types, i.e., arterial road, sub-arterial road, minor arterial road and collector road. Azadpur Mandi is located along the Grand Trunk (G.T.) Karnal road which connects inner Delhi to outer Delhi.

Growth of Registered Vehicle

Vehicles of the all over state as well as Delhi NCR region come to Azadpur Mandi. It received the influx of the vehicles which are increasing by huge numbers continuously. To meet the growing demand of vegetables and fruits of this region Mandi receives fruits and vegetables from all over the country which further distributed to next level of supply chain from here. In this process, Azadpur Mandi receives a large number of trucks and loaders and it is showing the sign of continuous increasing. On other hand the numbers of vehicles in Delhi as well as in the study area also souring with the increase of the population. The trends of motor vehicles count is presented in Fig. 2. It can be observed that the yearly growth rate has registered an exponential growth since last decade both in Delhi as well as in the study area. However, it is also observed that the growth in number of vehicle has been reduced in last year but it is not much to ease the load of vehicles in roads. In Azadpur Mandi, more than 5000 can be spotted every day. The numbers of the vehicle are increasing on the daily basis.

Growth of Different Type of Vehicle in the Azadpur Mandi

There are many types of vehicles have come to Azadpur Mandi with different perspectives like trucks and loader to transports the different products. As it known to all that this is the largest Mandi of Asia, it provides thousands of the people to earn their livelihood means. Due to apathy of public transport system and social compulsion, most of the people who work in Mandi come here with their own vehicles and add to the numbers of vehicles in road. In this study, all vehicles has been categorised in four categories to proper understanding the load of vehicles in arteries of Azadpur Mandi. The number of light motor vehicles has increased since 2011, and there has also been a rapid increase in the numbers of two-wheelers also. The distribution can see the growth of vehicles in the Azadpur Mandi for the various types of vehicles entering to Mandi (Fig. 3).

Fig. 3 shows that there has been a rapid increase in the number of Light Motor Vehicles (LMV) in 2015-2016. LMVs include motorcars, jeeps, taxis, delivery vans. Light Motor Vehicles are used for various applications ranging from personal to commercial use. However, there are total 7 seven gates in Azadpur Mandi for swiftly movement of traffic but the problem here is that all vehicles come at the same time since there’s no provision for different time slot for entrance of the vehicles, which is one of the reasons for traffic congestion in Azadpur Mandi.

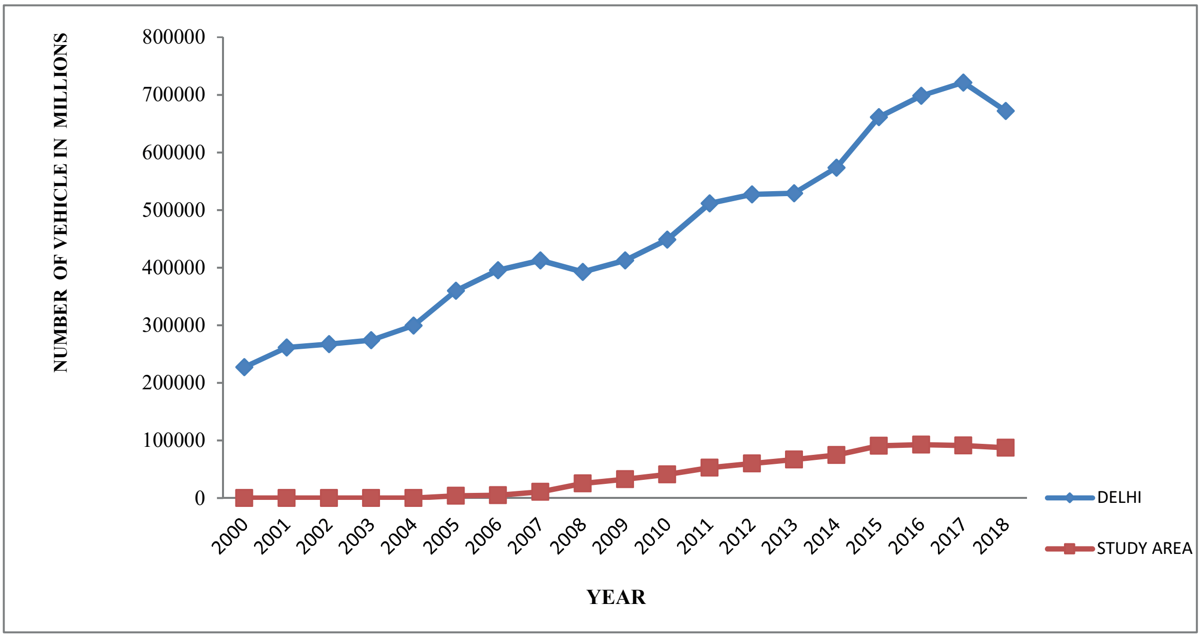

Fig. 2. Trend Comparison of the Total Number of Registered Vehicles in Delhi and Azadpur

Source: Regional Transportation Office (RTO), 2018

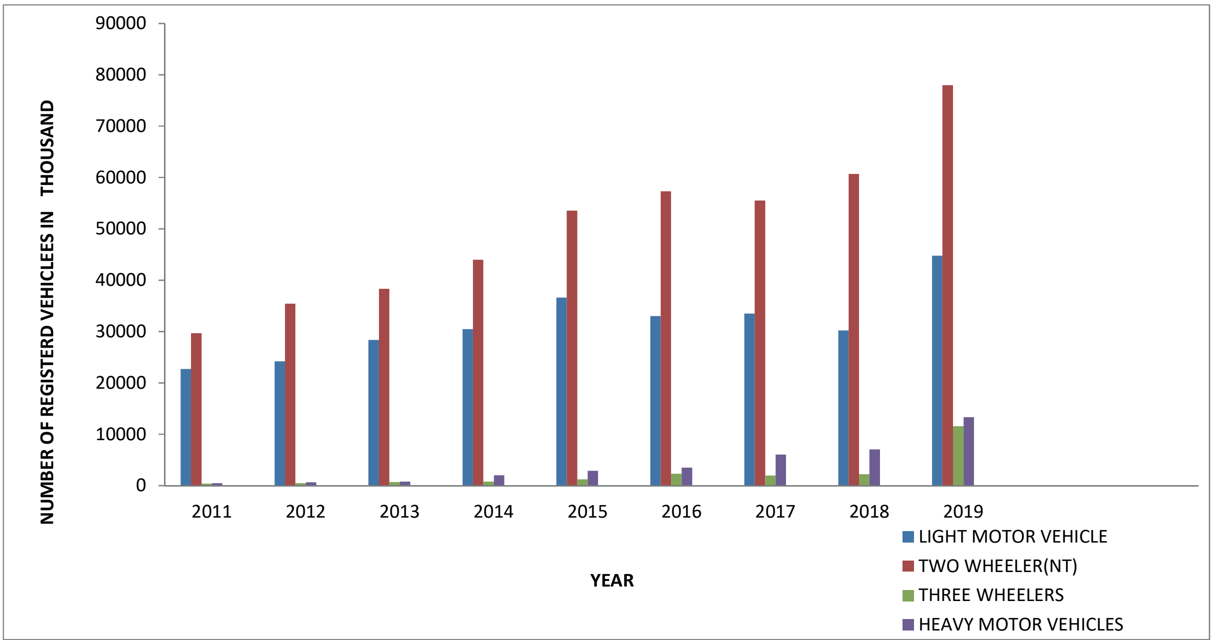

Fig. 3. Total Number of Category-wise Registered Vehicles in the Azadpur Mandi

Source: Regional Transportation Office (RTO), 2018

DISCUSSION

Traffic characteristics study is very vital for designing the required geometric features in the roadway. It includes volume of traffic, speed of traffic, and percentage of trucks or larger vehicles like bus, etc. Study of traffic characteristics helps to avoid direct conflicts, reduce crash rates and their severity, provides orderly traffic flow.

Traffic Characteristics

The lack of public transportation in Azadpur Mandi forced the increase in private mode for travel needs to result in an increase in privately owned vehicles. Most of the people use their own vehicles or hired private taxis, auto rickshaw, cycle rickshaw and cycles, e-rickshaw, ten tyre-trucks, six tire trucks etc. The poor management of traffic become worst in the peak hours when entire fleet of loaded vehicles enter the Mandi. There are many themes to study the traffic characteristic which has been discussed below;

Traffic Flow

Study of the traffic flow helps to understand the traffic characteristics of an area. Here to understand this and fulfil the objective of the study traffic flow has been measured in peak days and non-peak days. Table 1 shows Traffic flow near gate of Mandi and it has been observed that in peak days there are very high traffic flows which create traffic congestion primarily.

The above table shows the traffic flow of Grand Trunk (G.T.) Karnal road in peak days, which is Monday to Saturday (on Sundays the Mandi remains closed). The survey was conducted on 5th February 2018 from 9.00 am to 11.00am and then from 1.00pm to 3.00 pm. The number of vehicles from Azadpur to bypass was higher than bypass to Azadpur. This route is used for many different purposes

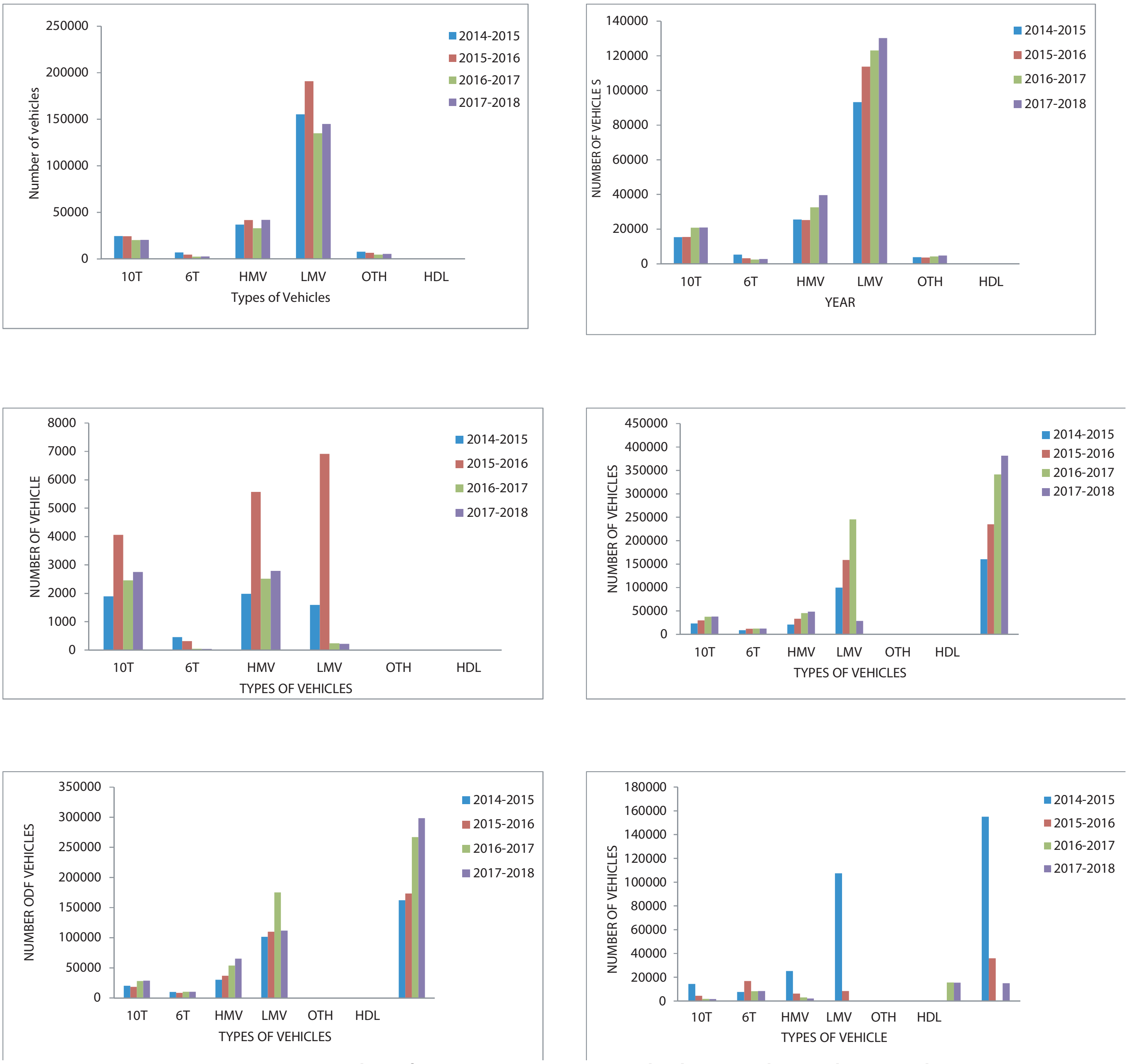

Fig. 3a. Total Number of Category-wise Registered Vehicles in the Azadpur Mandi

Source: (APMC), 2018

Table 1. Traffic Flow in Peak days

Local Field Survey (Traffic Flow) Peak Days					
Date 05/3/2018		Place G.T Karnal Road			Time: 9:00 Am to 11: 00 Am
S.No.	Name of Road	LMV (in no.)	MMV(in no.)	HMV(in no.)	TOTAL TRAFFIC FLOW
1	Azadpur to Bypass	462	749	557	1768
Date 06/3/2018		Place G.T Karnal Road			Time: 9:00 Am to 11:00 Am
2	Bypass to Azadpur	467	507	335	1309
Date 12/3/2018		Place G.T Karnal Road			Time: 1:00 pm to 3:00 pm
1	Azadpur to Bypass	580	639	987	2206
Date 13/3/2018		Place G.T Karnal Road			Time: 1:00 pm to 3:00 pm
2	Bypass to Azadpur	379	510	580	1469

Source: Primary Survey, 2018

like jobs, education, etc., as it connects inner Delhi to outer Delhi. Afternoon time slot 1.00pm to 3.00pm found more traffic than the morning slot. The cause of heavy traffic here was that this road linked Delhi to other states like Haryana, Himachal Pradesh, etc. It has been observed that local people also use this same route to reach their destinations.

Table 2 shows the traffic flow of G.T. Karnal road in nonpeak days. The survey was conducted on 11th November 2018 from 9:00 am to 11:00 am and then again from 1:00 pm to 3:00 pm. Nonpeak days received a smaller number of the vehicles as compared to peak days because on Sunday all offices and schools are closed along with the Mandi.

Table 3 shows the percentage of people for different opinions regarding the traffic flow for different age groups. 64.9 per cent respondents from 60 years above age group believe that there is an increase in the traffic flow and the volume in recent times. At the same time, 60.6 per cent in the age group of 40-60 years also said that there is increase in traffic flow.

Road Density

Road density study also helps to understand the traffic characteristic and provide a logical solution for the problem of traffic congestion. The road density of the Azadpur Mandi and the surrounding streets which are in the area is very high because the width of the street is just 3.5 to 4 meters. It received more than 5000 trucks and other sorts of vehicles every day. The wider roads are more significant to allow more vehicles to ply on it. The existing Right Of Way (ROW) of the secondary path is 7.5 m, and there is no significant differentiation among side lanes and the main road. People and vehicles use the same narrow road at the same place and makes the whole scene very chaotic.

Table 4 shows the percentage of respondents related to the composition of traffic in the study area. This table also shows the distribution of vehicles which created the most significant nuisance on the roads. According to the respondent's percentage of age group 40-60 years, people said Slow Moving Vehicles (SMV), buses, private cars, and two-wheelers were the most significant problem causing vehicles on the roads of the study area.

The age group of 20-40 years respondents said that 47 per cent of trucks and tempos were the most problematic vehicles in the study area. The old age group of above 60 years old age people said that the most problematic vehicles are the slow-moving vehicles since they are often loaded above their carrying capacity, which in turn slows them down and creates problems for other commuters. Most of the respondents were from the 40 to 60 years age group, and there were very fewer respondents in the age

Table 2. Traffic Flow in Non-Peak days (Sunday)

Local Field Survey (Traffic Flow) Non- Peak Days					
Date 4/11/2018		Place G.T Karnal Road			Time: 9:00 Am To 11:00 Am
S.No.	Name of Road	LMV (in no.)	MMV(in no.)	HMV(in no.)	TOTAL TRAFFIC FLOW
1	Azadpur to Bypass	230	749	289	794
Date 11/11/2018		Place G.T Karnal Road			Time: 9:00 Am To 11: 00 Am
2	Bypass to Azadpur	345	507	312	947
Date 18/11/2018		Place G.T Karnal Road			Time: 1:00 Pm To 3:00 pm
1	Azadpur to Bypass	320	520	324	1164
Date 25/11/2018		Place G.T Karnal Road			Time: 1:00 Pm To 3:00 pm
2	Bypass to Azadpur	360	254	360	974

Source: Primary Survey, 2018.

Table 3. Traffic flow: People perception

Age of the Respondents (years)	Increase in the flow of traffic in recent times (%)			
Below 20	Yes	No	Others	Total
20-40	18.8	17.5	63.7	100
40-60	50.4	21.6	28	100
60 Above	60.6	38.1	11.3	100
	64.4	24.5	11.1	100

Source: Primary Survey, 2018

Table 4. Distribution of Most Problematic Vehicle

Age of the Respondents (years)	Type of vehicles (%)Respondents Percentage							
	Slow moving vehicle	Two-wheeler	Three Wheelers	Private cars	Buses	Truck/Tempo	Others	Total
Below 20	15.5	27.1	12.6	6.6	18.8	13.5	5.9	100
20-40	14.3	11.1	20.0	15.8	14.3	21.0	3.5	100
40-60	25.4	15.0	15.0	20	20	11.8	4.8	100
60 Above	21.4	24.1	15.0	13.6	10.0	10.6	4.3	100

Source: Primary Survey, 2018

group Below 20 years and above 60 years. Because in the Mandi most people are in the age group of 40-60 years and have been working for more than 15 years there, they have seen more road traffic problems than the people of other age groups. As per respondent, the flow of traffic had increased in the last 15 to 20 years. They said that the number of trucks entering the city is increasing as the population is also increasing day by day. «log badhenge to zarurat to badhegi hi (when people increase, then the needs also increase)» was what one of the respondents said. Fig. 4 shows a typical traffic jam in the streets of the Mandi. It can be clearly seen that different kind of vehicles are entering and exiting at the same time on the seemingly narrow road. There are no separate lanes for different type of vehicles whatsoever. The very same road can be seen to be used for parking as well. There should be dedicated parking space for the vehicles so it can make resilient for people. It also can be seen in fig. 4 that some vendors have placed their shops on the road itself, and people are gathered near these stalls to eat. All this adds to the traffic jam in the study area.

The model share of passenger trips in the study area is presented in Table 5. The table shows that 95.5 percent of the 40-60 year age group people are rich aadhti or prominent merchants travel by their own cars. While 46.7 per cent palledar who are in 20-40 years age group use bicycle to commute into the Mandi. And 54 per cent of people commute by a commercial vehicle such as three-wheelers, e-rickshaw Bus, etc.

People's Perception of Road Traffic

In the survey results, 48 out of total respondents said, they were stuck for more than 5 hrs inside the Mandi due to bad traffic management. There are many schools, offices, hospitals, industries, and other institutions in nearby areas. Delay due to traffic affects everyone. Many respondents said they get late many times while reaching their concerned destinations. There should be different timings for different type of vehicles for entering in the Mandi, so it will not create chaotic environment, there should also be different lane for various type of vehicles so traffic congestion can be addressed.

Delay Due to Traffic

Table 6 shows the percentage of respondents for delay of traffic. Sixty-one per cent of respondents in the age group of 40-60 years said that they usually stuck in the traffic for less than 30

Fig. 4. Traffic Congestion in the Azadpur Mandi

Primary Survey, 2018

Table 5. Model Share of Passenger Trips

Age of the Respondents (years)	Mode of Transportation used by Respondents (%)						
	Bicycle	Two wheelers	Three-wheeler	Car	Commercial Vehicles	Others	Total
Below 20	23.3	20	24.4	0.1	27.1	5.1	100
20-40	23.7	24.5	12.9	4.5	25	9.4	100
40-60	10	23.7	13.3	5.5	24.2	3.3	100
60 Above	9.4	30	11.9	5.2	32.3	1.2	100

Source: Primary Survey, 2018

min. These people use to commute daily from these routes for various purposes. While 48 per cent of the respondents said that they are stuck for more than 5 hrs inside the Mandi due to bad traffic management.

Construction of the Flyover

Table 7 shows the percentage of people on their opinion related to the construction of the flyover. It shows how much traffic problems are reduced after the creation of the flyover. It also indicates whether there is any reduction in the traffic on the Grand Truck (G.T.) road after the construction of the flyover. Among all the respondents of age group 40-60 years, 71.2 per cent respondents said that the construction of the flyover had not improved the traffic condition inside the Mandi. While 45 per cent of the respondents of the same age group believed that traffic condition, to a more significant extent, has been enhanced after the construction of the flyover.

Problems Related To Road Traffic Condition in Azadpur Mandi

As per the findings of this study, Azadpur Mandi is facing severe problems. Among them, the first and the most serious problem is of traffic congestion. Almost everyone commuting to the Mandi face this problem. This ultimately results in massive loss of their precious time. As per the survey of the study, among all the respondents between 40-60 age group, 86 per cent of respondents believe that increase in traffic congestion inside the Mandi area has resulted in great danger for the pedestrians. Table 8 shows the percentage of respondents related to the road traffic inside the Azadpur Mandi. Among all the respondents of age group 40-60years, 63 per cent of the respondents believe that traffic congestion has created a lot of Air pollution (like fumes) inside the Mandi. Air contamination is a considerable natural hazard for the well-being, and it is assessed to cause roughly 2 million deaths because of PM 2.5 (Chatterjee 2018). The transient health impacts of particulate and vaporous air toxins have been all around recorded, through time-arrangement contemplates relating momentary heights in surrounding levels of such contaminants to increments in grimness and mortality from cardio respiratory conditions (Smoli et al. 2008).

Among the age group of 40-60 years, 52.4 per cent respondents said that they got irritated by the traffic Noise. While 40.5 per cent of the respondents among the age group of 20-40 years complained about delays due to traffic jams. Among all the respondents of the age group of 20-40 years, 64.7 per cent of the respondents complained that the condition of roads inside the Mandi is not safe for the pedestrians. In the same age group, 56.3 per cent of the respondents had a complain regarding the parking (Table 8).

The traffic conditions of the cities, especially in Delhi have deteriorated to a level of great concern (Davis et al. 2017). The current situation of the traffic conditions results from the road infrastructure of the Azadpur Mandi and the surrounding regions. Azadpur Mandi is located along the G.T. Karnal road. There are many densely populated

Table 6. Delay due to Traffic

Age of the Respondents (years)	How many hours do you stuck in the traffic (%)					
	Below 30 min	30min -1hrs	1-2 hrs	2-3hrs	Above 3 hrs	Total
Below 20	23.1	18	20.9	30	8	100
20-40	33.3	13.1	17.9	23.7	12	100
40-60	17	34.8	8.8	20.9	18.5	100
60 Above	2.4	46.9	28.8	11.1	10.8	100

Source: Primary Survey, 2018

Table 7. Construction of the flyover

Age of the Respondents (years)	Do you think the construction of flyover has reduced the traffic conditions (%)				
	Not improved	Partially improved	Improved to a larger extent	Others	Total
Below 20	44.1	30	19.6	6.3	100
20-40	17.7	28.9	45	8.4	100
40-60	21.2	26.2	40	12.6	100
60 Above	20.8	23.1	38	18.1	100

Source: Primary Survey, 2018

Table 8. Problem caused by Road Traffic in Azadpur Mandi

Percentage regarding road traffic conditions in Azadpur Mandi	Age of Respondents (%) years				
	Below 20 Yrs	20-40Yrs	40-60Yrs	60Yrs above	Total
Air pollution / fumes / Dust/dirt	18.2	33	33.6	18.2	100
Irritation from traffic noise	12.7	27	52.4	7.9	100
Congestion	9.1	15.2	60.6	15.2	100
Delay due to travel time	13.5	40.5	18.9	27	100
Pedestrian danger	16	13.3	60.7	10	100
Unsafe road condition	11.8	34.7	23.5	30	100
Parking Problem	6.3	40.3	37.5	16	100
Over speeding Frequent lane changing	14.3	30.7	25	35	100

Source: Primary Survey, 2018

residential colonies nearby such as Adarsh Nagar, Kewal Park, Jahangir Puri, Azadpur Village.

CONCLUSION

This research talked about the ownerships of the vehicle and found that the total number of registered private vehicle has increased. The urbanisation rate and the population growth of Delhi has increased which has caused a rise in fruits and vegetables demand. That's why the number of the vehicle into the Mandi has risen. Azadpur Mandi received several vehicles for the last ten-year including various type of loaded heavy motor vehicles to the light motor of the vehicle and the slow-moving vehicles. The Azadpur Mandi is situated in a strategically important place. People use this area for various purposes as it is surrounded by two important hospitals, Fortis and Max super speciality hospitals. A large number of people commute to Adarsh Nagar sabzi Mandi railway station, Jahangir Puri metro station and Adarsh Nagar metro stations. Many people come from Haryana every day for employment and education purposes. All these factors lead to worst traffic conditions in Azadpur Mandi and the surroundings of Mandi. The road infrastructure is not sufficient to cater to the traffic volume of the area. In Azadpur Mandi vehicles should shift the fuel system from petrol to CNG and electric and solar vehicles. There should be more research and development of alternative power systems for cars, and this should be a high priority of government and vehicle manufacturers of India. Hence my study result also suggests the criteria of Sustainable Development Goals 11 are also not being met under the current scenario.

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RESEARCH PAPER

ACHIEVING GENDER EQUALITY THROUGH ELECTORAL PARTICIPATION OF WOMEN: A CASE STUDY OF 2005, 2010 AND 2015 ASSEMBLY ELECTIONS IN PATNA (INDIA)

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ABSTRACT. United Nations Sustainable Development Goal 5 advocates for the promotion of gender equality. It ensures women's full and effective participation and equal opportunities for leadership at all levels of decision making in politics. Females have a right to vote in elections, be elected to government office, serve on boards, and make their voices heard in any process that will ultimately affect them, their families, and their communities. Investing women's right to political participation is a necessary step to achieve global gender equality and democratic governance.

The paper aims to analyze the spatio- temporal participation of women in assembly elections of 2005, 2010 and 2015 in Patna District, to find out association between women's literacy levels and voting among women in the study area, and to identify motivational and situational constraints of women's participation in electoral process. For the present study, Patna district has been selected as the study area. The author adopted questionnaire survey and key informant interviews as a means for data collection. The growing participation of women in elections indicates a silent movement of women empowerment. It is found that there is a rising trend in the voting participation of women in the study area. Both literate and illiterate groups are conscious about their voting rights.

KEY WORDS: Vote, Gender Equality, Elections, Political participation, Empowerment

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INTRODUCTION

United Nations Sustainable Development Goal 5 advocates for the promotion of gender equality. This goal ensures women's full and effective participation and equal opportunities for leadership at all levels of decision making in politics. Practicing female's right to electoral participation is a necessary step to achieve global gender equality and democratic governance. Moreover, gender equality is necessary for a peaceful, harmonious and sustainable world (United Nations 2015). The Constitution of India guarantees Equality, Liberty and the right to participate in elections in its Preamble and under part III of the constitution (Kashyap 2019). Females have a right to vote in elections, be elected to government office, serve on boards, and make their voices heard in any process that will ultimately affect them, their families, and their communities (Kashyap 2019). Participation in the electioneering process is not only confined to voting rights but it is also related to representation, political activism, political consciousness and many more (Begum 2015). The electoral participation gives women the ability to analyze, organize, and mobilize for social change. In this paper, we analyse the women's participation in 2005, 2010 and 2015 Assembly Elections in my study area of Patna district, which is the capital of state of Bihar.

Niti Aayog, the policy think tank of Government of India has developed a Sustainable Development Goal (SDG) index assessing the performance all states of India in achieving the targets of Sustainable Development Goals. According to Niti Aayog's SDG Index 2019, the state of Bihar has been allocated a composite score of 50 out of 100. In the fifth SDG- gender equality, Bihar scored 40 with the 17th rank among all the 29 states, which is a below satisfactory performance. The indicators considered for SDG 5 include crimes against women, discrimination against women, and access to reproductive health schemes, as well as indicators showing women's economic and political empowerment and leadership.

An analysis of the representation levels of women in India's legislative bodies with other South Asian countries could be relevant to understand the levels of women's electoral participation. Data from the Inter-Parliamentary Union (2016) suggest higher levels for Nepal, Afghanistan and Pakistan, mainly due to reservations of seats for women. Lack of reservation of seats for Indian women in legislative assemblies, combined with several inherent societal and attitudinal factors, seems to act as a gender barrier and major obstacle to participation in electoral competitions and occupying legislative space on equal terms with men. Women's participation in elections is closely related to their level of empowerment (Khanna 2009). It is associated with the equal status of women, providing equal opportunity, and freedom for their development. The women empowerment is synonym with their increased role in the process of decision making. Few decades' back women would rarely go and vote. But fortunately now the scenario is changing and women are going in large numbers to participate in the electoral voting. This is a manifestation of a sustainable and just society.

However, it is necessary to understand that the problems, demands and political aspirations of women are different from men. Interestingly, from the last decade onwards, the political parties in the state of Bihar have incorporated the women-centric issues in their election manifesto such as liquor ban to stop domestic violence, free cycle scheme for every school going girl child, fifty per cent reservation for women in all the three tiers of Panchayati Raj Institutions (PRIs) in Bihar that was introduced in 2006. As a result, women leaders constitute about 54 percent of the total number of leaders elected to PRIs in the State. Out of the 1, 35,805 members across the PRIs in Bihar, 73,204 are women (Mamta 2011). The government is also playing a vital role in the empowerment of women by launching various schemes such as Anganwadi schemes in which women are engaged in early education, taking care of pregnant women, guidance and counseling to lactating mothers. Bihar is one of the states that have shown the progress in the women's political empowerment over the last decade (Mamta 2011).

There have been studies on the geography of election, voting behavior, political consciousness of voters in different parts of India. Dikshit and Giri (1983) examined the changing nature of spatial pattern of the parliamentary voting results in India from 1951 to 1982. Dikshit and Singh (1993) emanated friend and neighbor influence in Indian elections and said that as the distance of residence of voter's increases from the residence of candidates there is a decrease in political affirmation.

Hussain and Mir in 1984 identified the voting determinants for 1983 Assembly elections in Jammu and Kashmir. Dikshit and Singh (1993) emanated friend and neighbor influence in Indian elections and said that as the distance of residence of voter's increases from the residence of candidates there is a decrease in political affirmation.

The Further, the scholars have also assessed the women empowerment through their increased participation in political arena. Devi and Lakshmi (2005) studied political empowerment of women in Indian legislature and suggested that women representatives should form 'critical mass' so as to act as a pressure group in the legislature. They can also raise voice on crucial concern to women such as contraception, abortion, violence against women, gender discrimination, maternity leave, child care etc. M.M.S. Negi (2011) explained the voting attitude of women in Uttarakhand with special reference to Garhwal. According to him political awareness plays an important role in forming and shaping political attitudes such as those related to voting. Rajeshwari Deshpande (2004) has utilized National Election Studies data with a case study of Lok Sabha 2004 elections to have a detailed and, nuanced understanding about women's voting behavior, their participation and political attitude. Women's overwhelming participation in 2004 elections can be a pointer to strengthening women's role in politics for coming future. However, Rai (2017) underlines that while the women's voter participation is on rise reaching the highest female voter turnout in 2014 Lok Sabha elections, the continued under-representation of women in legislative bodies and power structure of political parties is worrisome. This can offset the gains of people-driven feminization of electoral politics of India. Kumar, et al. (2019) have explained the role of women self-help groups (SHGs) in increasing the political participation of women by assessing their participation in last election and making choice of voting independently without coercion from family members and others. However, the perspective on voting behavior and electoral participation of women are highly limited therefore this paper focuses upon women participation which has rarely been touched upon. The present paper is all about women participation in voting, who enjoy very little freedom of choice particularly the political choice. The patriarchal system is deeply rooted in the society of State (Datta and Preet 2012). The main question therefore remains to be the extent of political choice which the women of the state regardless of their age, social, culture and economic status enjoy. This may range to very little freedom, more freedom or no freedom of choice at all (Carole 2007). Nevertheless women in the state cast their vote but their participation very often became victim of the male control of the household. The objectives framed for the study – are to analyze the spatio-temporal participation of women in assembly elections of 2005, 2010 and 2015 in Patna District, to find out association between women's literacy levels and voting among women in the study area, and to identify motivational and situational constraints of women's participation in electoral process.

Study Area

Patna district has been selected as the study area. It is the capital of the state Bihar which makes it one of the important districts among the entire 38 districts of Bihar. The latitudinal and longitudinal extents of this district are 25°12´ N to 25°44´ N and 84°42´ E to 86°4´ E respectively. Patna district is also known as the heartland of Bihar, therefore, who rules Patna, commands the entire state of Bihar and even influences the national politics. There are fourteen assembly constituencies in Patna district. These are Maner, Bikram, Bankipur, Patna Sahib, Danapur, Kumhrar, Paliganj, Mokama, Digha, Fatuha, Masauri, Bankipur, Phulwari and Barh. The district is bounded by the river Son on the west, on the north by the Ganga River and on the south by Nalanda, Arwal and Jahanabad districts. On the east the district is bordered by Begusarai and partly by Lakhisarai. According to the 2011 census, Patna district has a population of 5,838,465 in which the number of females is 2759953. The sex ratio is 897 females for every 1,000 males. Literacy rate is 70.68 percent in which female literacy rate is 61.96 percent.

METHODOLOGY

For a scientific and valid conclusion, pre field study, field study and post field study has been conducted. Pre-Field Study includes library work, data collection from Election Commission of India, Census of India and the Department of Statistics, Govt. of Bihar. Newspapers (Times of India, The Hindu, Dainak Jagran and Hindustan) are also a part of pre field survey for the study. Data collection has been arranged in order for statistical and cartographic treatment. Questionnaire has been prepared on the basis of the pattern which has emerged after the processing of the data through statistical and cartographic methods.

In the field survey, primary data collection with the help of questionnaire regarding their voting perception has been done. Respondents have been selected with the help

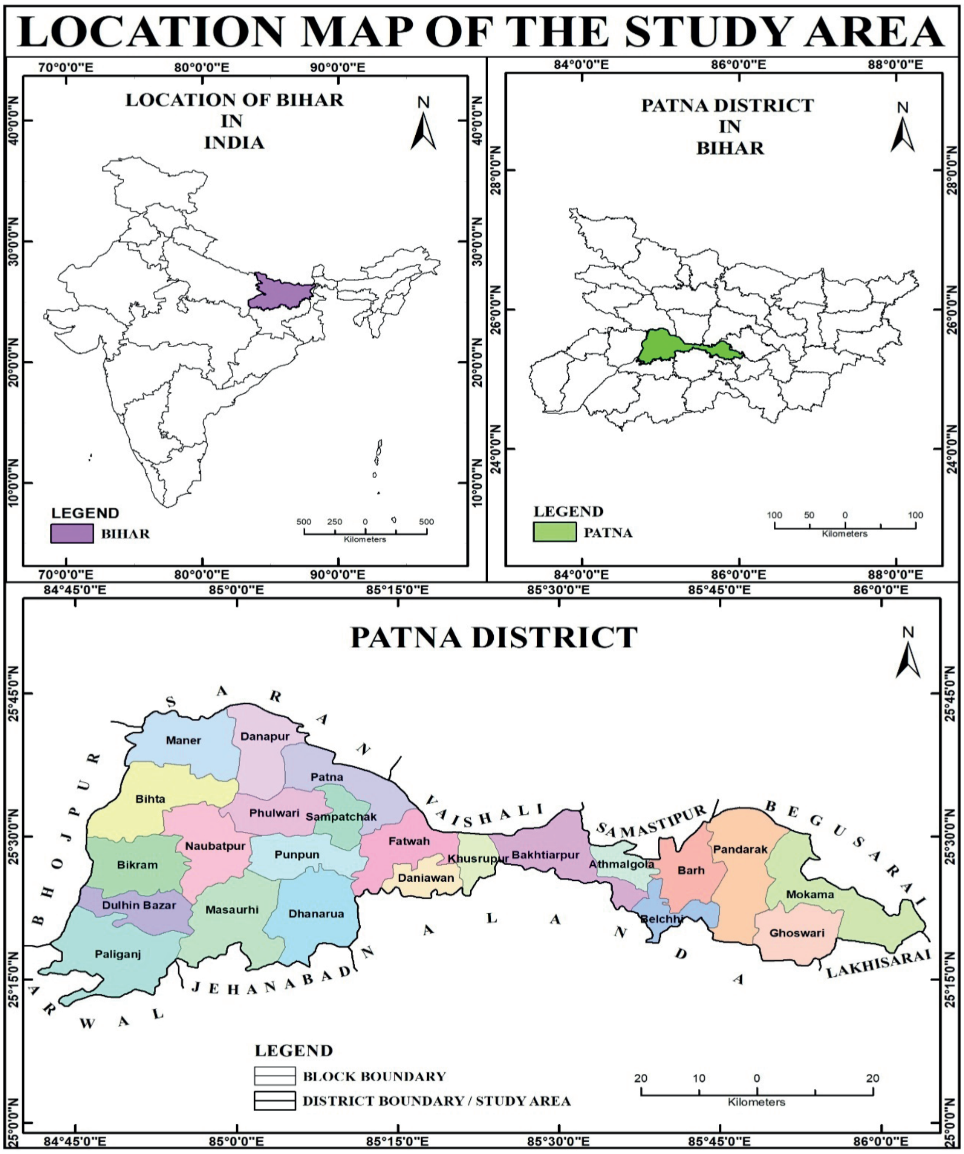

Fig. 1. Study area

of stratified random sampling technique. Tabulation and compilation of data collected through primary field survey has been done in order to find an appropriate result in post field survey. Statistical and mathematical treatment of data has been done and the result so obtained is represented by explanations and suitable diagrams using cartographic techniques.

A total of nine eighty six samples have been used in this study. 52.2 percent respondents are from rural areas, followed by 21.8 percent from semi-urban and 26.0 percent were urban residents. All of the fourteen assembly constituencies were visited and data were obtained through detailed questionnaire surveys.

Statistical analysis from February 2005 assembly election to 2015 assembly election had been done to find out mean, standard deviation, chi value and Bi-Variate Pearson correlation between male and female voters. The electoral data was collected from Election Commission of India.

RESULTS AND DISCUSSIONS

In this section, the Spatio- Temporal Participation of Women in Assembly Elections of 2005, 2010 and 2015 in Patna district is discussed. Palmer (1976) has pointed out that voting is the most common and important act of political participation. Increasing awareness among women voters about their rights began to influence the political scene (Fadia 2014) of the region. Electoral participation is a process in which the electorates participate in choosing their representatives. Voter's participation is measured as the percentage of registered voters in each constituency who actually exercise their voting right during the elections. Each voter has their own ideology, political orientation, judgment and expectations which pull them to vote for a particular candidate.

The recent participation level of women in the elections shows that there is an upsurge among women voters. 2014 General Elections saw women's voter turnout rising substantially to 65.3 percent from 55.82 percent in 2009. In 2015 female voter turnout rose to 68 percent tipping over that of men (Election Commission of India 2015). Women's active participation in electoral competitions is a valid indicator of the efficacious growth of democracy in any country of the world today (Nelson and Chowdhary 1994).

Bihar is one of the backward regions of the country, it is at the bottom of Niti Aayog's SDG Index, 2019 but there is remarkable growth of women in the electoral politics in terms of voting. The government regulated quotas and women centric political party manifestos such as 50 per cent reservation for women in the local body elections, scholarships for female students, free cycles and school uniform schemes for girls and a dedicated women police battalion in the state, 35 per cent reservation for women in state government jobs etc. motivates women to vote. Patna is one of the districts of state that have shown progress in women's political empowerment over the last decade. According to Election Commission report, 2010 and 2015 women's turnout was more than men turnout in the previous two consecutive assembly elections of 2010, 2015 in Bihar. The women voter's turnout in the 2010 assembly election was 54.5 percent whereas the men's turnout was 51.1 percent. In the 2015 assembly election the women voter's turnout was 60.48 percent whereas men voter's turnout was 53.32 percent in Bihar (Election Commission of India 2015).

Patna district is the capital of the State and the administrative headquarter is located in this district. Therefore, the voter participation in the election in this region is important to gauge the mood of the voters and has several implications on the state elections. Das Gupta and Morris-jones (1975) stated that the voter's turnout is positively related to social development. It is largely beneficial for fighting socio- political gender parity. Adhikari (2005) said that voter's participation is a raison d'etre of election and no election is meaningful unless the people participate in it.

In Patna district, the participation of women voters is less than the male voters however there is a rising trend of women's voting participation.

Voting Participation of Women in 2015 Assembly Election in Patna District

Ali and Lin, 2013 said that «understanding why people vote is fundamental to the theory and practice of democracy». Participation in the voting process is an indication of political awareness and empowerment of the voters. Secondary data of Assembly Elections of 2005, 2010 and 2015 in Bihar, collected from Election Commission of India clearly revealed that except Mokama and Barh among all the assembly constituencies, the female voting participation is lower than the male participation. Secondly, rural women are voting more than their counterparts in the urban centers. Falcao, V, 2009, observed a similar pattern in his study that urban voters are most literate and aware about their rights but are less enthusiastic about voting.

Figure 2 shows that the highest percentage of voting among women in 2015 Assembly elections is in Bakhtiarpur i.e. 58 percent whereas the lowest percentage is in Kumhrar assembly constituency i.e. only 36 percent. Interestingly, Kumhrar constitutency is an urban constituency located within the limits of Patna Municipal Corporation. The assembly constituency in which total voting percentage is more than 60 percent is Bakhtiarpur, Fatuha and Maner. In Mokama, Barh, Patna Sahib, Danapur, Phulwari, Maner, Paliganj and Bikram assembly constituencies the total voting percentage is between 50 to 60 percent. Digha and Bakhtiarpur have 42.8 percent and 40 percent of total percentage of voting respectively.

Mukhyamantri Balika Cycle Yojana (launched by the Chief Minister of Bihar in 2006) under which around 4 million bicycles have been given to the school going girls in Bihar. This has greatly changed the face of female education in Bihar. Eventually, many of these girls were eligible voters in 2015 assembly elections and were supposed to be reaching out to booths with great enthusiasm that is expected from a first-time voter.

Secondly, the decision to reserve 50 % of seats in rural and urban local bodies for women have also gone a long way in empowering females of the state of Bihar. The sense of empowerment has further strengthened their belief in the democratic system and this could also be a reason for higher turnout of women in the assembly election 2015.

'Hunar' programme, specifically launched for Muslim girls by the government, is a huge success story that has also been appreciated by NITI Aayog. Under this scheme, free skills training is being imparted to poor and out-of-school Muslim girl children to ensure their socio-economic and educational development. This has also resulted in young Muslim girls getting a new sense of empowerment and it is believed that they are participating in this festival of democracy with much zeal.

It is clear from the figure 3 that in the 2010 assembly election, the highest percentage of female voting was in Mokama i.e. 54.5 percent followed by Bakhtiarpur and Fatuha in which 58.1 percent and 55.7 percent votes have been polled. The lowest percentage of female voting is in Bakhtiarpur i.e. 33 percent. The total voting percentage is highest in Fatuha followed by Bakhtiarpur and Maner. Digha and Kumhrar have voting percentage 39.3 and 36 percent respectively.

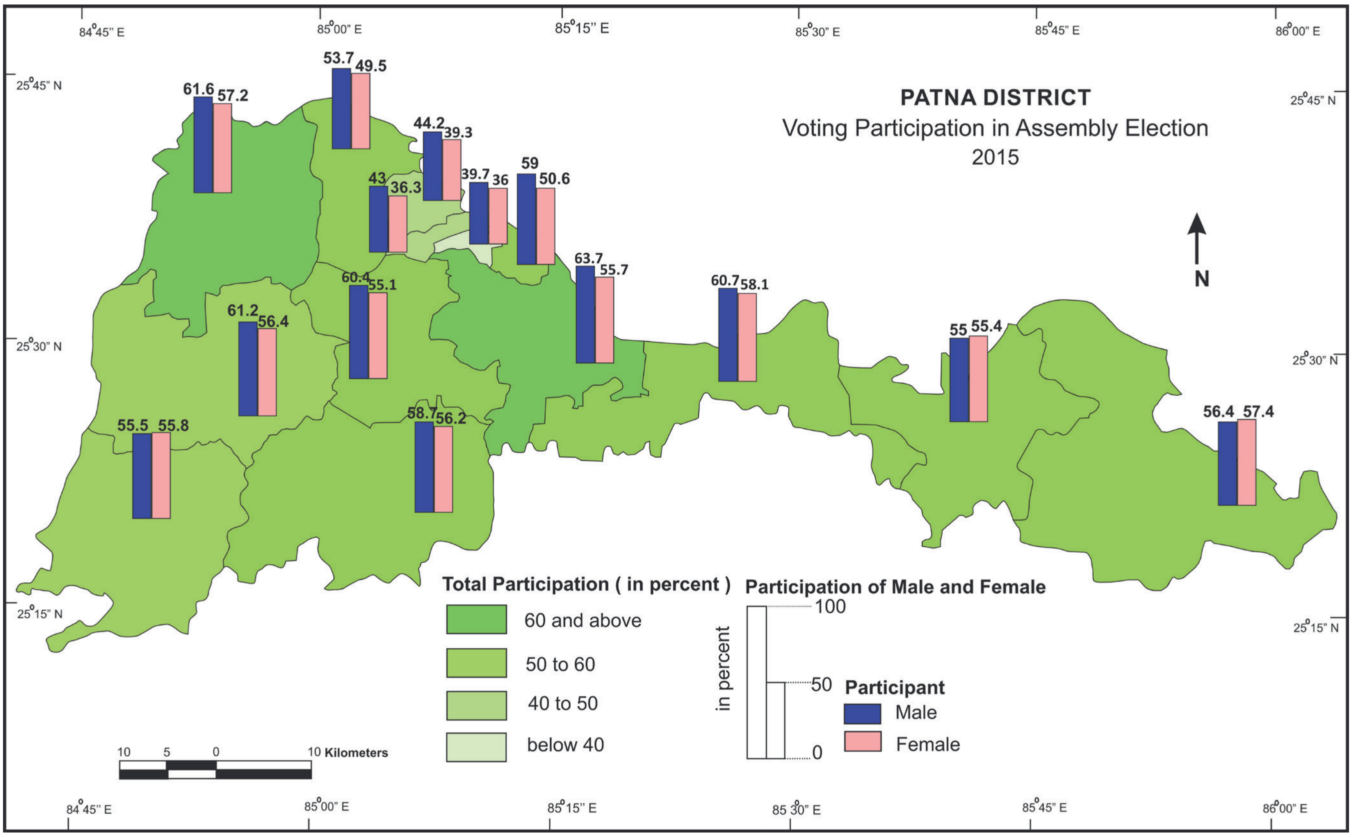

Fig. 2. Voting Participation of Women in 2015 Assembly Election in Patna District

Mokama, Barh, Patna Sahib, Danapur, Phulwari, Masaurhi, Paliganj and Bikram have total voting in between 50 and 60 percent. In Digha, Bankipur, Kumhrar, the total voting percentage is less than 45 percent.

In 2005, two elections were held; one in the month of February and other in the months of October- November in the same year. There was a fractured verdict in February 2005 Bihar Assembly Election. Since no government could be formed in Bihar, fresh elections were held again in October and November. In the February 2005 assembly election, the highest percentage of voting was in Bikram i.e. only 41.4 percent (figure 4) whereas in October, there was a decrease in the female voting participation.

The total voting percentage is the highest in Paliganj i.e. 46 percent (Figure 5) in October- November assembly election, which is higher by 1 percent in February assembly election. In both of the elections, the lowest total voting percentage was in Patna West i.e. 33.3 percent and 34 percent respectively.

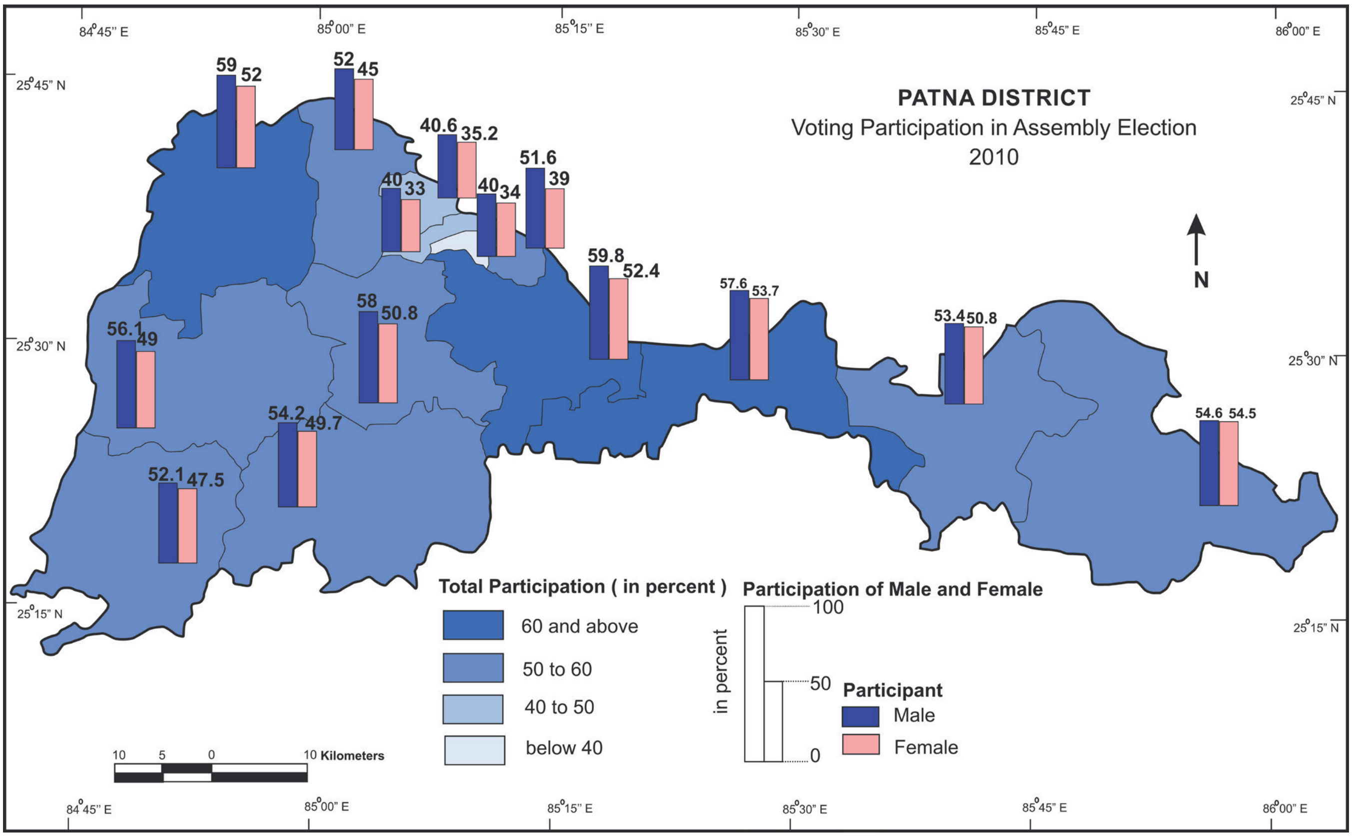

Fig. 3. Voting Participation of Women in 2010 Assembly Election in Patna District

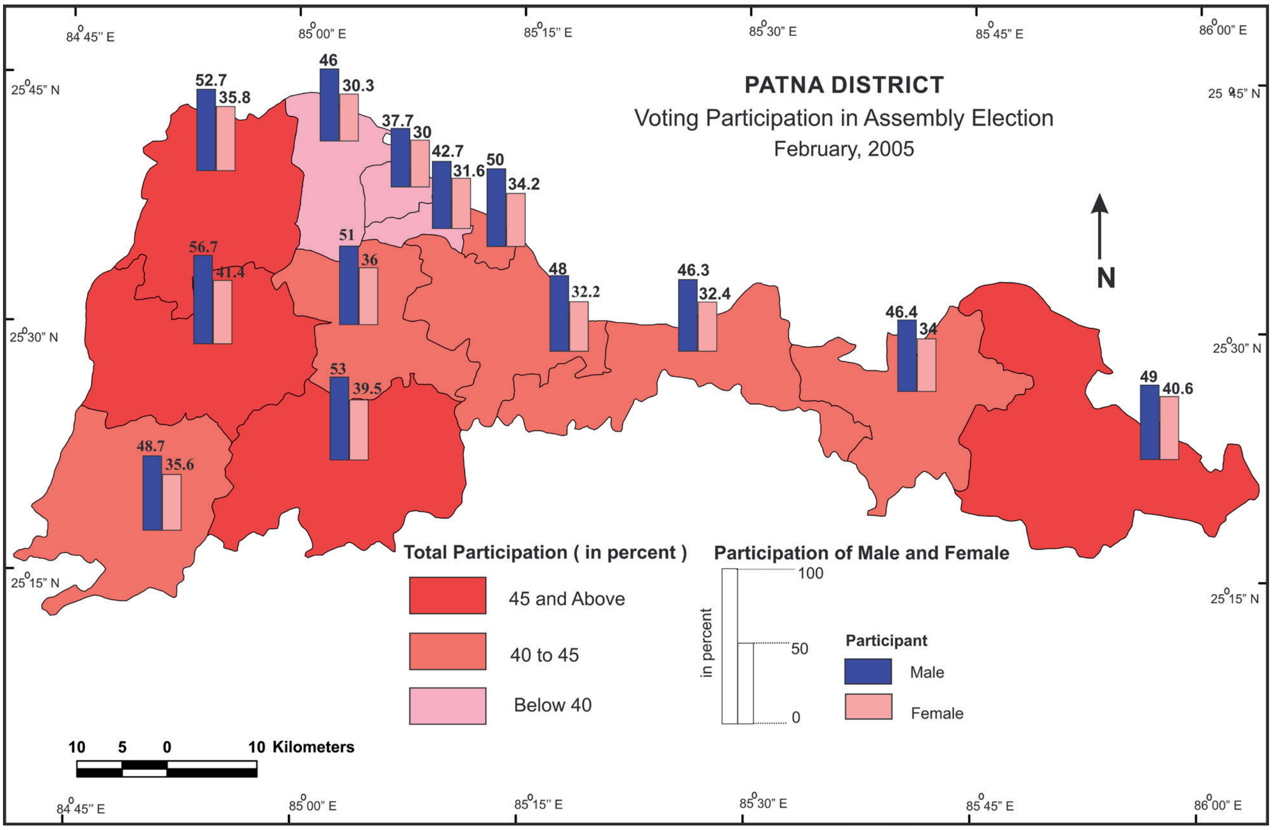

Fig. 4. Voting Participation of Women in October 2005 Assembly Election in Patna District

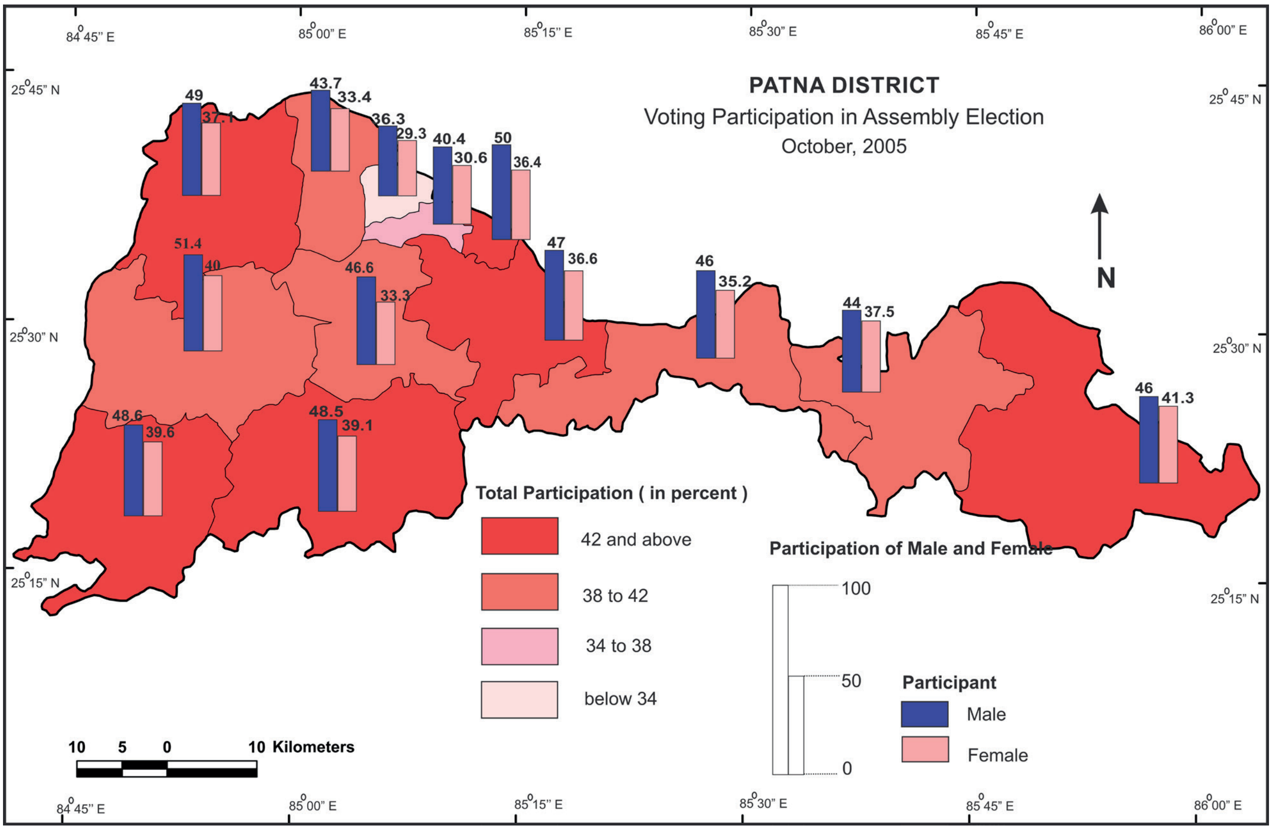

Fig. 5. Voting Participation of Women in February 2005 Assembly Election in Patna District

Female Participation in Voting in Assembly Elections of 2005, 2010 and 2015 in Patna District

The current study is an attempt to find out the role of women as voters in the political system in the study area. In Patna district, female voters comprise a significant share in elections. For the analysis of growth of female participation in electoral politics, the percentage of female voting in each assembly constituency for the assembly election of 2015, 2010, Feb 2005 and Oct-Nov 2005 are calculated. The number of constituencies were different in the assembly elections of 2010, 2015 February and October-November elections. There were fourteen assembly constituencies in 2010 and 2015 assembly elections and thirteen assembly constituencies in 2005 February and Oct-November. The temporal variation shows that there is a rising trend of women voters in each of the assembly constituencies.

Palmer (1976) has pointed out that each voter has their own ideology, political orientation, judgment and expectations which pull them to vote. It is found that the areas with a high voting percentage of male population have a higher voting percentage of female voters too.

This study found that in February 2005 election, male voters had statistically significantly higher voting percentage (48.32 ± 4.83) compared to the mean female

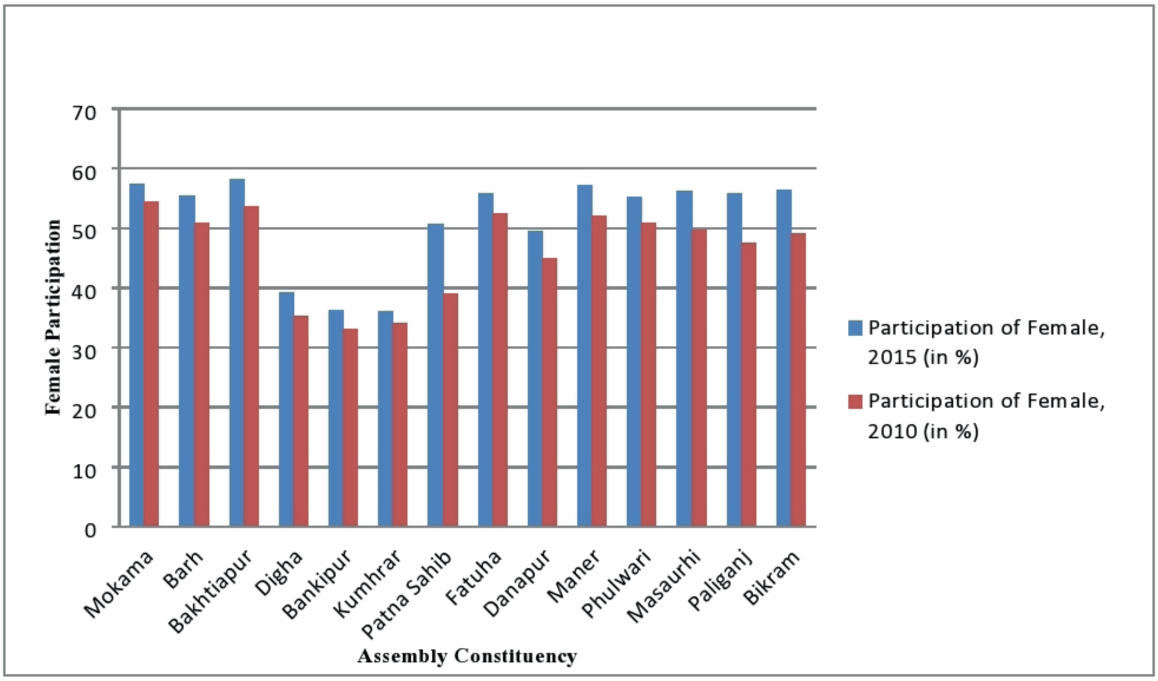

Fig. 6. Female Participation in Voting in Assembly Elections of 2010 and 2015 in Patna District

Election Commission of India 2010, 2015

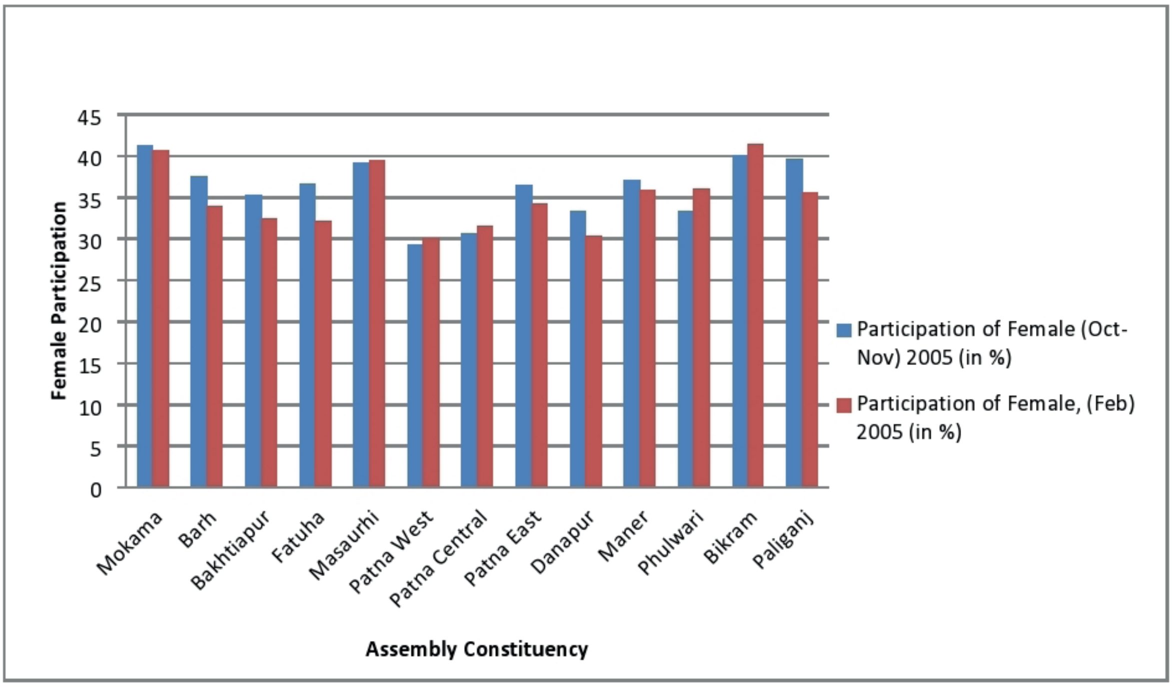

Fig. 7. Female Participation in Voting in Assembly Elections of Oct- Nov 2005 and Feb 2005 in Patna District

Source: Election Commission of India

Table 1. Male and Female Voting Participation in Assembly Elections 2005, 2010, 2015 in Patna District

Assembly Elections	Gender	Mean voting Percentage	Std. Deviation	Sig
Assembly Election 2015	Male	55.20	7.58	0.180
	Female	50.64	9.79	
Assembly Election 2010	Male	52.07	6.94	0.042
	Female	46.19	7.64	
Assembly Election (Oct) 2005	Male	45.96	4.12	<0.0001
	Female	36.11	3.64	
Assembly Election (Feb) 2005	Male	48.32	4.83	<0.0001
	Female	34.89	3.76	

Source: Election Commission of India, Compiled by author

voting percentage (34.89 ± 3.76), t (24) = 7.920, p <0.0001 (Table 1). A significant 9.85 percent of higher voting percentage is observed among male voters (45.96 ± 4.12) compared to female (36.11 ± 3.64), p<0.0001(Table 1). No significant difference in voting percentage is observed between male and female in 2010 and 2015 assembly elections in Patna district of India.

The mean voting percentage for men in 2010 election is (52.07± 6.94) compared to (46.19 ± 7.64), p=0.042 and in 2015 election for men voting percentage is (55.20± 7.58) compared to (50.64 ± 9.79), p=0.180.

Association between Literacy and Voting

A person aged seven and above who can both read and write with understanding in any language, is treated as literate (Census of India 2011). Bihar has a literacy rate of 63.82 percent with male literacy of 73.39 percent and female literacy rate of 53.33 percent, which is lowest in the country. In Patna district, the male literacy rate is 72.57 percent while female literacy rate is 51.04 percent. The literacy rate of sample population corresponds with the State figure. The literacy rate among female respondents is found as 52.9 percent (522/986) whereas 47.1 percent were illiterate. The literacy rate of urban and semi- urban regions is higher than the rural region. It is noticed during the field survey that illiterate voters are not aware about the political system of the country and they don't not have proper knowledge about the candidates. «Mass illiteracy has been a factor of voting behaviour in India. It is because of this weakness of the people that political parties, communal groups and militancy outfits are in position to exploit the sentiments of the votes of the illiterates constitute a big proportion of the votes polled and hence they play a big role in determining the outcomes of elections» (Akhter and Sheikh 2014).

Research done in many countries suggest that education and social status of individuals are major determinants of political participation (Nor, Gapor and Bakar 2011).In the study area both literate and illiterate groups are conscious about their voting rights. However, it was found that 97.8 percent of all illiterate population is registered voters and regular compared to 93.7 percent of literate population respectively. In both literate and illiterate groups, it was found that socio-economic development and willingness to practice voting right is the main reason behind casting their vote.

Table 2. Association between Literacy with Voting

Association of Voting		Illiterate	Literate	Total	Chi Value	sig.
		464 (47.1%)	522 (52.9%	986 (100.0%)		
Not registered Voter		10 (2.2%)	33 (6.3%)	43 (4.4%)	10.225	0.001
Registered Voter		454 (97.8%)	489 (93.7%)	943 (95.6%)		
Irregular Voter		117 (25.2%)	137 (26.2%)	254 (25.8%)	0.136	0.712
Regular Voter		347 (74.8%)	385 (73.8%)	732 (74.2%)		
Voting Motivation	Motivation	99 (21.3%)	32 (6.1%)	131 (13.3%)	52.874	<0.0001
	Practicing Voting Right	142 (30.6%)	196 (37.5%)	338 (34.3%)		
	Development	204 (44%)	257 (49.2%)	461 (46.8%)		
	Social Security	7 (1.5%)	8 (1.5%)	15 (1.5%)		
	Others	12 (2.6%)	29 (5.6%)	41 (4.2%)		

Source: Sample Survey, 2018

Voting is the easiest way to raise your voice. People must have adequate information about communicating their preferences to elected representatives. If they did not know about their political preferences they would have no motivation to engage in political deliberation (Bhatia 2013). Voting motivation varies from person to person; some people are motivated by the fact that voting is their civic duty, while others may vote for development, and social security.

Nowadays women are casting their vote more frequently, and in greater numbers, which is a remarkable turn of event in a deeply patriarchal, conservative society.

Motivational Constraints

According to Banerjee (2017), elections are not only cultural but also a moral event. People come to vote even though one vote is immensely small, but it has immense value. The quality of democratic choice critically depends on the voter's motivation. If voters are motivated, voting may result in smart choices because of information aggregation.

A total of 40.1 percent (395/986) the participant has faced motivational constraints compared to 59.9 percent who did not face any motivational constraints. Motivational constraints include lack of education, not liking the candidates, no faith in political parties, dissatisfaction from the government and political apathy etc.

Figure 8 show that 30 percent of women from rural areas, 47.4 percent from semi-urban and 53.5 percent from urban areas reported that they faced motivational constraints. 48.5 percent in Mokama, 29.7 percent in Barh, 7.8 percent in Bakhtiarpur, 44 percent in Paliganj, 47.8 percent in Bihta, 11.5 percent in Bikram and 53.9 percent from Bankipur stated motivational constraints.

Situational Constraints

It is one of the factors which accounts for differences in voter participation from place to place. Among the respondents, 48.6 percent (479/986) responded as they face situational constraints such as distance of home from polling booth, long queue, domestic responsibilities, and poor health condition during elections, and not living in the home town etc. Bihar, in past, has witnessed intimidation of vulnerable sections for voting in favour of particular political establishments (Yadav 2004).

Sometimes sporadic violence on the polling day prevents the people from casting their vote. 51.4 percent who did not face situational constraints during the elections. According to figure 9, 55 percent from urban areas, 54.9 percent from semi- urban areas and 42.5 percent in rural areas faced situational constraints. 55.8 percent from Mokama, 34 percent from Bakhtiarpur, 56.4 percent from Maner and 47.4 percent from Digha faced situational constraints during voting. It is reported that longer the line at the polling booth, the greater the likelihood that voters will become frustrated and leave before voting. Secondly, distance from polling booths discourages voter turnout in the study area.

Challenges of Electoral Empowerment of Women

The biggest challenge is the less representation of women in political parties. Women are still struggling for increased political participation (Alam 2015). Bihar is a least literate state in the country as per Census of India, 2011. The literacy rate among the women is 53.3%. The level of awareness among electors is closely associated with level

Table 3. Motivational and Situational Constraints

	Illiterate	Literate	Total	Chi Value	Sig.
Not faced motivational constraints	301 (64.9%)	290 (55.6%)	591(59.9%)	8.877	0.003
Faced motivational constraints	163 (35.1%)	232 (44.4%)	395 (40.1%)		
Not faced situational constraints	244 (52.6%)	263 (50.4%)	507 (51.4%)	0.477	0.49
Faced situational constraints	220 (47.4%)	259 (49.6%)	479 (48.6%)		

Source: Sample Survey, 2018

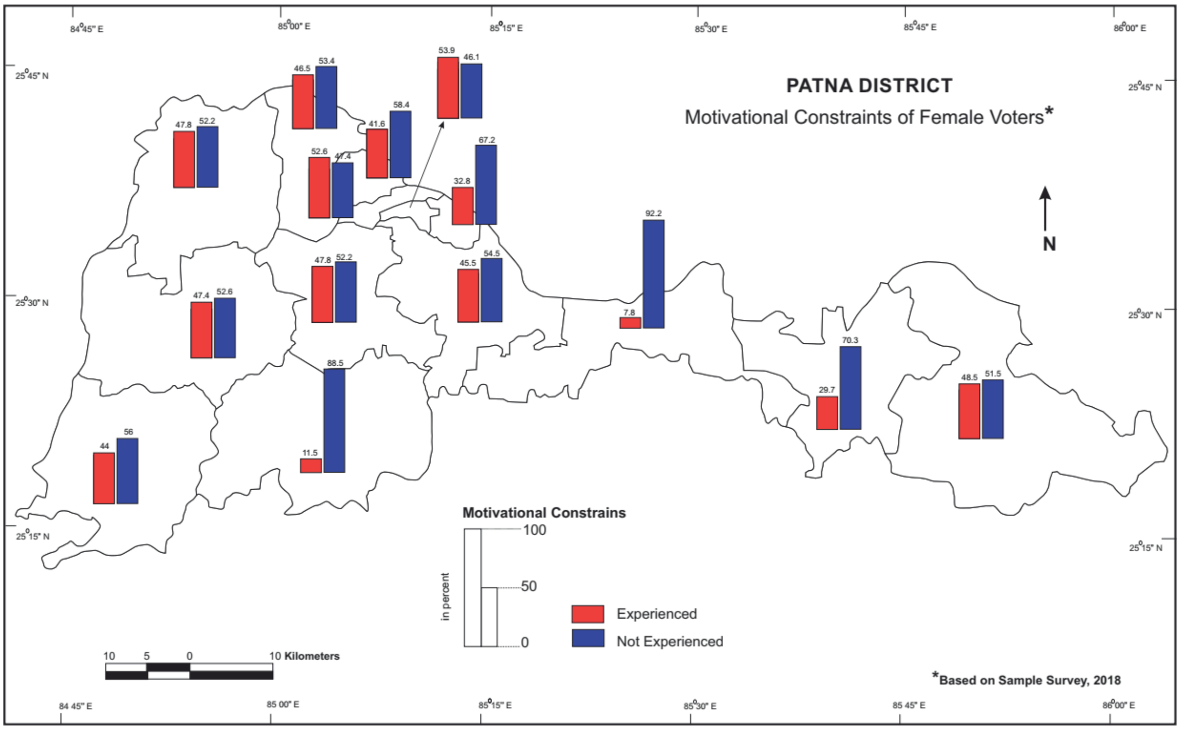

Fig. 8. Motivational Constraints of Female Voters in Patna District

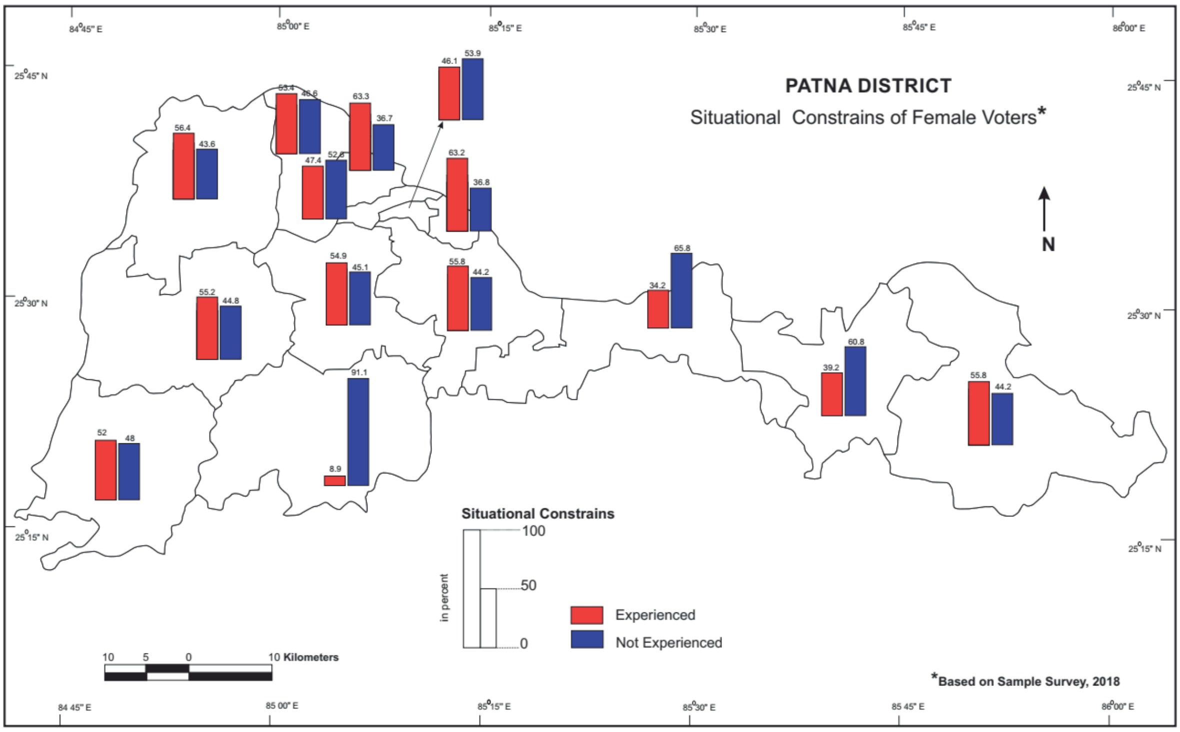

Fig. 9. Situational Constraints of Female Voters in Patna District

of education (Dahlerup D. 2005). Nevertheless Bihar is having a patriarchal society, where women are often seen as subordinate and inferior to man.

Apart from this there is a big gap in the registration of women in electoral rolls. Enrollment of women is not given priority due to the lower status of women in the society. The electoral roll gender ratio is not in consonance with the census gender ratio. The census gender is 918 whereas the electoral roll gender ratio is 875 in the 2015 assembly election. Cultural inhibition is also included in the challenges of women's electoral empowerment. Women do not come out of their home without the permission of the head of the family. In general, women still want a male member to go outside or to the polling station.

CONCLUSION

The above discussion summarizes that the active political participation of women in politics is very important to achieve United Nations Sustainable Development Goal Five. The research work tries to explain the electoral empowerment of women with reference to Patna District, more specifically to examine spatio temporal pattern of women's participation in assembly elections of 2005, 2010 and 2015. Increase in the temporal pattern of women's participation in elections is evident from the study; however, the growth rate of the women voting percentage is less than that of men. Increase in the voting shows that women in the study area are getting politically empowered. Bihar scored 40 out of 100 in SDG 5 with rank 17 among all the states. Amid all the 17 Sustainable Development Goals (SDGs) laid out by the United Nations, SDG 5, which stands for gender equality has been the toughest to fight and establish in India. Except Chandigarh, Sikkim, Kerala, Andaman and Nicobar Islands – all other states lie in the red zone or the «aspirant zone» according to the latest reports by SDG India Index Baseline Report (2019).Women empowerment and gender equality is very essential for human development so it must be integrated with all the SDGs. ■

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ENVIRONMENTAL CONSEQUENCES OF URBAN EXPANSION: CASE STUDY OF ENVIRONMENTAL LICENSING PROCESSES IN THE MUNICIPALITY OF GOVERNADOR VALADARES

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ABSTRACT. Urban growth is often accompanied by significant environmental changes, which include modification of the natural landscape and the problems related to it, such as real estate speculation, marginalization of the population, landslide risks, flooding, as well as pressure on environmentally protected areas. Therefore, it is necessary to understand how will new urban development affect the already modified space without generating further environmental problems. The research aimed to analyse five projects of allotments in Governador Valadares/Brazil between 2015 and 2017. Besides the information on the projects themselves, geographic information systems (GIS) were used along with laws and bibliography. The biggest obstacle observed was the lack of standardization in the process required by the City Hall, which culminated in projects with different characteristics, including those that did not present important analyzes, such as the Civil Construction Waste Management Plan. It is necessary to move forward in discussions related to urban environmental sustainability, standardizing the possible actions, not only in the municipality of Governador Valadares.

KEY WORDS: environmental impact assessment; sustainable city growth; urban planning; environmental urban planning

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INTRODUCTION

In the second half of the twentieth century with the growth of the economy and the creation of numerous jobs in the cities, the Brazilian population started the movement of internal migration, leaving the countryside and settling in the cities. During this period, Brazilian cities grew enormously and soon they concentrated around 50% of the country's population (Grostein 2001).

This process culminated in the formation of large urban centers, which has led to several negative consequences, such as real estate speculation, marginalization of the population, landslide risks, flooding, as well as pressure on environmentally protected areas (Alberto 2009; Stanganini & Lollo 2018).

In order to fulfil the population demands, the civil construction sector increased enormously. The sector started to influence the dynamics of cities, either by consolidating the pattern of urbanization marked by environmental problems or by creating new concepts of urban development in which environmental and safety standards are placed as differentials against traditional forms of construction. The first, without taking into account existing environmental standards repeatedly go through attempts of adaptation in processes of land tenure regularization, implementation or adaptation of urban afforestation. The second is usually the result of projects that claim to emerge from a sustainable base. But what makes these ventures sustainable or not?

In that context, some macro policies have been developed in Brazil in an attempt to remedy the existing problems in the urban environment such as the Statute of Cities in 2001. The norm aimed to consolidate the role of municipalities as agents that promote the adoption and implementation of the instruments to optimize and boost the development of urban areas, such as the Master Plan and Environmental Zoning, as well as others that aim to ensure the sustainability of processes, such as the Environmental Impact Assessment for projects in the urban area (Brazil 2001).

The Forest Code itself (Federal Law No. 12,651 / 2012 – Brazil 2012) brings important considerations about the importance of environmental preservation in rural and urban areas but fails to define how permanent preservation areas in urban areas should be treated.

Other regulations, like the Resolution of the National Environment Council (CONAMA) No. 369 (BRAZIL 2006), try to standardize the cases in which there may be an intervention in permanent preservation areas (APP). However, the overlap or gaps in the legislation allows different interpretations which ends up limiting the effective application of normative instruments (Fardin et al. 2018).

The concern with these problems reached such a point that it became the subject of discussion at United Nations conferences and was later included as one of the Sustainable Development Goals (SDGs), particularly SDG 11. The objective establishes that urban areas must reinforce planning instruments at different scales, reducing the impact on the environment, ensuring resilience for cities and better quality of life for the population.

The guarantee of the existence of sustainable cities comes up against the very definition of sustainability. Heloisa Costa, when discussing concepts related to environmental sustainability, states:

it can be said that the concept of sustainable development has been transformed into a huge «umbrella», capable of harboring a wide range of innovative, progressive proposals / approaches, or that, at least, move in the direction of greater social justice, improvement of the population's quality of life, more dignified and healthier environments, commitment to the future. Such comprehensiveness, if, on the one hand, has the merit of «basing» initiatives and proposals from different origins, on the other, by showing the imprecision of the concept, it tends to trivialize it, to transform it into a piece of rhetoric and, therefore, unsustainable by definition. (Costa 1999 p. 8)

Urbanization involves legal, administrative, environmental and social aspects, which should, at least in theory, go together in order to guarantee sustainability, especially in the development of new urban areas. Brazil already has some legislation that aims to guarantee such improvement, particularly Federal Law no. 10.257 / 2001, which creates the City Statute, and Federal Law no. 6.766 / 1979, which regulates the division of urban land (Brasil 1979 & 2001). All those laws and regulations together are used in the Environmental Impact Assessment of urban allotments.

The different interpretation of the procedure and analysis of environmental impact assessment has direct consequences on the environment. Ribeiro & Vasconcellos Junior question «what is the extension of the failures and flaws of the AIA that affect its effectiveness in the Brazilian environmental licensing process»?

The Guide «How to build more resilient cities», a document published by the United Nations, does not give details on what it considers to be sustainable development, stating that each city should build this concept based on the existing context (United Nations 2012). In this state of uncertainty about which concept would be more appropriate, this work, however, does not intend to define that concept.

Silveira et al. (2020) point that, although the sustainability concept is not very well defined, to accomplish long term economic and environmental stability it is necessary to integrate and acknowledge concerns about economic, environmental and social consequences. Besides, urban expansion needs to be supported by other policies. Standards should be well defined and analysed in all fields (Amado 2018)

In this context, it becomes necessary to gather information that can support the future development of this important concept that can impact not only the environment but also the safety of those who live in cities. In this sense, the present work sought to analyse the processes of environmental impact assessments of allotments in Governador Valadares during the period from 2015 to 2017. The highlights were correlated to urban sustainability in order to understand the impact of the projects' approval at the city scale. The study also aims to contribute to the reflection on the importance of clearer definitions in environmental policy worldwide.

MATERIALS AND METHODS

The study has been developed based mainly on the analyses of five impact assessment studies of allotments located in Governador Valadares/MG/Brazil. Along with the study of the existing research and the analysis of secondary data from the study area, this information was used to reflect the impact of urban growth on the environment and sustainability.
The process of research included the following stages:

- First, relevant data were gathered from bibliographic research, starting with laws (federal, state and municipal), city documents and other legal papers. Information from the existing research literature was also analysed, which allowed to compare the Brazilian Standards with other studied areas;
- After that, the study period of two years was selected due to the large number of documents that were included in each assessment, which were also stored in paper at the City Hall. Once the impact assessment projects were chosen, the obtained data were reviewed, summarized and analysed qualitatively. Classes for the analysis were selected based on the correlation to sustainable development and included such parameters as water demand, protected areas and sanitation;
- Also, data containing shapefile maps of the urban area, hydrography and neighbourhoods were gathered from the Brazilian Institute of Geography and Statistics (IBGE) database. These data were integrated, reviewed and processed through GIS (Geographic Information Systems) in order to extract information relevant to the interest areas and correlate it with the data on the allotments;
- Finally, data interpretation and generation of thematic maps were done to obtain the results of the study, based on which certain recommendations were given.

Area description

The municipality of Governador Valadares was chosen because it is considered a medium-sized city[1] with a population of 245,125 inhabitants. The selection was also made based on the existing infrastructure, expansion opportunities, goods and services available.

The city initially emerged from an instalment plan, which expanded without proper planning, resulting in several irregular settlements and numerous environmental problems. It suffers from recurrent flooding, even when the rainfall does not occur in the municipality (Genovez et al. 2012; Prefeitura Municipal de Governador Valadares 2015), and is also characterized by high temperatures throughout the year, which creates discomfort for the population.

The city is located in the central watershed region, on the banks of the Doce River, which is its main water source. In 2015 with the collapse of the Fundão tailings dam the city suffered from a lack of water due to the high demand and inability to pump water from the river.

The present study analysed all the licensing processes for the urban subdivisions located in the municipality of Governador Valadares from January 2015 to December 2017, which included a total of five allotment projects (Figure 1), in order to verify if these projects were planned by the entrepreneur and evaluated by the environmental agency on a sustainable and standardized basis.

[1]Water grant is a term used in Brazil that refers to the right to use a specific amount of water for a determined period of time.

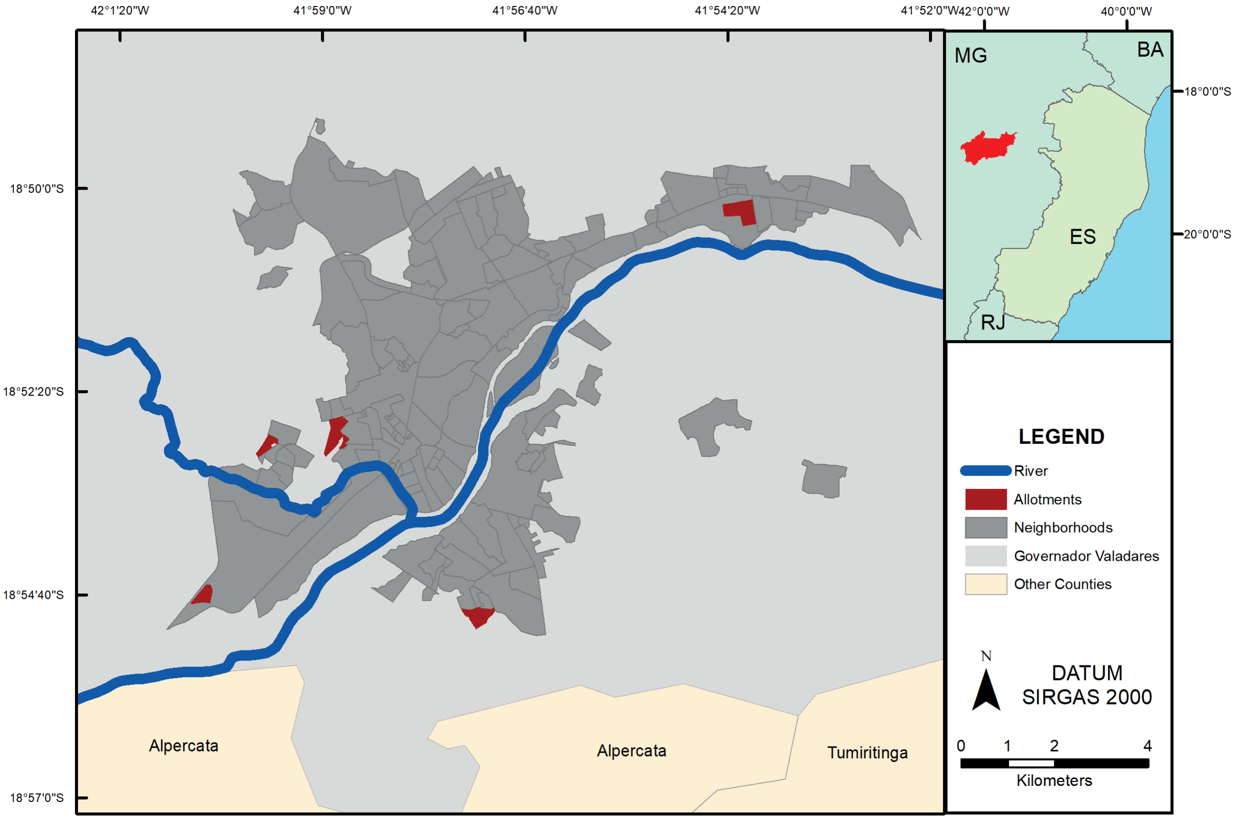

Fig. 1. Location map of the analysed allotments in relation to neighbourhoods in Governador Valadares (MG)

RESULTS

Allotments impact assessment in governador valadares from 2015 to 2017

To understand the concept of sustainability is important to recognize that it is not relativistic as the Earth's biophysical limits are absolute (Fischer et al. 2007). Based on this statement, various impacts cannot be analysed apart from each other. Another challenge is to adapt to different social, cultural and political contexts, which can be challenging with different impact assessment rules not only in Brazil but in many countries. To illustrate these points, we present the results of five recent impact assessment projects of allotments, analysing not only their effects separately but the combination of all of them.

Integrated water demand planning: pleading for projects x municipal water grant[1]

In order to estimate the impact of the subdivisions on the city's water demand, calculations were made to identify the volume of water that is spent by the allotments. This calculation took into account the demand per inhabitant per day for residential[2] and commercial[3] lots and its results are shown in Table 1.

Table 1. Estimated water demand for the studied allotment projects

VENTURE	LOTS QUANTITY	ESTIMATED VOLUME (L/DIA)
01	20 unidades	8,550
02	476 unidades	270,368
03	208 unidades	118,144
04	452 unidades	256,736
05	211 unidades	119,848
Total	1,367 unidades	776,456

[1] Water grant is a term used in Brazil that refers to the right to use a specific amount of water for a determined period of time.
[2] The calculation was based on the values in Annex C of the Technical Standard of the Basic Sanitation Company of the State of São Paulo (Sabesp) NTS 181 (Basic Sanitation Company of the State of São Paulo 2017) and performed by determining the arithmetic mean between the values water consumption per day stipulated for: residences (95L / per capita / day), luxury residences (165L / per capita / day), apartments without individualization (127.5 L / per capita / day), apartments with individualization (100L / per capita / day) and luxury apartment (222.5 L / per capita / day). This value was multiplied by four, the average number of people in a household estimated by the Brazilian Institute of Geography and Statistics, which gave a total consumption of 568 L / lot / day (Brazilian Institute of Geography and Statistics 2008).
[3] The calculation was based on the values contained in Annex C of the Technical Standard Sabesp NTS 181 (Basic Sanitation Company of the State of São Paulo 2012) and performed by determining the arithmetic average between the consumption of water day stipulated for: outpatient clinics (22.5 L / service / day), public or commercial buildings (40 L / per capita / day), full-time schools (45 L / per capita / day), boarding schools (95 L / per capita day), schools by term (22 L / per capita / day), offices (40 L / per capita / day), sewing workshops (40 L / per capita day) and auto repair shops (75 L / per capita / day), averaging at 47.5 L / per capita / day. This value was multiplied by the maximum number of people in a microenterprise (9 employees), just for comparison purposes, which generated a demand of 427.5 L / lot / day.

Based on the grants issued by the National Water Agency (ANA) to the municipal water and sewage services concessionaire in the period of execution of the projects, a volume of 2,007,433.98 m³/day[1] was granted in the «right to use» category for the city of Governador Valadares. The total sum required by the five allotments is equivalent to 776,456 L / day or 776.45 m³, which is less than 1% of the total amount.

However, some questions need to be considered about the existing situation as well as the individual and collective effect of these ventures on the environment. According to Directive 2000/60/EC of the European Parliament, which establishes community actions on water resources policy, when planning the possible uses of water it is necessary to think about the best environmental option, taking into account the technical feasibility and the associated costs to the project (European Union 2000).

In this context, a question about granting of the right to use water for supply arises. Is there a maximum growth limit for a municipality? Would the growth limit be determined by the maximum regional environmental supply range? Growth limits must involve perceptions of risk associated with growth, taking into account favorable and unfavorable scenarios, and involve the population, industries and government in decision-making so that the decision is beneficial to all.

According to the document of Raworth (2012) titled «A safe and just space for humanity», the planet presents growth boundaries that need to be respected, some of which have already been crossed. The relationship is complex as it involves limits that are not always defined by countries' physical barriers but need to be defined in favor of the safety of life on the planet.

Thus, thinking about water demand in isolation no longer makes sense, it needs to be considered in a larger context in order to guarantee the city's resilience. Tucci (2009) states that integrated water management in the urban environment is essential for the development of cities. According to the author, the city is part of a large hydrographic basin, which can be composed of several sub-basins, and needs to be concerned with the water it draws and returns to rivers since these are factors external to the perimeter of the city, but which interact and influence its dynamics and, therefore, need to be analyzed together (Figure 2).

An instrument that can assist in these definitions is the collective granting of water use. In this type of authorization, the right would be granted to a group of users, not just to a beneficiary.

Tamburino et al. (2019) say that when individuals make choices towards collective action there is a better long-term outcome for everyone. Spolidorio (2017) states that negotiated water allocation has the potential to strengthen the processes of water use, generating effective social participation and making the water users regulate themselves.

Municipal sanitation

With regard to the release of sanitary sewage, the municipality has a right to use grant for this type of release of 13,547.58 m³ / day[2]. If we take into account that 80% of the collected water is discharged in the form of sewage, the five allotments together generate 621.16 m³ of sewage water per day, which is also little compared to the discharge limit granted.

However, according to the National Water Agency (ANA), in 2013 the municipality of Governador Valadares had 95.4% of the sewage water collected, but not treated (National Water Agency 2017). Currently, the city has only one sewage treatment plant (ETE), the ETE Santos Dumont, which is still under construction and upon completion should meet about 75% of the municipality's demand. In this sense, although the discharge may seem insignificant, it will put even more load on a system that is already below the expected environmental conditions.

In this scenario, would it be feasible to ask the entrepreneur to treat the sewage generated by his subdivision? One possible idea would be to create a decentralized sewage treatment system. Some authors point out that decentralized water and sewage systems can offer benefits such as less vulnerability to extreme events, accidents or disasters (Capodaglio 2017), which could contribute to increasing the resilience of a city that is already experiencing problems on a recurring basis.

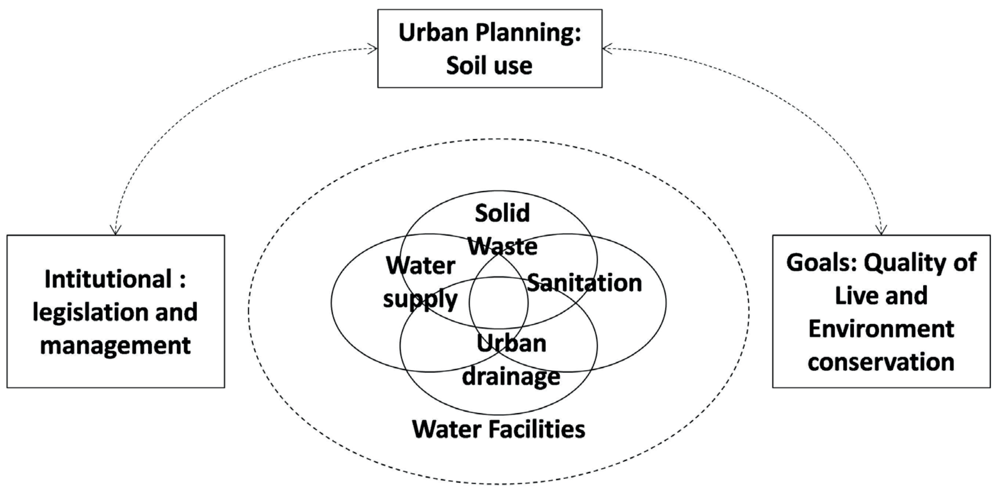

Fig. 2. Components of Integrated Urban Water Management. Source: Tucci (2009)

[1]Interference codes 817773, 817772, 817755 and 817754, issued on behalf of the Autonomous Water and Sewer Service, in the right to use category. The value given in annual volume in m³ was transformed into daily values for comparison purposes. Available at: http://www.ana.gov.br. [Accessed 20 Oct. 2019].

[2]Interference codes 881061 and 881042, issued on behalf of the Autonomous Water and Sewage Service, in the preventive category type of sewage release. The value given in annual volume in m³ was transformed into daily values for comparison purposes. Available at: http://www.ana.gov.br. [Accessed 10 Oct. 2019].

Regarding the costs for implementing the system, it is necessary to compare the costs of treatment in loco with the costs of transport (construction of the network) of this effluent to a possible ETE. Recently, the installation of decentralized systems has become increasingly more attractive, as they use simpler technologies and end up making the systems competitive with affordable cost (Jorsaraei et al. 2014; Capodaglio 2017), however, it needs to be taken into account at the time of project development.

It is worth mentioning that the intent here is not to suggest a way of solving the mentioned problems but to contribute to discussions that may assist in more sustainable growth.

Lower urban density also impacts the costs of installing the needed infrastructure after allotments have already been built (Monkkonen 2013). Besides, when the sewage is released into the public systems, the costs of its treatment are no longer of sellers/buyers become of all the citizens, which is a transference of environmental costs (Braga 2013).

Protected territories: preservation areas, vegetation removal and urban afforestation

Municipal Complementary Law No. 187/2014 (Prefeitura Municipal de Governador Valadares 2014b) states that intervention in the Permanent Preservation Area (APP) is only allowed in the case of social interest, public utility or low environmental impact. Although one of the developments (05) is located in an area declared by law to be of social interest, there was no request to remove vegetation located in APP.

There was a request to remove vegetation by Allotment 04, but the area is not located in APP. The entrepreneur indicated the existence of an area of 50 m^2 with the presence of exotic tree vegetation, Leucaena leucocephala (Lam.) of Wita being the predominant species. Suppression was authorized and the Suppression and Final Destination Report was requested.

Although the size of the area to be removed is small compared to the area of the allotment, it is necessary to analyze the standard adopted by the city which takes into account a larger scale. As stated in several minutes of the Municipal Council for the Defense of the Environment (CONDEMA)[1], there are also other areas requesting and receiving approval for suppression of vegetation in the municipality.

The suppression of vegetation, although not located in APP, leads to a decrease in the infiltration of rainwater, which may contribute to the occurrence of problems during rainy periods (Fardin, et al. 2018). The removal of vegetation creates even more impermeable surfaces, generating changes in runoff and drainage (Santos & Haddad 2014). Studies indicate that when green and permeable areas are increased compared to conventional urbanization, it leads to a decrease in peak flow (Tavanti & Barbassa 2012), which would be extremely beneficial in the case of the municipality of Governador Valadares, considering its flooding history, in addition to several other ecosystem services.

Consequently, regardless of the possibilities for suppression that exist in the legislation, it is essential to consider the dynamics of the water resources existing in the hydrographic basin prior to the approval of a new vegetation suppression.

With regard to urban afforestation, Municipal Law n°178 (Prefeitura Municipal de Governador Valadares 2014a) indicates that spaces for public use in the new subdivisions, including leisure and reforested areas, should comprise at least 12% of the total area of the allotment. The delimitation of these areas can be observed in the Environmental Control Report (RCA) of all allotments.

This distribution of areas leads to questions about the effectiveness of this action. Although the law does not define that the 12% should be planted in a continuous area, studies indicate that planting trees in impermeable areas imposes stress on the plant, which could be solved with the use of permeable pavement nearby (Mullaney et al. 2015) or by planting continuous areas without the presence of any type of paving. Thus, the suppressed area, although small, would be part of a broader context of ecosystem services. According to Endreny (2018), for every $ 1 invested in urban afforestation, there is an average return of $ 2.25, which does not encompass all the possible benefits generated. The author puts this in number:

London's urban forest is estimated to have 8,421,000 trees, generating annual benefits of 132.7 million pounds (not including all services), a replacement cost of 6.12 billion pounds and a value for convenience of 43.3 billion pounds. The London study was extrapolated to the megacities of Beijing, Buenos Aires, Cairo, Istanbul, Los Angeles, Mexico City, Moscow, Mumbai and Tokyo and estimated that the annual benefit of forests in these metropolitan areas had an average annual value of US $ 505 million, the potential to achieve nearly $ 1 billion in annual benefits and an additional $ 7.9 billion in total carbon storage value. (Endreny 2018)

Despite the benefits of urban afforestation, which also include improved water infiltration in the soil, increased landscaping, a better sense of well-being by the population and positive changes in the local microclimate, only three of the projects (01, 02 and 05) stated a plan to plant trees on the sidewalks, although indicating only the minimum presence of 12% of green areas.

The allotments in relation to the Municipal Zoning and the City Plan

Complementary Law No. 201/2015 (Prefeitura Municipal de Governador Valadares 2015), which provides guidelines for the use and development of urban and rural land in the municipality of Governador Valadares, establishes that to expand, build or start some type of activity in urban or rural areas of the city, depending on the location of the project, environmental studies may be required by the executive bodies to prevent negative impacts resulting from this implementation. Because of this, the studied allotments were analyzed in order to identify which type of area they occupy (Table 2).

Table 2. Location of the allotment projects under study in relation to the Municipal Zoning of Governador Valadares

Venture	ZONE	CHARACTERISTICS	
		LOTS QUANTITY	GOAL
01	Urban expansion zone	20	Commercial
02	Urban expansion zone	476	Residential
03	Urban expansion zone II	208	Residential
04	Water influence zone	452	Residential
05	Social interest housing zone II	211	Residential

[1]Available at: http://www.valadares.mg.gov.br/detalhe-da-materia/info/conselho-municipal-de-defesa-do-meio-ambiente-codema/12036. [Access 05 Mar. 2020].

Although all the analyzed allotments have environmental studies approved by the city hall, according to the current legislation, every allotment must have a previous study, which indicates the possibility of development in the previously defined location. However, no documents were found to prove the existence of this prior analysis.

Allotments 01, 02 and 03 are located in Urban Expansion areas, these areas are located within or contiguous to the perimeter considered urban and present good natural conditions to be occupied. The legislation states that the urban parameters should be defined at the time of formalizing the request.

Allotment 04 is located in an area defined as the Water Influence Zone and differs from the other areas, as it is located close to the Doce River and is influenced by the rainfall regime during the rainy season (Prefeitura Municipal de Governador Valadares 2015). According to the legislation, these areas must have specific construction criteria that guarantee lower density compared to the other areas of the city and greater permeability between the constructions.

This point needs to be addressed more carefully by the entrepreneur and the licensing agency since, as it was previously said, the municipality has numerous records of floods in its urban perimeter (Genovez et al. 2012; Prefeitura Municipal de Governador Valadares 2015).

In this sense, the projects were analyzed based on a study carried out by the Mineral Resources Research Company in conjunction with the National Water Agency and the Minas Gerais Water Management Institute, which defined the floodplain of the city of Governador Valadares based on previous rainfall observations and application of a hydraulic model (Figure 3).

From this study, it was possible to observe that four out of five analyzed allotments are located within the floodplain of the river, two of them in areas with a high risk of flooding, which, considering a return period of less than ten years, are frequently flooded.

The report, which dates back to 2004, recommends that changes should be made to the municipality's Territorial Zoning, suggesting that in areas with a high chance of flooding there should be only territories intended for public leisure use, such as parks and squares, while the areas with a medium and low possibility of extreme events (TR between 10 and 100 years and TR> 100 years) should be occupied by buildings that do not suffer significant losses in case of a flood event, including houses and commercial establishments (Mineral Resources Research Company 2004). However, despite the recommendations, the City Hall continues to carry out allotment projects in floodable areas.

The flooding problem in the municipality is so recurrent that in a study carried out on the perception of floods by the residents of the municipality, it was shown that the population, although not living in risk areas, signaled some problems related to floods (Amorim et. al. 2018). Affected residents also reported problems such as «bad smell, contamination, disease» and claim that flooding affects the quality of life in the city.

Analysis of expected environmental impacts and adopted measures

Table 3 presents a summary of the main impacts expected during the installation and operation phase of the studied subdivisions according to the entrepreneur's manifestation in the documents presented and the requirements of the environmental agency.

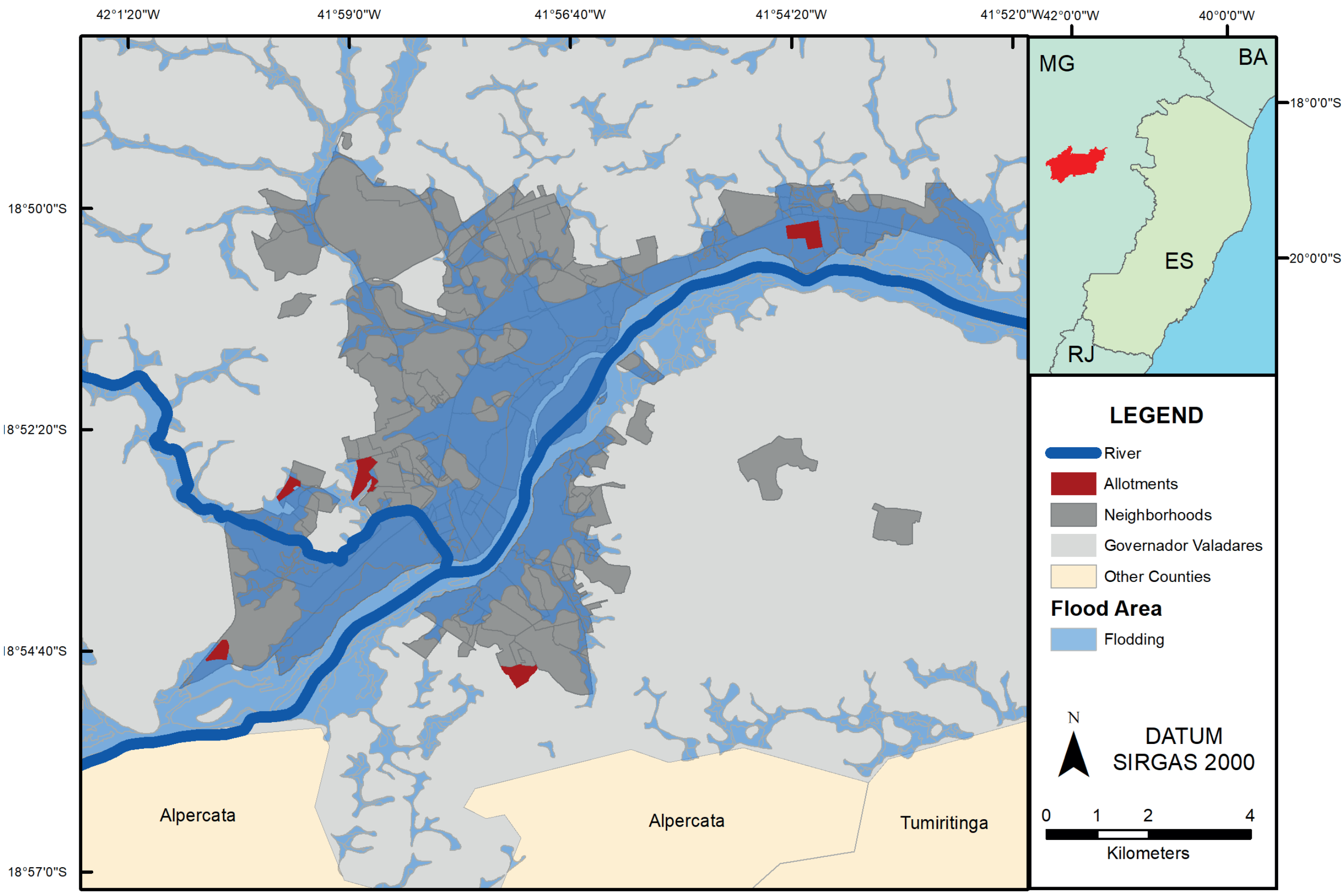

Fig. 3. Floodable channel of the Doce River within the municipality of Governador Valadares, with emphasis on the analysed neighbourhoods under analysis

Table 3. Main expected environmental impacts in the installation and operation licenses of the analysed subdivisions

NEGATIVE IMPACTS				
Venture	Soil compaction and erosion	Emission of air pollutants	Alteration of the original vegetation	Generation of construction waste
01	X	X	X	
02	X	X	X	
03	X	X		X
04		X	X	
05	X	X	X	

Soil erosion and compaction are characteristic impacts of allotment activities, which are caused by the processes of cleaning the allotment, removing the existing vegetation cover and earthwork procedures (Pereira 2015). Except for allotment 04, the other studies, in addition to mentioning these impacts, attached a list of measures that would be taken to control these processes.

Allotment 04 has not stated that this impact will occur, however, it included procedures similar to those that will be developed in other areas, particularly leveling of the occupied areas with the use of trucks and other earthmoving equipment. Therefore, there remains a doubt regarding the information provided as well as the own analysis of the environmental agencies, which did not take this impact into account.

Roedel & Dias (2018) when analyzing impact assessment studies of allotments in Brusque/SC also indicated that all of the three projects were going to cause problems related to soil movement, including erosion. It is even more concerning in a city, which was already affected by a massive amount of sediments coming from the disruption of the Fundão dam, and indicates the need to rethink the minimum content of impact assessment for the allotment projects. This is especially important because different views of the professionals who carry out the analysis can lead to different assessments, which may be the result of the professional's training often prioritizing training in their main field at the expense of complementary training for analysis and interpretation of environmental impact assessments (Morgan et al. 2012).

Another environmental impact quite common in allotment projects is the emission of air pollutants in a form of particulate matter. All projects indicate the presence of this impact, particularly during earthmoving processes in the installation phase and from car circulation in the operation phase in which the facilities will be built, while no circumvention measures have been suggested.

Air pollutants control is very important because it affects not only the site but also the entire neighborhood, as harmful substances can be transported far from their original location. If not considered in advance, mitigation or control measures can fail, exposing the population to pollution (Lollo & Rohm 2009). To reduce this potential impact all the projects suggested sprinkling area with water.

However, none of them suggested anything for the operation phase, indicating that at this point the entrepreneur is not responsible and impacts are controlled by each individual construction site. Although it is permitted according to the legislation, this issue raises some concerns as it is completely different to evaluate one separate construction compared to 476 like in Allotment n. 02. If all the studied allotments are taken into account, the number of new construction sites reaches 1367.

All these activities have great potential for generating waste, especially Civil Construction Waste (RCC). RCC is generated during construction activities, such as land preparation, excavation and other actions that generate material with polluting potential. CONAMA Resolution No. 307 states that this material must be disposed according to the Municipal Construction Waste Management Plan, which «will aim to establish the necessary procedures for the environmentally appropriate handling and disposal of waste» (Conselho Nacional de Meio Ambiente 2002 & 2012a).

The municipality of Governador Valadares has Complementary Law No. 167/2013 institutes the Plan, which states that the person responsible for generating the waste must carry out its correct characterization, sorting, packaging and transportation (Prefeitura Municipal de Governador Valadares 2013). Even so, only Allotment 03 reported that Civil Construction Waste (CCW) will be generated.

This lack of indication of the generation of waste leads to numerous questions, such as: Who is responsible for the absence of this information in the licensing process, entrepreneur or inspection agency? As a management plan was not indicated, where did this waste go? In the light of current legislation, how to ensure that the next licensing processes are carried out correctly?

These questions are even more relevant when observing the document «Diagnosis of the Situation of the Provision of Sanitation Services, Urban Cleaning and Solid Waste Management», requested in 2015 by the municipality to support the creation of the Municipal Basic Sanitation Plan. In this report, it was found that the municipality's CCW was not properly disposed and that there are numerous points for disposal of clandestine debris since the municipality does not have a sorting and processing plant.

In this context, is important to identify what does the legislation say. However, the existing laws do not cover all environmental aspects included in the precepts of many other technical standards, which are dispersed in numerous normative instruments and require a standardization of methodologies to facilitate the correct application. Rotaru et al. (2019) indicate that standards of environmental monitoring have high importance and should be used in a plan-do-check-act cycle. The disperse standardization creates a new field of expertise, leading to a knowledge monopolization that does not contribute to the mitigation of the environmental stress (Xavier et al. 2019).

Despite this, it seems that land policy-making alternates between restraining practices that exceed the legal framework and unclear laws and policies, which results in ambiguity (Ho 2001) and different outcomes for allotments, community and environment.

Regarding the removal of vegetation, only Allotment 03 does not indicate that it will occur. The environmental consequences of this removal were discussed in the section on protected areas.

When all parameters are analyzed together, an absence of an interdisciplinary approach can be observed in the process of developing the studied allotments as well as in the analysis by the different management Agencies involved. The responsibility of the Environmental Secretary in the impact assessment is not restricted to green spaces management. However, it has to be integrated with other Agencies, so they can act together pursuing the same goal. According to Arretche (2006), accountability and attribution definition must start individually, defining the collective goal and establishing mechanisms to integrate and coordinate the process. This integration is fundamental for reaching better evaluation practices.

Another problem these scattered approvals generate is an unequal proportion of services since they are concentrated in the city center. With the sprawled area there is more transportation needed causing higher greenhouse gas emission, more land speculation nearby city center and smaller green areas as well as multiple other problems (Polidoro et al. 2011). These new areas are entirely dependents on nearby poles, which usually results in social exclusion and often increases the cost of infrastructure to the city. (Amado 2018).

Based on the analyzed processes, it was also observed that there was no standardization in the requirements. In their initial requests, the entrepreneurs presented few mitigating measures leaving the city to make demands. As a result, the ventures' spending on environmental measures was more or less equal to the sum of the initial propositions and the requirements made by the licensing agency.

The lack of a base document to guide the development and subsequent analysis of the processes also increased the time spent by entrepreneurs to license their ventures, which took 14 months on average, although this discussion is not the focus of this analysis.

FINAL CONSIDERATIONS

The five analyzed allotments indicated five major environmental impacts: soil compaction and erosion, emission of air pollutants, alteration of original vegetation and generation of construction waste. The latter was indicated only in one of the projects. None fulfilled all legislation aspects. The biggest obstacle observed was the lack of standardization in the process required by the City Hall, which culminated in projects with different characteristics.

In general, the complexity of the addressed topic is determined by the administrative and legal aspects, training and even awareness of those involved in the analysis of environmental issues in the development process. There is also a lack of connection between the planning instruments and their practical application in the environmental licensing of subdivisions.

For further studies of impact assessment projects, it is necessary to move forward in the discussions related to urban environmental sustainability and standardizing the possible actions, not only in the municipality of Governador Valadares but in the entire country. Standardization, however, must maintain a margin for adjustments related to the characteristics of each location in order to facilitate the licensing processes, not to plaster. Therefore, it is important to create a manual containing minimal information to be addressed in environmental impact assessment to assist managers and entrepreneurs, optimizing and streamlining the process.

Despite the challenges outlined before, the collaboration between public power, engineers, scientists and involved citizens can result in environmental impact assessments with less prejudice and more benefits for all. Therefore, further studies should be carried out to understand how to make this participation effective.

Another topic that needs to be explored is the impact assessment of allotments during the operation phase, which includes the construction at each lot, in order to understand if there is a cumulative impact that should be addressed during the preliminary studies.

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RESEARCH PAPER

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CONSTITUENT ENTITIES OF THE RUSSIAN FEDERATION WITH CITIES OF OVER ONE MILLION INHABITANTS: THE STATE OF AND TRENDS IN THEIR INTERNAL DISPARITIES

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ABSTRACT. Sustainable development in Russia requires work to be done in a number of areas. One of the mechanisms for solving internal problems is to decrease the gaps in the level of socioeconomic development between the country's regions. This article provides an overview of the current state of the internal disparities in the socioeconomic development of the constituent entities of the Russian Federation that include cities with a population of over one million.

The constituent entities of the Russian Federation were analyzed in terms of the concentration of their population in the administrative centres. The population concentration ratio for cities of over one million inhabitants and the population polycentricity ratio for the corresponding entities were calculated. The ranking of entities was carried out based on these indicators. An analysis of the "contributions" of cities and peripheral areas to the formation of the gross regional product of the studied entities of the Russian Federation was carried out. The economic concentration ratios of cities with over one million inhabitants were calculated. The relationship of this indicator with the population ratio was established. Based on this, the following categories were identified: entities that are not in danger of a population or economy hyper-concentration in the administrative centre; entities with moderate population concentration in the city of more than one million inhabitants combined with an upward trend in their economic concentration; and entities with a high concentration of the population and economy in the administrative centre and signs of decrease in the population and economic concentration.

KEY WORDS: cities with population of over one million, administrative centre, population concentration ratio, population polycentricity ratio, economy concentration ratio, internal disparities

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INTRODUCTION

The involvement of Russia in global economic processes inevitably leads to the transformation of the spatial development of its regions. In modern conditions, issues regarding the regulation of the spatial organization of the economy are becoming key on a functional basis in Russia (Animitsa 2013). The need to ensure the competitiveness of the constituent entities of Russia leads to the use of their strengths. In this regard, the current spatial organization of the socioeconomic regions of the country has been deformed, which typically reinforces the exiting disparities in territorial development. One of these disparities is associated with stable settlement trends in recent decades. This trend is expressed in the powerful migration outflow of the population directed from east to west and from north to south (Obedkov 2018) as well as from peripheral areas to regional centres (Zubarevich 2013) and the largest megacities in the country (Varshavskij 2018; Blyahman 2014). Against this background, the most noticeable and ever-increasing trend is the "contraction" of the population into cities with over one million inhabitants and the "desertion" of rural areas. In the presence of significant economic gaps, uneven development both between the regions of Russia and within them is objectively inevitable (Buchvald and Kolchugina 2019).

The purpose of this study is to review the current state and some trends in the development of internal disparities among entities with cities of over one million inhabitants by establishing a relationship between their population and economic concentration ratio.

MATERIALS AND METHODS

The works of many Russian and foreign scientists were devoted to the special contribution of megalopolises to the economic growth of the state and the obvious advantages of the agglomeration effects (O'Hara 1977; Carlino 1978; O'hUallachain and Satterthwaite 1992; M.A. Saxenian 1994; Venables 1994; Lyons 1995; Krugman 1996). According to modern sources, disruption of a stable settlement system poses a direct threat to the country's national security (Shmidt et al. 2016). Following the relevant state strategy to ensure its security, it is necessary to reduce the level of interregional differentiation in the social and economic development of the constituent entities of the Russian Federation (Buchvald and Kolchugina 2019). Measures to achieve this goal are included in the Strategy for Spatial Development of the Russian Federation until 2025. However, the problem of determining the tools for its implementation remains open for discussion (Minakir 2018, Kuznecova 2019, Zubarevich 2019).

According to researchers, in Russia, unlike any other developed country in the world, there are still quite strong contrasts between the centre and the periphery of provinces in terms of living conditions and population. This sharp differentiation was initially based on climatic, natural resource, cultural and historical factors. This also includes the results of the historical formation and evolution of the territorial structure of the Russian economy, as well as the specifics of the current state-territorial structure of the country (Animitsa et al. 2009; Blochliger and Durand-Lasserve 2018). Additionally, the internal territorial differentiation in the regions of the Russian Federation does not contribute to their balanced social and economic development (Minakir 2019).

By the beginning of the 20th century, Russia was still an agrarian country with approximately 2% of the population living in large cities. In Soviet Russia, large-scale industrialization led to the increased growth of population and economic importance of large cities. If the crises in the first half of the twentieth century did not allow for the formation of a clear trend in this process, then the middle of the century was marked by the emergence of new cities with over one million inhabitants against the background of decreasing role of the regions' periphery. By the end of the 1980s, as the country entered a new crisis, urban growth began to slow down but contrasts in the economic importance of administrative centres and that of the peripheral regions remained.

In the 1990s, research on the topic was interrupted and there were no clear trends. By the beginning of the 21st century, the economic recovery in administrative centres expanded the range of jobs available there that were lacking in many regions. This gave a new impetus to the concentration of demographic and economic potential of regions in their largest cities including cities with over one million inhabitants.

Of course, there is high variability in the economic contribution of cities to regional development. However, overall, the following pattern has emerged concerning the distribution of productive forces in Russia: the more developed is the region, the more noticeable is its internal polarization. The issues of centralization and reasons for this phenomenon have been studied by G.V. Ioffe and others (Ioffe and Nefedova 2001). The spatial relationship between the cities and rural areas in Russia is considered in the works of A.I. Treyvish and T.G. Nefedova (Treyvish and Nefedova 2010). The dynamics and consequences of the compression of rural regions in Russia along with the idea of the Russian periphery as a socioeconomic phenomenon were disclosed in the works of T.G. Nefedova (Nefedova 2008 and 2012). The growing economic centralization in Russia intensified more than a hundred years ago, and the contrast between large urban centres and the rest of the territory is becoming more noticeable. Polarization has manifested itself not only between the regions of the country but also intra-regionally.

The "centre-periphery" theory ("the theory of four Russias"), as one of the models that experts use today to explain the country's internal heterogeneity (Zubarevich 2015 and 2019), is generally applicable to the constituent entities of the Russian Federation. The hierarchy in the intra-entity space in this case looks as follows: centre, which corresponds to the administrative centre and/or the largest city in the entity; semi-periphery territorial agglomerations (excluding the main city) and, in their absence, the smaller and medium-sized cities in the entity; periphery - small towns and rural settlements not included in the agglomeration (if any). These three types of spaces, which are connected throughout the country and exist in each region, have different potential and resources for development (Khlestova 2017).

In this study, the author considers the current state of the population and economy distribution between administrative centres and peripheral regions using sample entities with cities of over one million inhabitants. These entities differ in the severity of their internal socioeconomic contrasts. However, the persistence of the population and economy "contraction" in these entities is especially characteristic.

During the research, analytical, synthetic and statistical methods were applied. The research was based on data from the Federal State Statistics Service, "Institute for Urban Economics" Foundation.

Differentiation of administrative centres in the constituent entities of the Russian Federation by population concentration

The population is a part of the economic potential of a region that is closely tied to the region's location. Therefore, the location of the population often repeats the patterns in the territorial structure of the economy (Zubarevich and Safronov 2019). The identification of the population placement features in the constituent entities of the Russian Federation was carried out using the indicator for the concentration of the population in administrative centres (except for the Moscow and Leningrad regions, since the special status of Moscow and Saint Petersburg, as well as the existing characteristics of their socioeconomic development (Chalov et al. 2015) does not allow them to be evaluated accurately within the framework of this study). The classification of administrative centres based on this indicator is presented in Table 1.

The cities were combined into 6 groups according to the share of the population of an entity living in the administrative centre. Thirty-seven percent of the cities covered by the study belong to the third group, in which 31-40.9% of the population is concentrated in the administrative centre. A total of 24% of the administrative centres have a population concentration of 41-50.9%. Around 8.5% of cities were in the groups of less than 21% and 51-60.9% of the population living in the administrative centre. An exception is Magadan, where almost 70% of the Magadan region population is concentrated (Table 1).

During the grouping process, the following features were also identified. The first group includes the administrative centres of those constituent entities that include cities with population concentration exceeding the value of this indicator for the administrative centres themselves. For example, the population concentrations of Nefteyugansk, Nizhnevartovsk and Surgut are 1.3-3.7 times larger than that of the capital of Khanty-Mansiysk Autonomous Okrug. The same is true for Noyabrsk and Novy Urengoy in Yamalo-Nenets Autonomous Okrug; their population concentration is more than two times higher than of the capital, and the value of this indicator for Nadym is almost equal to that for Salekhard. More than 24% of the population of Ingushetia lives in Nazran, while only 1.8% lives in Magas. The population

Table 1. Estimated water demand for the studied allotment projects

№	Group number (part of the region's population living in the administrative centre, %)					
	1	2	3	4	5	6
	less than 20.9%	21-30.9%	31-40.9%	41-50.9%	51-60.9%	61% and more
1	Magas	Belgorod	Syktyvkar	Kursk	Tyumen	Magadan
2	Khanty-Mansiysk	Mahachkala	Arkhan-gelsk	Yoshkar-Ola	Petropavlovsk-Kamchatsky	
3	Salehard	Tver	Kazan	Kirov	Astrakhan	
4	Stavropol	Irkutsk	Yakutsk	Orel	Tomsk	
5	Simferopol	Vladimir	Chita	Izhevsk	Naryan-Mar	
6	Grozny	Cherkessk	Pskov	Kostroma	Novosibirsk	
7	Kemerovo	Vologda	Vladivostok	Saransk	Omsk	
8		Rostov-on-Don	Yuzhno-Sakhalinsk	Vladikavkaz		
9		Barnaul	Saratov	Voronezh		
10		Krasnodar	Abakan	Ulan-Ude		
11		Ufa	Chelyabinsk	Lipetsk		
12		Blagove-shchensk	Ekaterin-burg	Petroza-vodsk		
13		Gorno-Altaysk	Krasno-yarsk	Birobidzhan		
14		Orenburg	Bryansk	Khabarovsk		
15		Anadyr	Samara	Kaliningrad		
16			Kyzyl	Ryazan		
17			Majkop	Yaroslavl		
18			Novgorod	Ulyanovsk		
19			Tula			
20			Kurgan			
21			Smolensk			
22			Elista			
23			Nizhny Novgorod			
24			Murmansk			
25			Penza			
26			Ivanovo			
27			Perm			
28			Volgograd			
29			Kaluga			
30			Cheboksary			

of Novokuznetsk is only 5 thousand less than in the capital Kemerovo. Among the cities in the second group, the value of this indicator for Vologda is 0.5% less than for Cherepovets.

There are several constituent entities of the Russian Federation with the administrative centres belonging to groups 2-4, which also include some cities with lower concentration. Usually, these cities cannot be compared with the capital cities in terms of population concentration and are at a lower level of city classification in terms of population size, but they stand out significantly among other settlements. These include Naberezhnye Chelny in Tatarstan, Novocheboksarsk in Chuvashia, Severodvinsk in Arkhangelsk region, Orsk in Orenburg region, Togliatti in Samara region, Engels and Balakovo in Saratov region, Dimitrovgrad in Ulyanovsk region, Bratsk and Angarsk in Irkutsk region; Sochi and Novorossiysk in Krasnodar Krai, Biysk and Rubtsovsk in Altaysk Krai, Ussuriysk, Nakhodka and Artyom in Primorsk Krai and Komsomolsk-on-Amur in Khabarovsk Krai.

Most likely, for the entities, in which there are some kind of alternative economic centres that complement the capital, especially if they are not part of an existing agglomeration, the problems of population hyper-concentration and "contraction" of economic potential are smoothed out to a certain extent. It seems that this situation is much more typical of entities with cities of more than one million inhabitants. These cities in terms of the share of the entity population living in them are scattered across groups 2-5. Therefore, entities that include these larger cities will be rather heterogeneous in their territorial development and therefore can be representative objects of the study.

The concentration ratio, which specifically reflects the population concentration in entities with cities of over one million inhabitants, was adopted as the main criterion for ranking the entities. This indicator is calculated using the following formula:

$$Rpc = Psac / PSp \qquad (1)$$

where *Rpc* is the population concentration ratio, *PSac* is the population of the administrative centre and PSp is the population of the entity's periphery. The *PSp* indicator is calculated using the population of the entity outside of the administrative centre.

The resulting ranking of the cities with over one million inhabitants for this indicator are presented in Fig. 1.

Based on this indicator, cities with more than one million inhabitants are conditionally divided into 3 groups. The cities with relatively low population concentration are Rostov-on-Don, Ufa and Kazan, in which less than a half of the entity's population is concentrated (i.e., the concentration coefficient did not exceed 0.5). Chelyabinsk, Ekaterinburg, Samara and some other cities were characterized by an average concentration ratio from 0.5 to 1.0, while Novosibirsk and Omsk were identified as having the highest population concentration. Since the ratio here is significantly higher than 1.0, it can be said that in these cities there is a hyper-concentration of the population of their corresponding entities.

To some extent, natural resource conditions and the specifics of their economic development also affect the concentration of the population into cities with over one million inhabitants. The economy of the city itself is based on industry and services. At the same time, the administrative centres of entities with a developed primary economy sector are characterized by lower concentration coefficients due to a smaller network of settlements. Several entities have alternative centres in addition to their capitals that appear to have significant economic value. However, their presence is an exception rather than a rule.

Another used indicator was the population polycentricity ratio. It characterizes the degree of population dispersal between the capital and other large cities in the entities with cities of over one million inhabitants. The population polycentricity ratio is calculated by the formula:

$$Rpc = Pskg \,/\, PSr \qquad (2)$$

where *Rpc* is the polycentricity ratio, *PSkg* is the share of cities with a population of over 100 thousand people (excluding the city with population higher than one million), and *PSr* is the share of the remaining population in the total population of the entity.

The ranking of entities with cities of over one million inhabitants according to polycentricity ratio is presented in Fig. 2.

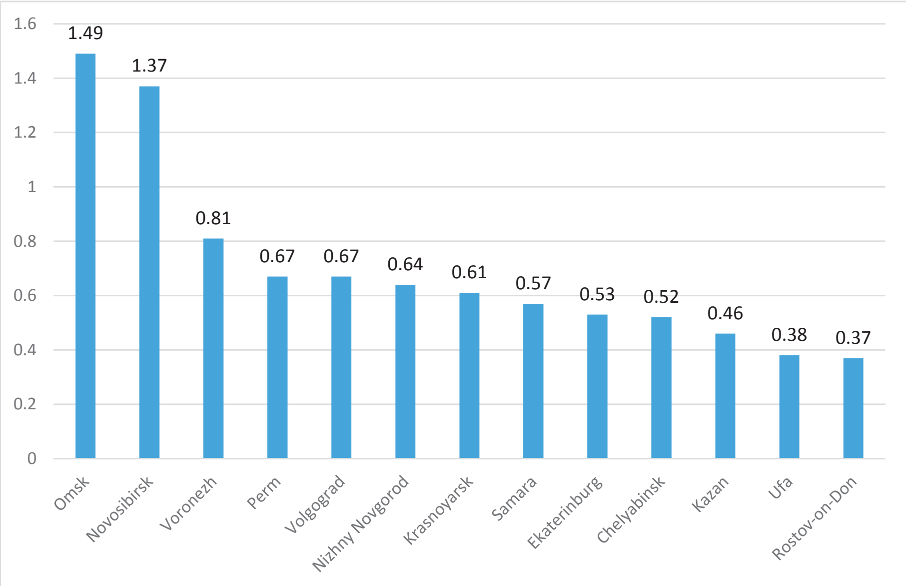

Fig. 1. The ranking of cities with over one million inhabitants according to the population concentration ratio of the corresponding entity (as of the end of 2017)

Source: Federal State Statistics Service

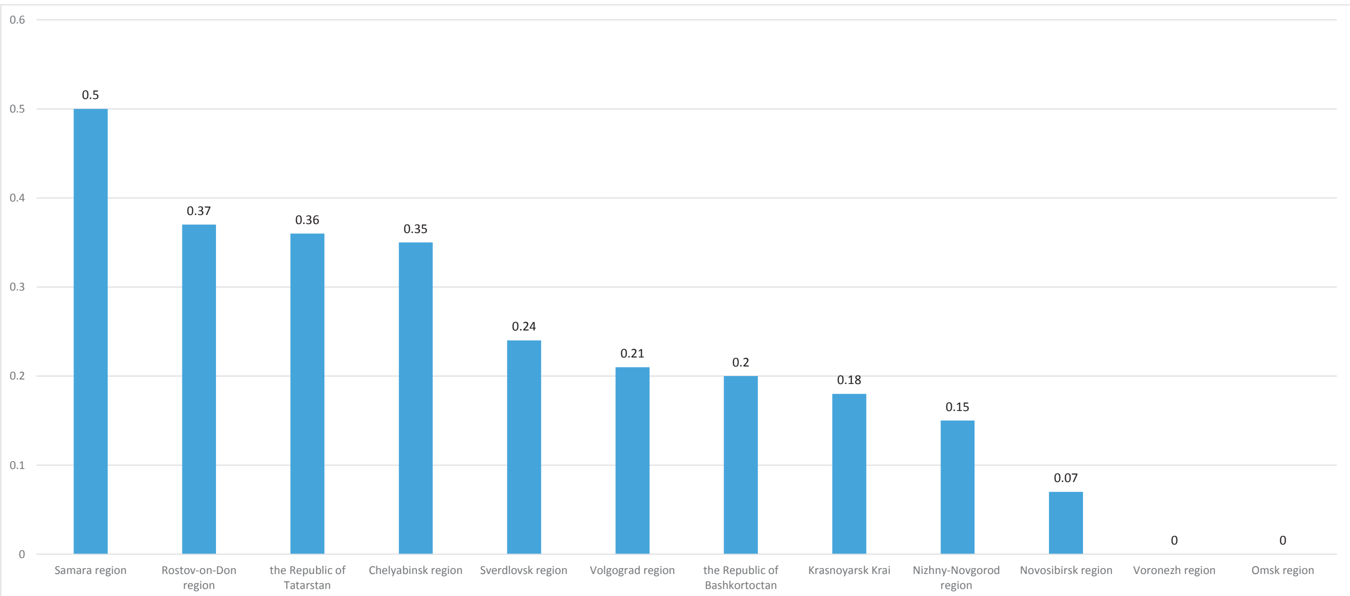

Fig. 2. The ranking of entities with cities of over one million inhabitants according to the polycentricity ratio (as of the end of 2017)

Source: Federal State Statistics Service

The figure shows that the ranking of entities according to this indicator is almost exactly the opposite of the previous ranking. The leader in terms of the dispersion rate is Samara region, followed by Rostov-on-Don region, Chelyabinsk region and Tatarstan. Novosibirsk region has a very low polycentricity ratio. Voronezh and Omsk regions ranked last as they do not have any cities with a population of over 100 thousand people.

Economic differentiation of the constituent entities of the Russian Federation with cities of more than one million inhabitants

To identify the actual economic differentiation in intra-entity spatial research, the analysis of the dynamics of the gross regional product (GRP) produced by each entity was carried out. This indicator considers the entity as a whole, and the degree of participation of administrative centres and peripheral territories in its formation was determined.

The gross product of the studied cities (city gross product, CGP) and urban agglomerations is presented on the official website of the Institute of Urban Economics[1,2],. The gross product of the periphery in the constituent entities with cities of over one million inhabitants was calculated based on indicators from the Federal State Statistics Service[3] by excluding the CGP (and the gross product of the city's agglomeration in 2015) from the GRP of the constituent entity. The indicators for 2015 and 2017 are compared within the respective entities (Fig. 3).

In absolute and relative terms, all the entities of the Russian Federation demonstrated growth in their GRP in 2017 compared to 2015. The dynamics, however, was different as the increase in the range of 5-10% was observed for Volgograd, Voronezh, Omsk and Samara regions as well as Bashkortostan; 11-15% in Tatarstan, Rostov-on-Don region, Chelyabinsk region and Perm Krai, and 16-18% in Krasnoyarsk Krai along with Novosibirsk and Nizhny Novgorod regions. Growth of more than 20% was observed in Sverdlovsk region.

The inflation rate, which varied insignificantly for the considered entities in 2017 (within 1.7%, from 101.4% to 103.1%), also strengthened the emerging trend in the growth of GRP. This is especially true for entities with the highest inflation rate between 2015 and 2017. These include, first of all, Sverdlovsk region, as well as several entities with relatively low rate of the absolute growth of their GRP (Volgograd, Voronezh and Samara regions).

At the same time, the main contribution to this indicator is made by the administrative centres of the respective entities. Therefore, according to the 2015 data, 30-35% of

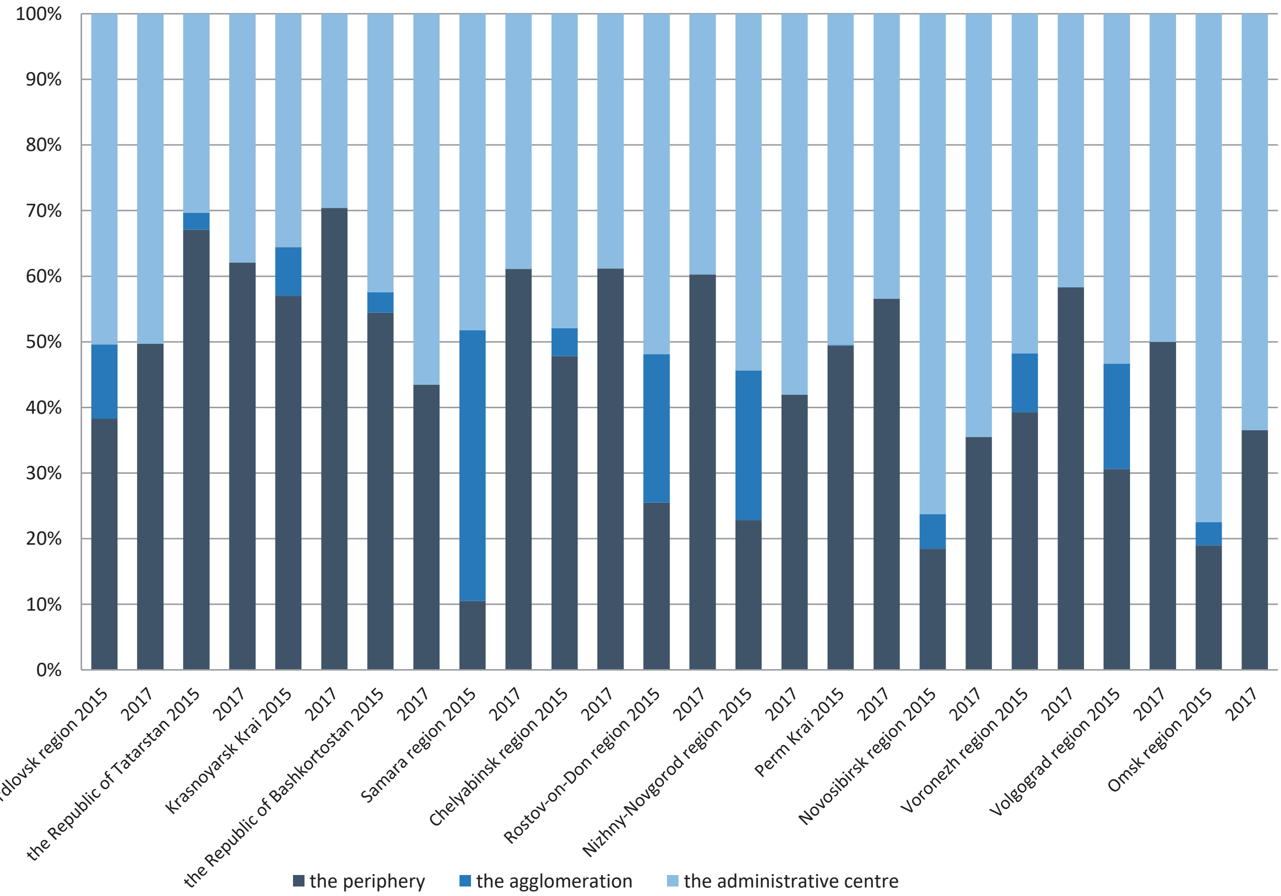

Fig. 3. Contributions of cities with over one million inhabitants and peripheral territories to the formation of the GRP of the constituent entities of the Russian Federation

Source: Federal State Statistics Service; The Institute for urban economics

[1]Institute for Urban Economics. Rating city IUE. Available at: http://www.urbaneconomics.ru/research/analytics/rating_city_IUE. html Accessed 01 April 2020L / per capita / day), boarding schools (95 L / per capita day), schools by term (22 L / per capita / day), offices (40 L / per capita / day), sewing workshops (40 L / per capita day) and auto repair shops (75 L / per capita / day), averaging at 47.5 L / per capita / day. This value was multiplied by the maximum number of people in a microenterprise (9 employees), just for comparison purposes, which generated a demand of 427.5 L / lot / day.

[2] Institute for Urban Economics. The economy of Russian cities and urban agglomerations. Available at: http://www.urbaneconomics. ru/sites/default/files/vypusk 5 rossiiskie_aglomeracii v globalnoi_ekonomike.pdf Accessed 12 March 2020

[3] Rosstat, 2017-2019. Aviable at: https://www.rosstat.gov.ru / bgd/regl/b18 _14p/ Main. html Accessed 01 April 2020

the GRP of Tatarstan and Krasnoyarsk Krai was produced in the capital cities, and 42-48% was produced in the capital cities of Bashkortostan as well as Chelyabinsk and Samara regions. More than 50% of the GRP of the corresponding entities was produced in Voronezh, Volgograd, Rostov-on-Don, Perm and Ekaterinburg. The absolute leaders in this respect were Nizhny Novgorod, Novosibirsk and Omsk (70.4%, 76.2% and 77.4% of the GRP, respectively).

Due to their economic characteristics, these entities differ in the degree of development of their settlement systems. While Nizhny Novgorod region is characterized by a relatively developed network of cities (with the large cities of Arzamas and Dzerzhinsk, and another 25 small and medium cities), in Novosibirsk region there are only 13 cities (1 large) and in Omsk region – only 5 (all of which are small). Taking into account the area of the entities, this is clearly not enough to support the development of the peripheral territories. Thus, significant economic differentiation between the centre and the periphery of the studied entities becomes obvious.

It should also be noted that cities with a population of over one million almost inevitably become centres for the formation of agglomerations. The level of their socioeconomic development, of course, cannot be equated with that of the periphery of the entities. However, judging by the 2015 data, these cities act as the "engines" of growth for most of these entities.

Among agglomerations where economically important non-metropolitan settlements are quite extensive, the Samara-Togliatti region stands out. This name already indicates at least a dual-centre territorial structure. Samara accounts for only approximately 55% of the CGP produced here. Zhigulevsk, Novokuibyshevsk, Oktyabrsk, Syzran, Togliatti, Chapaevsk and Kinel play the most important economic roles. More than 31% of the CGP of the Nizhny Novgorod agglomeration was produced outside the central city (in Bor, Dzerzhinsk and other settlement). For the Rostov-on-Don agglomeration, 24% of the CGP is produced outside Rostov-on-Don (Azov, Bataysk, Novocherkassk, Novoshakhtinsk, Taganrog), and 21.6% of the CGP is produced outside the Volgograd agglomeration (mainly in the city of Volzhsky).

A total of 15-20% of the CGP is produced outside the centres of the Voronezh (Novovoronezh), Sverdlovsk (Aramil, Asbest, Beloyarsky, Berezovsky, Verkhnee Dubrovo, Verkhnyaya Pyshma, Degtyarsk, Zarechny, Malyshevsky, Novouralsk, Pervouralsk, Polevskoy, Revda, Reftinsky, Sredneuralsk, Sysert, Uralsky) and Krasnoyarsk (Zheleznogorsk, Divnogorsk, Sosnovoborsk) agglomerations.

Other capital cities are characterized by a significant degree of concentration of the economic potential in their corresponding agglomerations. Thus, extra-metropolitan areas in the Ufa, Kazan and Chelyabinsk agglomerations produce only 7, 8 and 8.2% of CGP, respectively. The cities of the Novosibirsk agglomeration (Berdsk, Iskitim, Koltsovo, Ob) account for no more than 6% of the CGP, and those of Omsk contribute no more than 4.4%. In the Perm agglomeration, almost the entire volume of CGP is formed in the capital city of the corresponding entity.

The analysis of the GP produced by administrative centres and peripheral territories (excluding agglomerations for which the data were not available) of the studied entities in 2017 revealed the following features. For each entity, the leading role of the administrative centre in the formation of its GP was preserved. Volgograd, Kazan, Ufa and Samara strengthened their positions in absolute and relative terms. Together with the economy of the Sverdlovsk region, the CGP of Ekaterinburg has also increased. This allowed the administrative centre to maintain its share in the formation of GRP.

However, for other cities with over one million inhabitants, the opposite trend emerged. With the smaller CGP values than in 2015, the share in the formation of the GP of the corresponding entities decreased for the following administrative centres: Omsk - by 13.8%; Novosibirsk, Rostov-on-Don and Nizhny Novgorod - by 12-12.5%; Voronezh - by 10%; Chelyabinsk - by 8.3%; Perm - by 7%; and Krasnoyarsk - by 6.2%. Accordingly, the "contribution" of the periphery to the formation of this indicator increased. For Krasnoyarsk Krai, it exceeded 70% (due to the GPs of Achinsk and Norilsk); in Chelyabinsk and Rostov-on-Don regions it became more than 60% (also due to the GPs of other cities). The situation in Voronezh region and in Perm Krai are in line with these examples. The share of the peripheral territories of Nizhny Novgorod, Novosibirsk and Omsk regions in the formation of the GP, despite this trend, remained low - at 35-40%.

From the analysis of the GRP growth rates from 2015 to 2017, only two entities with positive dynamics in the GPs of both the administrative centre and the periphery were identified. These were Tatarstan and Sverdlovsk region, which are characterized by an average population concentration in the capital cities (0.46 for Kazan and 0.53 for Ekaterinburg) and have a fairly developed network of settlements (46 cities in the Sverdlovsk region, including the large cities of Nizhny Tagil, Kamensk-Uralsky and Pervouralsk, and 6 cities in Tatarstan, including the large cities of Almetyevsk and Nizhnekamsk, as well as the largest city, Naberezhnye Chelny).

However, it should be noted that the growth of GP within the capital and peripheral territories of Tatarstan also differs significantly. While the CGP of Kazan for the considered period increased by 45%, the GP in the rest of the entity increased by only 2.5%. Thus, there is a very noticeable acceleration in the development of the capital of the Republic. For Sverdlovsk region, the differences in these indicators were not significant (20 and 21%, respectively). With the general growth of GRP, this may indicate relatively stable and balanced economic development in this entity. This is due to the presence of "auxiliary" economic points with centres being one of the main conditions for the formation of a supporting framework and comprehensive realization of a territory's potential.

Negative growth in GRP from 2015 to 2017 of 12-19% was demonstrated in the periphery of entities, in which the administrative centres have strengthened their positions in the economy. These are Bashkortostan along with Volgograd and Samara regions (with an increase in CGP of 20% for Volgograd and 40% and 41% - for Samara and Ufa, respectively). This may indicate a continuing concentration of the economic potential into the central cities and deepening of the territorial differentiation, which may cause the formation of economically weak areas in this context and, possibly, incomplete realization of the economic potential in the constituent entities of the Russian Federation.

In contrast, in some cases there was also noticeable positive growth in the GPs of the entities, in which the CGPs of their administrative centres decreased (for Voronezh, Rostov and Chelyabinsk regions as well as for Perm Krai and Krasnoyarsk Krai, the CGPs of the administrative centres decreased by 27-44% in 2017 compared to 2015, for Nizhny Novgorod region the decrease was 67%). An understanding of the interdependence of these trends was obtained by assessing the dynamics of the GPs of the entities' capitals. For Perm, Nizhny Novgorod, Krasnoyarsk and Chelyabinsk, the decline in CGP for the considered period ranged from 2 to 5%. Therefore, the development in the periphery of the entities was truly significant. The GP of Rostov-on-Don decreased by 12%, but the increase of GP in the periphery amounted to 44%. Meanwhile, in Voronezh the CGP decreased by 16.5% with no significant increase in the GP of the periphery of the entity, which may reveal certain risks to its further development.

The most significant increase in the "contribution" of the periphery to the formation of GRP was in Novosibirsk and Omsk regions (71 and 74% growth in their absolute values from 2015 to 2017, respectively). Such changes along with the general growth in the GP of the entities may indicate, for example, the beginning of some economic dispersion away from the capital cities that already have hyper-concentrated populations. But more precisely the reason for this phenomenon can be revealed only from a detailed analysis of the economy of each of them in the considered period.

RESULTS AND DISCUSSION

Based on the obtained data, the ratio of economic concentration was calculated for the administrative centres of the studied entities of the Russian Federation. To calculate this ratio, the following formula was adopted:

$$Cec = CGP / PGP \quad (3)$$

where *Cec* is the economic concentration ratio, *CGP* is the city gross product and *PGP* is the peripheral gross product (the difference between the *GP* and *CGP* of the corresponding entity).

Even though these two indicators are calculated using different methods, their ratio allows to characterize the differentiation in the intra-regional economies. The values of the economic concentration ratio for entities with cities of over one million inhabitants in 2015 (blue columns) and in 2017 (light-blue columns) are shown in Fig. 4.

The diagram shows that the economic concentration ratio in the administrative centres of the studied entities of the Russian Federation generally correlates with the ratio for population concentration while exceeding it to varying degrees. At the same time, the dynamics of the economic concentration ratio from 2015 to 2017 is ambiguous. The pattern of this correlation allows us to identify the features of the modern economic development of these regions as formed by the population and economic components.

Thus, the entities in which the population concentration in the capital is associated with a centralizing trend in the economy are distinguished, these are Volgograd region, Tatarstan and Samara region. To date, the population concentration in the administrative centres of these entities is moderate. However, while the trend towards the "concentration" of the economy continues, there are certain risks for the further development of the agglomerations they form, especially in the peripheral territories.

Entities with a decrease in the share of cities in the formation of GRP such as Perm and Krasnoyarsk Krais along with Rostov-on-Don, Voronezh and Chelyabinsk regions, are also characterized by relatively low population concentration. This probably indicates that there is no threat of the population and economy hyper-concentration in the capital cities at this time. The situation is similar for Nizhny Novgorod region, although the concentration of the economy in the administrative centre there is quite high.

In Sverdlovsk region, the CGP of Ekaterinburg and the GP of the periphery are comparable, while the population concentration in the administrative centre is relatively low. This region can be classified as stable in terms of the dynamics of the economic concentration ratio. At the same time, it seems possible to assess the interaction tendencies between the centre and periphery in more detail, taking into account only the aspects of its agglomeration development.

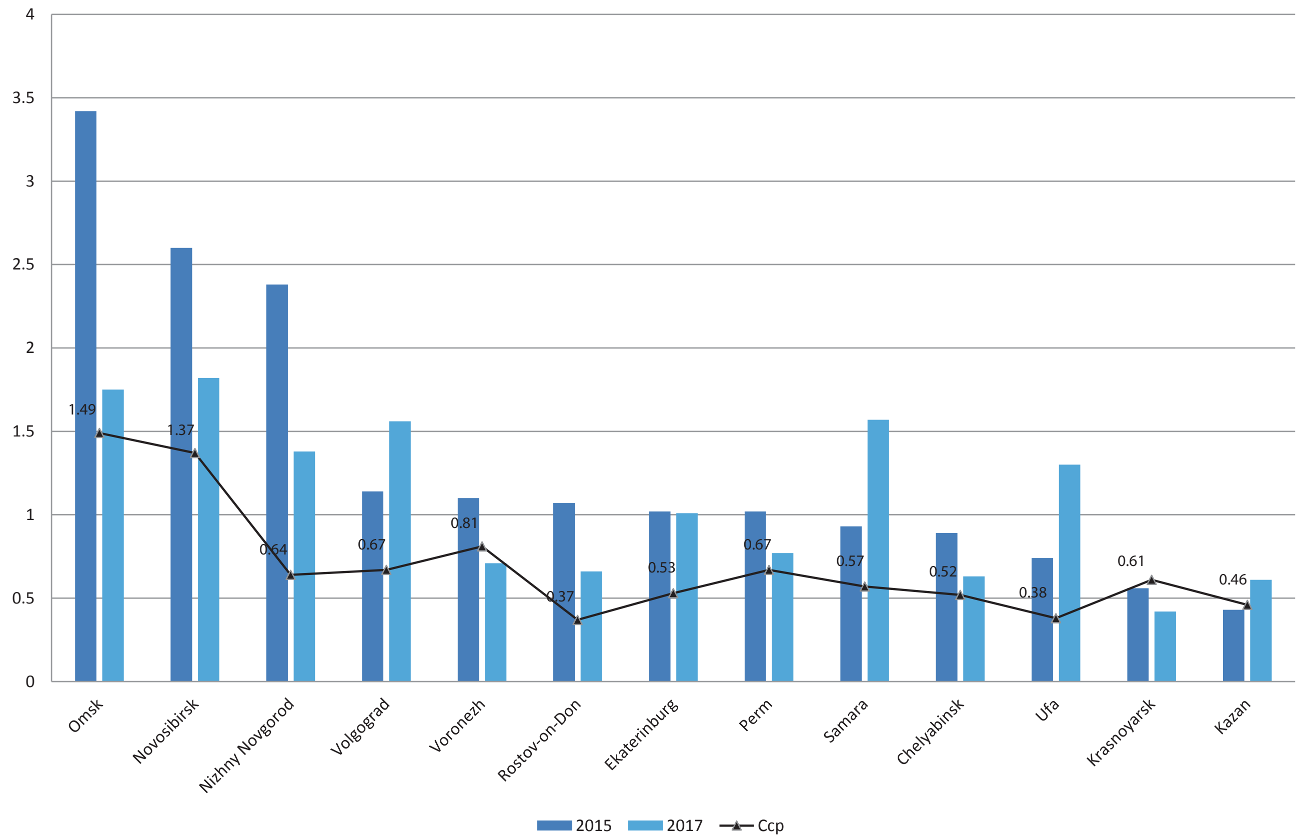

Fig. 4. Economy concentration ratio dynamics (ratio between CGP and PGP of an entity)

Omsk and Novosibirsk are absolute leaders in terms of the population and economy concentration within the cities with more than one million inhabitants. It is in these constituent entities of the Russian Federation where the differentiation between the centre and periphery is sharply manifested. However, judging from the materials analyzed, there are signs of active dispersion forces. This is expressed primarily in the economic dispersion away from administrative centres and an increase in the role of the periphery in the formation of GRP. However, the territorial disparities in economic development are still very significant today.

CONCLUSION

An analysis of the population and economic concentration ratios in the constituent entities of the Russian Federation with cities of over one million inhabitants confirms the existence of significant disparities in the development of these entities' spatial economies. The periphery of the entities and other large cities almost always lag significantly behind the administrative centres.

Of course, large cities and agglomerations formed around them are the "drivers of the economy" and "engines of growth". However, the concentration of socioeconomic potential in one area inevitably leads to the "desolation" of territories (Lebedeva 2015). This is expressed in a large gap between the level of development in the centre and periphery of an entity along with higher population concentration in the administrative centre. However, for the constituent entities of Russia with cities of more than one million inhabitants, various internal tendencies towards the "reorganization" of the spatial economy were observed. These tendencies are evident due to the specificities of the spatial development strategies of many entities.

This is happening not only due to the influence of globalization but also to the general trend in the post-industrial transformation. If in the past the leading factors in the placement of productive forces were labour, capital and natural resources, now the factors of information, knowledge, qualified personnel, the image of the territory and the availability of innovative infrastructure facilities start to play a more important role (Pelyasov 2014). Under these conditions, the cities with more than one million inhabitants are more attractive to the population and promising in terms of economic development. The strategies of the federal districts are also linked to the development of their territories, primarily, of large agglomerations. The districts plan to create a service infrastructure for doing business that meets international standards, including the widespread use of the achievements of national research institutes.

At the same time, practice shows that the effective functioning of an entity is negatively affected by both the excessive dispersal and the hyper-concentration of economic potential in one settlement. This serves as an incentive to establish strategies for the spatial development of Russia's regions. The peculiarities of their implementation probably determine the different directions of the internal "reorganization" of the spatial economies in the entities with cities of over one million inhabitants. However, it seems inappropriate to speak of these strategies as stable trends today.

It seems that the optimal option for the spatial development of these entities would be a polycentric model. Such models have already been widely developed by modern researchers and are included in strategies for the spatial development of hyper-concentrated entities of the Russian Federation (Zubarevich and Safronov 2019), industrial megalopolises (Lavrikova et al. 2017; Lavrikova 2019) and other types of settlements. The presence of additional or alternative economic entities at the same time smooths out the consequences of high levels of population and economy concentration in the capital cities and stimulates the socio-economic development of the adjacent peripheral territories. It is the provision of polycentric entities that will be the necessary condition for maintaining the balance between various types of settlements as the basis for supporting their framework and economy. Therefore, this should be the most important aspect of the implementation of a strategy for the economic and national security of the state.

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RESEARCH PAPER

CLIMATE VARIABILITY AND ADAPTATION AMONG SMALL HOLDER BANANA FARMERS IN MOUNTAIN REGIONS OF KENYA

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ABSTRACT. Banana production is the mainstay industry for majority of small holder farmers living in the mountain regions of Kenya. These regions are affected by climate-related impacts at all levels of the value chain. This paper therefore discusses climate trends, related impacts, and adaptations in banana value chain in Mt. Kenya region for the period between 1980 and 2017. The study locations were purposively selected from Mt. Kenya region to include both Imenti South and Mukurweini sub-counties. A sample of 381 respondents was selected using simple random sampling. Triangulation research design was used to guide the study by integrating both qualitative and quantitative methods in data collection and analysis. Historical document analysis was used to examine climatic data (temperature and rainfall) from the Kenya Meteorological Department, Nairobi. Results showed that rainfall and temperature have changed during the study period. Temperature trends in Mukurweini showed R^2 = 0.3314 while in Imenti South R^2=0.3441 with an overall annual increase in temperature in Mukurweini by 0.02°C while in Imenti South we registered an increase by 0.016°C for the study period. Mukurweini sub-county rainfall trend line had R^2=-0.1064 while Imenti South sub-county had R^2=-0.1014. Adverse effects of climate variability on banana value chain included low yields in both Mukurweini (79.2%) and Imenti South (60.2%) sub-counties. Farmers in the study area preferred irrigation (57.2%) followed by crop diversification (13.9%) as adaptive strategies to climate variability.

KEY WORDS: Adaptations; banana; climate variability; value chain; small-holder farmers

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INTRODUCTION

Agriculture, the mainstay activity for the smallholder farmers, is exposed to various menaces, ranging from weather variability, pests, and diseases to price volatility in the markets. Increased frequency of extreme climate events is projected to negatively affect local agricultural production, especially the subsistence sector and smallholder farmers located in the low-latitude areas (Wik et al. 2008). Agricultural production is particularly sensitive to climate hence crop yields depend largely on climate variables mainly temperature and rainfall patterns and amounts. Dynamics in these climatic variables affect agricultural productivity through physiological changes in crops (Chakraborty et al. 2000). According to Brown and Funk (2010), Mt. Kenya region has been experiencing climate variability related impacts. It has been recognized that adaptation strategies can minimize the adverse impacts of climate erraticism on crop production (Kabubo and Karanja 2005). Adger et al. (2003) reported that adaptation is one of the policy options to reduce the negative impact of climate change on smallholders; food productivity and access can be improved with proper adaptations at household level (Di Falco and Veronesi 2013; Di Falco 2014).

Previous studies conducted in the region have focused on socio-economic aspects of banana production and agribusinesses' prospects. However, little attention was paid to the extent of climate variability effects as well as associated adaptation measures in driving banana value chain development within the region. This study therefore aimed at evaluating the climate trends, related variability, impacts, and corresponding adaptation strategies on banana value chain development among small holder farmers in Mt Kenya region.

Banana production among smallholder farmers

Bananas provide an important source of food and income for millions of smallholders in East Africa and other developing countries globally (Arias et al. 2003). Banana production as a horticultural crop and fruit is a new venture within Mt Kenya region, where coffee farming was previously dominating until 1990. According to Africa Harvest Biotechnology Foundation International (AHBFI) (2015), approximately 390,000 banana farmers operate in Kenya, of which approximately 84% are smallholder farmers (cultivating <0.2 hectares). Majority of the smallholder producers have become more reliant on the income generated from banana sales, especially in areas that were negatively affected by declining incomes from traditional cash crops such as coffee (Wambugu and Kiome 2001).

Climate variability impacts on banana value chains development

Value chain comprises all value-generating activities required to produce, deliver, and dispose of a commodity (Schmitz 2005). Agricultural production is inherently delicate to climate variability owing to the close natural connections and dependencies that exist between climatic weather conditions and plant growth (GOK 2013). High temperatures coupled by declining rainfall increase crop water demand by 12–15% (Washington and Pearce 2012) and reduce crop yields. When infrastructure is affected by extreme climate, particularly frequency of flood events that cut down communication lines, there are impacts on food distribution, influencing people's access to markets to sell or purchase food (Abdulai and CroleRees 2001). Weak infrastructure hampers efficient flow of products laterally on the chain thus constraining the flow and exchange of market information along the chains (Trienekens 2011). Lack of well-established banana value addition activities within the chain has been reported to constrain smallholders in other banana studies in Africa (Mwangi and Mbaka 2010; Ouma and Jagwe 2010). Mwangi and Mbaka (2010) recommended to maximize banana value through cleaning, packaging, and labelling to promote competition.

Adaptation strategies to climate variability

Climate variability adaptation refers to responses or changes within the production system geared towards reducing the negative effects and enhancing the positive influences of climate variability. The severity of environmental impacts due to climate related experiences can be reduced by adaptation strategies. Heavy dependence on rainfed crop production increases the susceptibility of smallholder farmers in the rural settings to harmful effects of climate variability (Mertz et al. 2009).

There are limits to adaptation and adaptive capacity for some human and natural systems if the warming exceeds 1.5°C from current levels particularly for the poor and disadvantaged populations (IPCC 2018). This calls for responsive measures to curb and reduce the associated effects of climate variability. Soil conservation measures, planting trees, water management, varying planting dates as well as crop diversification are some of the adaptation measures recommended for smallholder farmers (Gbetibouo 2009).

This study was guided by the Action Theory of Adaptation (Eisenack and Rebecca 2011). The theory focuses on the challenges linking biophysical factors and agricultural production. It emphasizes on the changes and contribution of meteorological variables. The theory is based on temperature and rainfall as the main climate variables.

The focus of this study is thus based on Action Theory of Adaptation to climate variability and focuses on the climate impacts on banana value chain and adaptation strategies of banana farmers in the region. This theory has previously been used to study poverty and vulnerability reduction related to climate risks in Kenya (Eriksen and O'brien 2007).

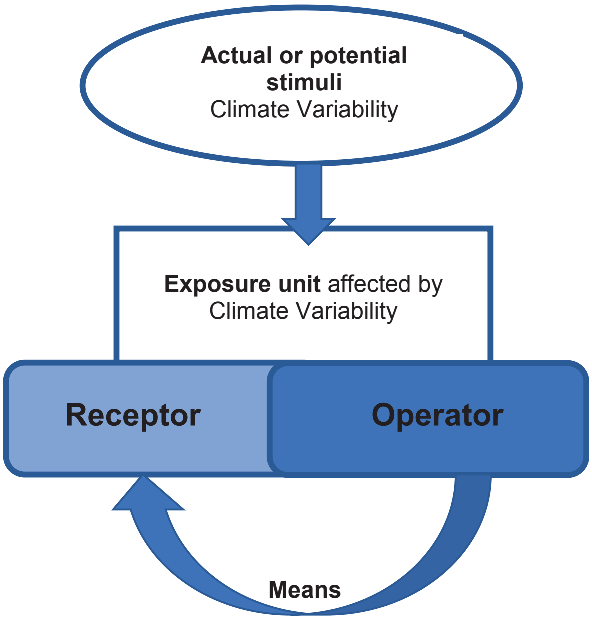

Fig. 1. Schematic representation of the Action Theory of Adaptation
(Adapted from: Eisenack and Rebecca 2011)

Table 1. The experiment design

County	2010		2011		2012	
	Area (Hectares)	Quantity (Tons)	Area (Hectares)	Quantity (Tons)	Area (Hectares)	Quantity (Tons)
Meru	5,027	124,793	5,843	150,485	6,241	315,720
Kirinyaga	4,089	140,195	4,224	181,920	4,148	160,606
Kisii	4,573	101,540	4,942	112,152	4,167	66,889
Nyamira	2,112	42,245	2,151	43,051	1,795	33,792

Source: MoA (2012)

The Meru county leads in banana production in Kenya followed by the Kirinyaga county. This indicates that banana production is one of the major economic activities in Mt Kenya region. The banana acreage continued to rise in the Meru county as compared to other counties, which showed declining trend in acreage (Table 1). The challenges in banana production are: prevalence of insect pests and diseases and high post-harvest losses (MoA 2012).

METHODS AND MATERIALS

General description of the study area

The objective of the study was to establish climate trends and associated variabilities related to impacts and adaptations on banana value chain in Mt Kenya region. For the purpose of understanding changes in banana production, and climate variables (rainfall and temperature) over time, we selected a target period from 1980 to2017. A period of 30 years is enough to study climate and calculate the trend. The study sites are located in Meru and Nyeri counties, which are among the main banana growing counties in Kenya (Fig. 2). The Meru county falls approximately between longitudes 370 0′ 00″ and 380 30′ 00″ East and latitude 00 20′ 00″ North and 00 40′ 0″ South (GOK 2015a). The Nyeri County is located between longitudes 360 and 380 East and between the equator and latitude 00 38´ South (Murphy and Chirchir 2017). The rainfall regime in the Nyeri county is equatorial due to its location within the highland zone of Kenya (GOK 2015b). The major economic activities, which the local community is engaged in, include agriculture and livestock production specifically dairy, banana, coffee, and tea farming.

Study design

The study adopted mixed study design to evaluate climate variability trends, their impacts on banana value chain and adaptation strategies used in Meru (Imenti South sub-county) and Nyeri (Mukurweini sub-county) within the Mt. Kenya region. The study area was purposively selected to include Agro-Ecological Zones (AEZ) and diverse locations where banana production has been grown for the target period from 1980 to 2017. According to GOK (2009) population statistics, the population of Imenti-South was approximately 179,604 people; the number of households was 47,197 while the population of

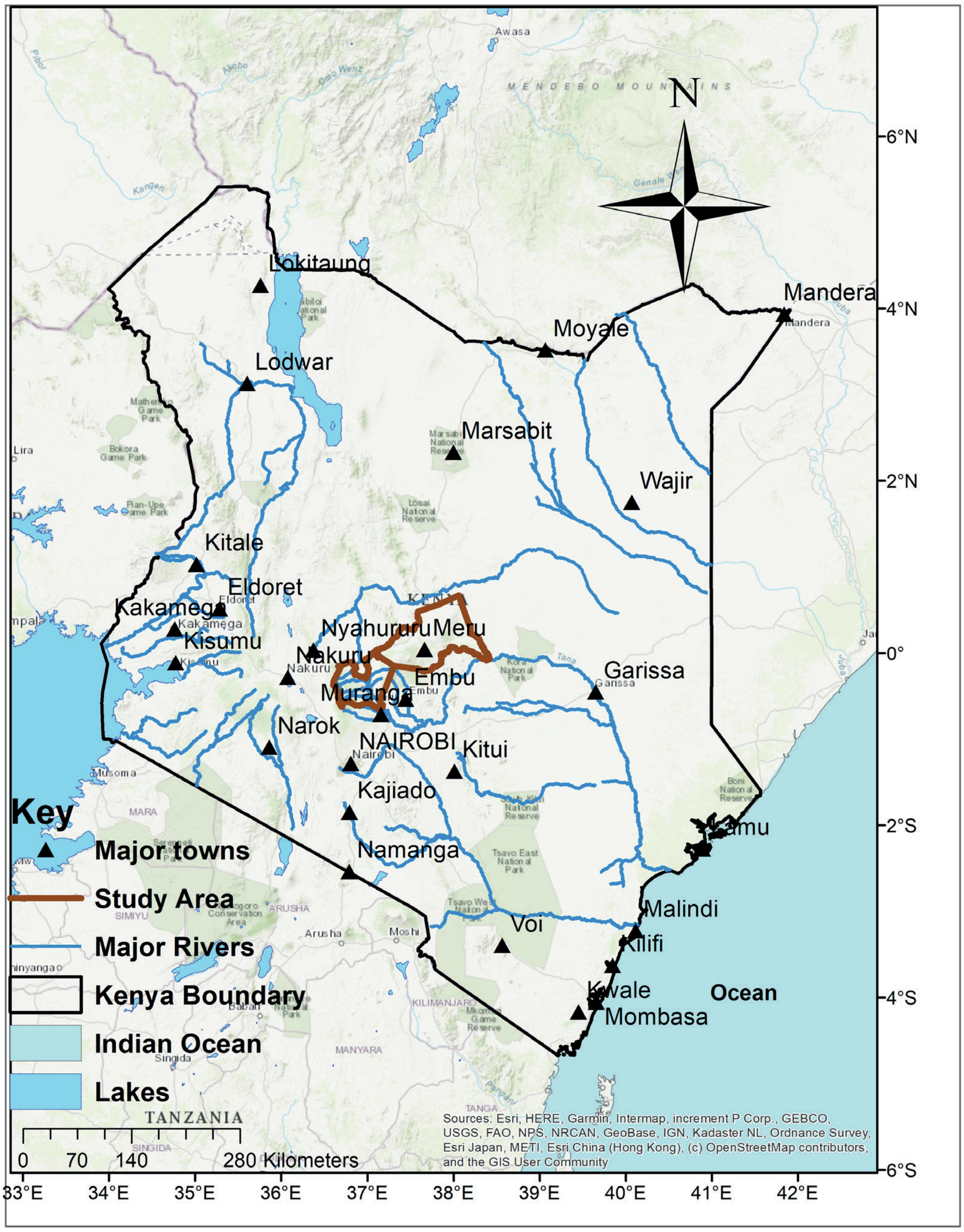

Fig. 2. Map of Kenya showing the location of the study areas in Meru and Nyeri counties

the Mukurweini sub-county was 83,932 people and the number of households was 24,083 households. Simple random sampling was used to obtain sample size of 381 participating respondents for the study using the method described by Krejcie and Morgan (1970).

Data collection methods

Data collection included both primary and secondary sources. Questionnaires were used to capture the impacts of climate variability and adaptation strategies from individual households. Key issues on the impacts of climate variability on banana value chain were captured using in-depth interviews from key informants. Focus Group Discussion sessions were undertaken in each study site to validate data collected from individual households; 381 participants were interviewed (130 in Nyeri and 251 in Meru). Climatic data (temperature and rainfall) for Imenti South and Mukurweini sub-counties were obtained from the Kenya Meteorological Department in Nairobi. Banana production data was obtained from Horticulture Crop Directorate (HCD). In the period from 1980 to 2017 we had daily recorded data on rainfall and temperature for the two study areas , which were analyzed using time series to examine possible trends over the 37-year period under consideration.

Limitations of the study

Two climatic elements, i.e. temperature and rainfall, were studied as presumably influencing banana value chain within the region while other biophysical factors were held constant during the study period from 1980 to 2017. The climatic data was sourced from the adjacent weather stations, which were not specific to the study sites while the selected study sites were assumed to represent the banana growing regions.

RESULTS AND DISCUSSIONS

The impacts of climate variability were evaluated by their effect on various components of banana value chain comprising production, marketing, processing, and value addition. Changes in climate in terms of temperature and rainfall were analyzed annually. For both numerical and graphical measures, we analyzed temperature and rainfall data for the overall study period from 1980 to 2017.

Temperature

The study's null hypothesis was that there is a negative trend in temperature within Mt. Kenya region. Temperature data from the two study areas revealed that Imenti South sub-county was slightly warmer than Mukurweini sub-county with mean average temperatures of 18.2°C and 18.6°C, respectively (Figure 3). There was a gradual increase in temperature in the two locations from an average of 17.7°C in Mukurweini and 18.1°C in Imenti South in 1980 and rising gradually to 18.2°C and 18.6°C in 2017 in Mukurweini and Imenti South, respectively. The highest mean temperature for Mukurweini sub-county was registered in 2009 – 18.8°C while the highest mean temperature for Imenti South sub-county was 18.8°C; it was registered in 2015. The lowest mean temperature in Mukurweini sub-county was 17.6°C; it was registered in 1982; while in Imenti sub-county it was 17.3°C; it was registered in 1985 and 1998. As evidenced from Figure 3, the two study areas showed increasing linear trends of temperature as shown by positive slope in the trend line equations. The study findings further revealed an increasing trend of temperature in Mt. Kenya region, which is represented by a positive slope in the corresponding trend line equations (Figure 3) thus $y = 0.0206x + 17.727$ ($R^2 = 0.3314$) for Imenti South and $y = 0.0149x + 18.129$ ($R^2 = 0.3314$) for Mukurweini. We reject the null hypothesis and accept the alternate hypothesis. The yearly trend line analysis of Mukurweini sub-county presented R^2 =0.3441 which translates to 33.14% change while in Imenti South $R^2 = 0.3441$ translating to 34.41% (Figure 3).

This indicates that there was a positive but gradual change in temperature with a peak year occurring after every 3 to 5 years in the study areas. In Mukurweini the overall temperature change for 37 years (1980–2017) was 0.8°C translating to 0.02°C of annual increase while in Imenti South, the overall temperature change for 37 years was 0.6°C translating to 0.016°C annually. These findings concur with IPCC (2001), which showed that temperatures are projected to increase by around 0.4°C in East Africa for the same period.

High temperatures (particularly a change >3°C) are projected to dramatically affect agricultural productivity, farm incomes, and food security (Rosenzweig et al. 2014). This concurs with Niang et al. (2014) who projects an increase in temperature and precipitation in East Africa. It was observed that in the study areas, the temperature would get to peak after every three to five years and result in drought in the region. These findings

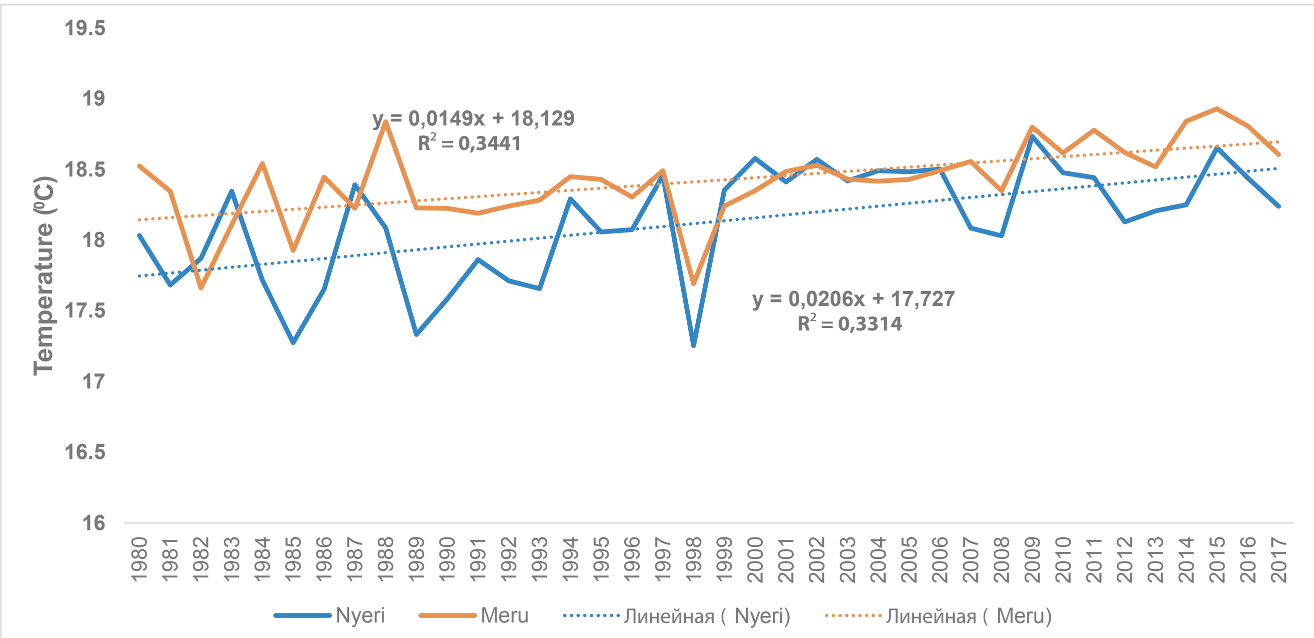

Fig. 3. Time series of annual temperature data for Meru (Imenti South sub-county) and Nyeri (Mukurweini sub-county) and their linear trend lines

further agree with NEMA (2014) who noted that drought is a frequent phenomenon in Kenya occurring after every 4 years, thus impeding agricultural investments (GOK 2013).

Rainfall

The study's null hypothesis was that there is a positive trend in temperature within Mt. Kenya region. The highest recorded average annual rainfall for Mukurweini and Imenti South sub-counties between 1980 and 2017 were 949 mm and 1286 mm, respectively (Figure 4). High rainfall amounts were recorded in Imenti South in the years 1986, 1997, and 2002 amounting to more than 1800 mm annually while in the years 2000, 2004, and 2015, we recorded the lowest amount of rainfall (below 1000 mm annually). In Mukurweini sub-county, the rainfall was moderate – below 1500 mm annually except in the years 1997, when we recorded 1,620 mm. Rainfall amount below 600 mm was recorded in the years 1987, 1999, 2000, and 2005. Linear regression analysis of the rainfall data showed that rainfall decreased in both study locations and rainfall peaks were identified to occur after every four to seven years as shown in (Fig. 4). The study findings further reveal a decreasing trend in rainfall in Mt. Kenya region, which is represented by a negative slope in the corresponding trend of linear equations (Fig. 4) thus $y = -9.1757x + 1510.7$ ($R^2 = 0.1014$) for Imenti South and $y = -6.4444x + 1087.7$ ($R^2 = 0.1064$) for Mukurweini hence we reject the null hypothesis and adopt the alternate hypothesis. Similar trends in temperature have been documented by (IPCC 2001; Rosenzweig et al. 2014). The authors recognize that rainfall trends in Africa are changing and the continent will experience increased drier conditions with rainfall decreasing at a rate of between 10% and 20% in Southern Africa and between 10% and 50% in eastern and northern parts of Africa (Shongwe et al. 2009; 2011; Schlenker and Lobell 2010).

Impacts of climate variability on banana value chain

The effect of climate variability on banana production was analyzed based on respondent's assessment of climate factors such as scarcity of water for irrigation, changes in planting dates, labour cost, reduced yields, delay in harvest and pest and disease infestations while aspects of banana value chain under consideration were mainly in production, marketing, and value addition.

Banana production

To understand the effects of climate variability on production, surveys involving farmers were conducted to find out the effect of climate variability on banana production. In the two study areas, reduced yield was reported as the main effect of climate variability on banana production with 79.2% of respondents in Mukurweini and 60.2% of respondents in Imenti South. Scarcity of water for irrigation was reported as the second most important effect of climate variability on banana production with 11.5% in Mukurweini and 19.1% in Imenti South (Table 2).

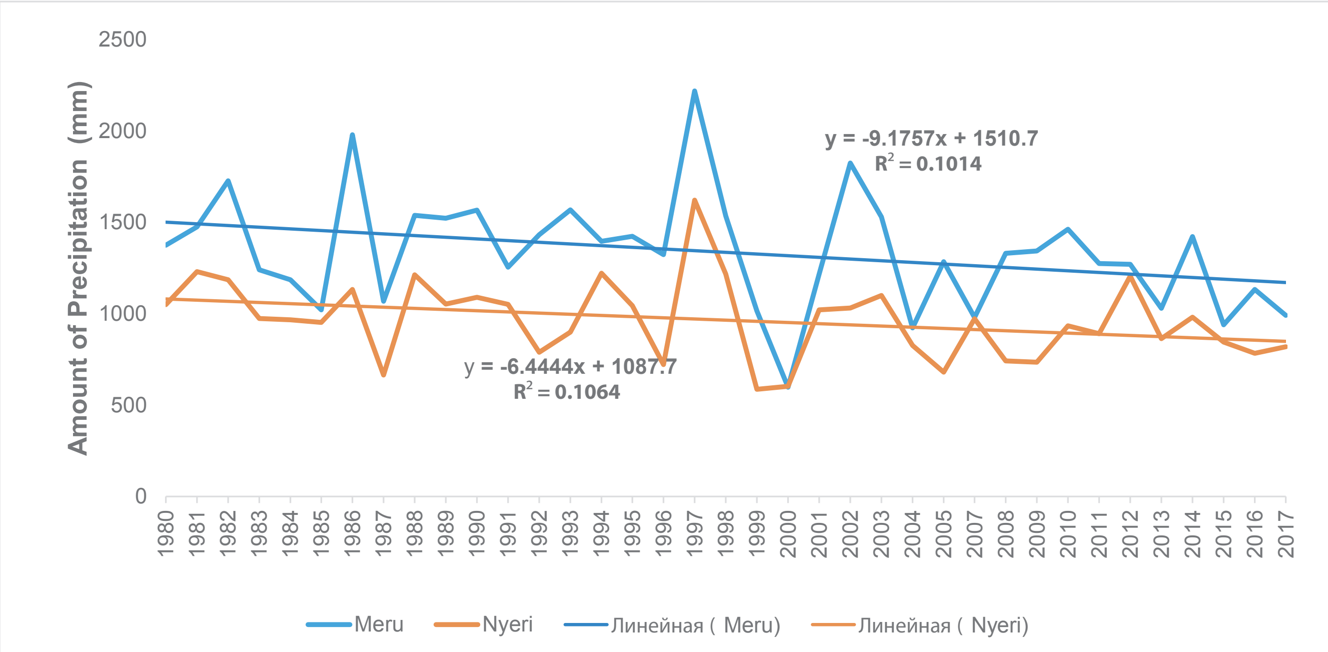

Fig. 4. Time series of annual Rainfall data for Meru (Imenti South sub-county) and Nyeri (Mukurweini sub-county) and their linear trend lines

Table 2. Effects of climate variability on banana production per study location

	Mukurweini (n=130)		Imenti South (n=251)	
	Frequency	Percentage	Frequency	Percentage
Scarcity of water	15	11.5	48	19.1
Changes in planting dates	7	5.4	15	6.0
Labour cost	1	0.8	3	1.2
Reduced yields	103	79.2	151	60.2
Delay in harvesting	2	1.5	22	8.8
Pest and diseases infestation	2	1.5	12	4.8
Total	130	100•0	251	100•0

These findings concur with Karienye and Kamiri, (2020) who found out that decrease in temperature levels led to corresponding increase in banana production in the period from 2009 to 2012 while increase in temperature led to a decrease in production in the period from 2013 to 2015 in a study conducted in Kenya. Furthermore, Rodomiro (2012) noted that climate variability may affect banana and plantain yields negatively in Latin America. Studies conducted in some Feed the Future (FtF) countries in Africa, Asia, and Latin America revealed that drought stress is either the most important or the second most important constraint in banana production in the region (Van Asten et al. 2011). Meanwhile, highland bananas are projected to experience significant yield loss due to increased risk of pest and diseases if the temperature increases by 2°C (Thornton and Cramer 2012).

Transportation of banana production to the market

The effect of climate on banana transportation was analyzed based on respondent's interpretations of transport issues such as changes in transport cost, accessibility to farms and handling of production, which affected the quality (Figure 5). The results indicated that majority of the respondents (52.3%) in Mukurweini and (45.0%) in Imenti South sub-counties found high cost of transport as the main effect of climate variability during rainy seasons that affected banana transport. Approximately 34.6% and 29.5% of the respondents in Mukurweini and Imenti South, respectively, cited lack of accessibility to the farm during the same period to have been affected by climate changes. Miriti et al. (2013) noted that rural areas in Kenya have poor roads connectivity. Poor infrastructure in the study area during the rainy season made roads impassable due to an increased cost of transport from the farms to the market or collection centers. This confirms the findings of other authors such as by Wambugu (2005); Mwithirwa (2010). Mwithirwa (2010) reported that 95% of the traders used poorly maintained roads in dry weather to access major buying areas thus hindering timely access to the production centers.

Miriti et al. (2013) in the studies conducted in Mt. Kenya region reported that bad rural road was the main constraint (ranked the highest) faced by banana farmers in the area. In the study region it was observed that banana markets have been set up close to banana producing areas such as Kanyakine in Imenti South and Ichamara in Mukurweini sub-counties where buyers from far areas come to buy bananas immediately after they are harvested. Such markets are situated along the tarmac roads due to accessibility by long distance buyers (Fig. 6).

Effects of climate variability on banana post-harvest handling

Post-harvest handling of banana products was affected by climate variability by 13.1% and 25.5% in Mukurweini and Imenti South, respectively (Fig. 5) and, thus, affected the market value of the fruit. The mode of transportation coupled with inefficient handling of the products led to high levels of deterioration and wastage of the banana fruit. These findings are supported by Technoserve (2004) who showed that poor handling of horticultural products inflicted physical damage of the fruits at all levels and led to high post-harvest losses estimated at 40%. In addition, poor handling during banana ripening can significantly reduce green and shelf life, which lasts 5–10 days after harvest. Strategies such as appropriate means of transportation and proper storage that could reduce post-harvest losses are not available in the region and where they are available access might not be equitable due to social differentiation (Hailu et al. 2013).

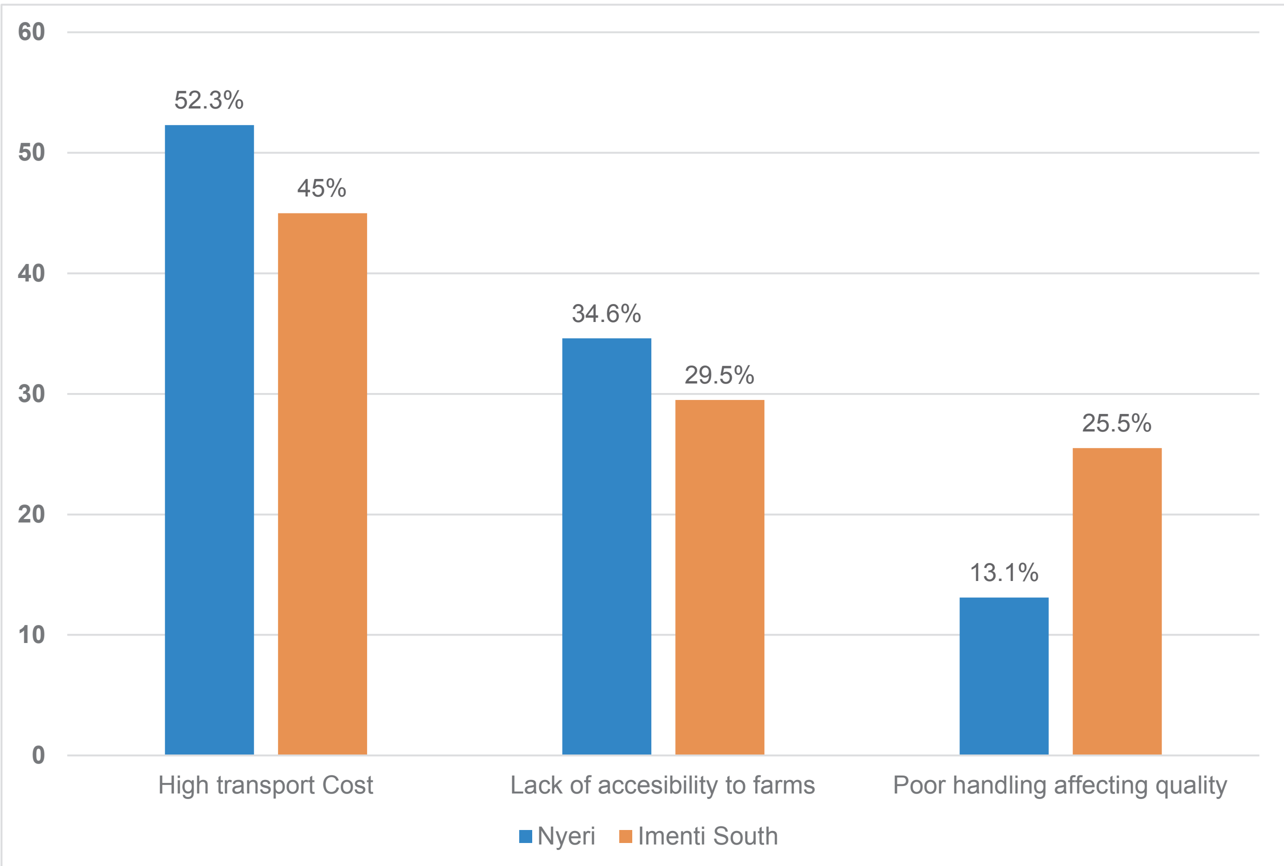

Fig.5. Effect of climate variability on banana produce transport

Fig. 6. Lorries waiting to load bananas along the roadside in urban centers in Imenti South sub-county along the Meru-Nairobi highway (the Kanyakine Market) Dated 23rd June 2017

Fig. 7. Mode of transport from farm to collection points/Market in the study areas

When mode of transport was considered, it was observed that most of the respondents (43%) in Mukurweini preferred using human labour where women carry the load on their backs and motorcycles commonly referred to as "boda boda" both while in Imenti South most farmers (56%) preferred to use motorcycles (Fig. 7).

Effects of climate variability on banana processing and value addition

Post handling of banana products and processing technologies adopted by the respondents as a result of the effect of climate variability in the region were indicated as cleaning of banana products to enhance their value, improved packaging, and value addition (flour production, crisps, wine juice) and ripening.

Majority of the respondents cited cleaning (48.6%) as the main strategy of banana value addition in the study region. In Mukurweini sub-county, majority of the respondents ranked ripening of bananas the first (45.3%) followed by cleaning (24.6%). In the Imenti South sub-county, farmers preferred cleaning (60.9%) followed by packaging in crates and sacks (26.3%) (Table 3). Ripening at the farm level was aimed at increasing market demand at the local market while cleaning the fruits was aimed at making the fruit more appealing to buyers thus increasing the selling price. Processing of banana fruits to other high-value products was limited in the study region. However, the number of farmers engaged in producing flour (3.1%), crisps, and wine juice is small (0.5%). These findings concur with MoA (2016), which observed that banana processing facilities in the Meru county were limited. This is hindered by low investments in agro-processing, lack of business and technical skills. Agro-processing industries among smallholder farmers would unlock their production potential hence earning more from banana enterprise. Mbuthia and Wambugu (2018) reported that banana value addition could prolong the shelf life of bananas, create more jobs in the sector and enhance domestic and international marketing. MoA (2016) concluded that value addition could help small holder farmers to earn more from their products if adopted.

Effects of climate variability on banana farmers' welfare

Climate variability has effect on the welfare of the smallholder farmers. The effect on welfare was identified as reduced income thus depending on the seasonal source of food for the household. During the dry season income increased due to market demands whereas during the

Table 3. Value addition strategies adopted by banana farmers

Study location	Cleaning	Packaging	Ripening	Processing			
				Flour	Crisps	Wine juice	Total
Mukurweini	32(24.6%)	25(19.2%)	59(45.3%)	11(8.5%)	1(0.7%)	2(1.5%)	130(100%)
Imenti South	153(60.9%)	66(26.3%)	25(10.0%)	1(0.4%)	1(0.4%)	5(2.0%)	251(100%)
Total	185(48.6%)	91(23.9%)	57(22.0%)	12(3.1%)	2(0.5%)	2(0.5%)	381(100%)

rainy season the income reduced. The food security was achieved during rainy season while during dry season food insecurity was felt due to declining yields. This indicates that climate variability has direct impact on farmers' household welfare.

Effects of climate variability on banana marketing trends

The effect of climate variability on marketing was identified as high market demands, low market prices, and low quality of products depending on seasons. Further we found out that different seasons have significant effect on banana trading. Majority of the respondents in Mukurweini sub-county (50.7%) indicated that during high rainfall seasons bananas were of low quality while in Imenti South sub-county the respondents reported low market demands (50.6%) during the period with high rainfall (Table 4). During the dry season majority of the respondents (36.9%) in Mukurweini and 45.8% in Imenti-South indicated that bananas were of small size and low quality referred to as "seketa" (Table 4). High quality bananas create demand for the products in the market thereby increasing the incomes of farmers. The perceived quality plays a major role in price determination (Dijikstra 1997).

Banana consumption also varies with seasons thus affecting trade. During high rainfall seasons, consumption goes down due to availability of alternative food such as maize and vegetables and consequently low market demands for banana. During hot seasons banana ripening is hastened and there is a high consumption rate due to a high demand on bananas. Extreme weather events, i.e. a large amount of rainfall or extreme temperatures are detrimental to the quality of fresh products. High rainfall and low temperatures delay ripening of bananas while consumption is equally low.

Adaptation strategies to climate variability in the region

Five adaptation strategies were reported by banana farmers in the region as shown in Table 5. Majority of respondents in Mukurweini Sub-County preferred crop diversification (36.2%) and planting of drought tolerant banana varieties (32.3%) as their adaptive strategies to climate variability.

In Imenti South, most farmers preferred irrigation (84.9%) as the best option to unreliable and unpredictable rains within the seasons. Crop diversification was preferred as an alternative to providing food for the family. These findings are supported by Shikuku et al. (2017) who observed that inclusion of dual-purpose sweet potato variety in cropping system would be sufficient to offset the negative impacts of climate variability in studies conducted in Machakos County. Some respondents in Mukurweini and Imenti South sub-counties preferred no adaptation strategy – 8.5% and 5.9%, respectively. In Mukurweini sub-county irrigation as an adaptation strategy was least opted (3.8%) while in Imenti South sub-county drought-tolerant banana varieties were least preferred (2.0%) (Table 5).

Irrigation as an adaptation strategy has been supported by the studies conducted by MoA (2016), which found that most farmers in Meru County irrigate their banana stems in between seasons due to availability of water and this was much more widespread in the drier parts of Imenti South, specifically in Mitunguu. Use of irrigation in banana production increases the produce per season thus making banana fruit an all year-round crop with constant harvest. In Mukurweini farmers depended on rain-fed system of production thus experiencing challenges brought about by climate variability such as decline in production.

Dependence of banana production in the study region

Banana production in the study region was primarily aimed at income generation (53.0%) and provision of food (47.0%) as shown in Table 6. In Imenti South and Mukurweini Sub counties, bananas were mainly grown for income generation (fees, cater for medical expenses, source of income, and more profit) and therefore variation in production or in the markets have a serious effect on farmer's livelihood sustainability. This shows that banana harvest plays significant role on the households' welfare.

Table 4. Effects of climate variability on banana marketing

Study location	Long rain season				Low rain season			
	High market demands	Low market prices	Low quality of products	Total	High market demands	Low market prices	Low quality of products	Total
Mukurweini	32 (24.6%)	32 (24.6%)	66 (50.8%)	130 (100%)	44 (33.8%)	38 (29.3%)	48 (36.9%)	130 (100%)
Imenti South	45 (10.4%)	127 (50.6%)	98 (39.0%)	251 (100%)	105 (41.8%)	31 (12.4%)	115 (45.8%)	251 (100%)
Total	77 (20.2%)	159 (41.8%)	164 (43.0%)	381 (100%)	149 (39.1%)	69 (18.1%)	163 (42.8%)	381 (100%)

Table 5. Adaptation strategies among the respondents

Study location	Drought-tolerant varieties	Crop diversification	Shifting of planting dates	Irrigation	No adaptation	Total
Mukurweini	42(32.3%)	47(36.2%)	25(19.2%)	5(3.8%)	11 (8.5%)	130(100%)
Imenti South	5(2.0%)	6(2.4%)	12(4.8%)	213(84.9%)	15(5.9%)	251(100%)
Total	47(12.3%)	58(13.9%)	37(9.7%)	218(57.2%)	26(6.8%)	381(100%)

Table 6. Significance of banana production in the study regions

Location	Income	Food	Total
Mukurweini	66(50.8%)	64(49.2%)	130(100%)
Imenti South	135(53.8%)	116 (46.2%)	251(100%)
Total	201(53.0%)	180(47.0)	381(100%)

Sustainability of the small-scale banana production

Changes in climate and its variability in terms of temperature and rainfall were analyzed annually to understand the sustainability of banana production in the region. As the temperature and rainfall varies the small holder farmers got enlightened on the best adaptation strategies hence sustainable production despite climate variability.

Small-scale banana production in the region is of paramount importance; it ensured sustainable functioning of the households in terms of food security. The production brings income to the households, which serve as a source of income for fees for school going children and caters for medical expenses for the family. The higher is the profit generated by farmers the lower are the associated risks.

Irrigation as an adaptation strategy will promote sustainability among smallholders. Irrigating banana stems in between seasons due to availability of water will ensure constant production throughout the year. Use of irrigation in banana production increases the output per season. Mixed cropping of banana with other crops provides food security for the family hence promoting sustainability among the households.

Post-handling technologies such as cleaning of the banana products, improved packaging and value addition (flour production, crisps, wine juice) and ripening promotes sustainability of the production. These technologies boost market value of the products.

CONCLUSIONS

This study has revealed that climate has been changing during the study period between 1980 and 2017. The overall annual change in temperature in Mukurweini sub-county for the study period was 0.02°C while in Imenti South it was 0.016°C, which translates to 0.2°C and 0.16°C per decade, respectively. These climate trends negatively affect banana productivity in the region hence food insecurity in the region, therefore adaptation measures are critical. The main impact of climate variability on banana sustainability in the study area was decline in banana production as a result of low rainfall incidences leading to a reduced banana production and low quality of products such as small bunches referred to as "seketa". High temperatures lead to damage of banana crops and increased host pests and diseases leading to further decline in yields. These findings agree with other studies, which found that inter-annual unpredictability in precipitation have negative consequences on rural livelihoods especially crop productivity.

High transport cost was the main effect of climate variability during rainy seasons that affected market aspects of banana value chain development. When mode of transport was considered, it was observed that most of the respondents in Mukurweini (Nyeri County) preferred to use human labour (women carry the load on their backs) and motorcycles commonly referred as "boda boda" both when transporting bananas to the collection point or market centers while in Imenti South (Meru County) most farmers preferred to use motorcycles. In order to make banana transport sustainable it is important to improve the road networks from farms to the collection or market centers. To enhance the market value and sustainability of the production, farmers in Mukurweini sub-county preferred ripening of bananas before delivering to the market while in Imenti South sub-county they preferred cleaning bananas and packaging in crates and sacks thus enhancing their value. During high rainfall seasons, bananas were reported to be of low quality in Mukurweini while in Imenti South we registered low market demand thus increasing wastage and low prices. This implies that there is a need for farmers to embrace value addition, which helps the small holders' farmers to earn more from their products owing to sustainability in banana production.

The most preferred climate adaptation strategy varied between the two study areas with Mukurweini farmers preferring crop diversification and Imenti South farmers opted for irrigation of the banana crop. Therefore, from these finding it can be concluded that climate variability is perceived differently in the region and adaptation measure undertaken by farmers varies within the region. It is worth noting that irrigation as an adaptation strategy on banana production promotes sustainability in the region while crop diversification ensures food security among the households. High-quality bananas create demand on the product in the market thereby bringing more money to the farmers hence promoting sustainable production.

RECOMMENDATIONS

The study proposes the following areas for further research at banana production level: sustainability of water harvesting on banana production and level of adoption of drought-tolerant varieties and crop diversification among the small holder's farmers in the region. Regarding banana transportation further studies should be conducted on the impact of road network on banana production. At marketing level, the effect of market information on banana production should be studied. The level of adoption of value addition on banana should be studied. Another suggested area of further research is to ascertain the impact of number of rainy days in each year on banana value chain in the region.

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RESEARCH PAPER

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BIOREMEDIATION OF SOIL OF THE KOLA PENINSULA (MURMANSK REGION) CONTAMINATED WITH DIESEL FUEL

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ABSTRACT. This work focuses on the creation and use of associations of hydrocarbon-oxidizing microorganisms. Bioremediation of soils with the help of mixed cultural and associations of microorganisms provides wider adaptive possibilities than individual species. This is especially important in conditions of short northern summer. The results of field experiments showed that microbial associations based on indigenous microorganisms (bacteria *Pseudomonas fluorescens, P. putida, P. baetica, Microbacterium paraoxydans* and fungi *Penicillium commune, P. canescens st. 1, P. simplicissimum st. 1*) with mineral fertilizers reduced the content of total petroleum hydrocarbons in the Hortic Arthrosol soil of the Kola Peninsula by 82% over 120 days. Also, the microbial associations with mineral fertilizers had a positive effect on the physical properties of the soil, increasing its humidity. The bacterial-fungi associations changed the number, abundance and structure of the indigenous community of microorganisms. *Penicillium canescens*, which was included in the composition of fungi association, became dominant. During the rapid decomposition of hydrocarbons are released to the soil toxic intermediates or metabolites of the microbial oxidation of hydrocarbons. Hydrocarbon oxidizing microfungi suppressed the germination of test plant seeds to one degree or another. *Penicillium commune* fungal metabolites inhibited seed germination only by 29% for *Lepidium sativum* L. and 24% for *Triticum aestivum* L. This species can be used for bioremediation of petroleum contaminated soils.

KEY WORDS: diesel fuel, petroleum-contaminated soil, bioremediation, hydrocarbon-oxidizing bacteria, microfungi, phytotoxicity

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INTRODUCTION

The constantly increasing anthropogenic impact results in the high accumulation of various xenobiotics in ecosystems. Mineral oil and petroleum products are major pollutants among all environmental contaminants because of their danger, quick spreading capacity, and slow decomposition in the environment. The petroleum hydrocarbons in soil lead to a loss in the soil's fertility, causing soil structure damage, a change in water–air and redox conditions, a loss of infiltration capacity, the appearance of anaerobiosis, and a decrease of biogeochemical activities (Das and Chandran 2011; Adams et al. 2015).

Potentially hazardous sources of contamination with petroleum products in the Kola region include oil tank farms, fuel and power facilities, major industrial plants with their own vehicle fleets, petrol filling stations, and military facilities that use various petroleum products.

Purification of petroleum-contaminated areas is a challenge for environmental remediation. Thus, there is an urgent need to develop methods for reducing the negative impact of petroleum hydrocarbons on the natural ecosystem. This investigation is especially important for the North Kola region. The self-purification and self-recovery rate of petroleum contaminated soil depends on soil type, petroleum composition, contamination rate, solar radiation intensity, concentration of macronutrients, temperature and oxygen concentration (Grotenhuis et al. 1998; April et al. 2000).

Mechanical remediation of contaminated soil leads to the disturbance of the soil profile as well as to removal of the topsoil layer. The use of various sorbents and solutions creates a danger for secondary environmental pollution. Thereby, the effective removal of hydrocarbons from the soil by only one of methods (mechanical, physical, and chemical) is almost impossible. Consequently, the successful remediation of petroleum contaminated soil can be based on complex approaches only. Biological method is more advanced and promising for the final elimination of hydrocarbon and other types of pollution (McGill 1977; Koronelli 1996; Pinedo-Rivilla et al. 2009; Adams et al. 2015; Korneykova et al. 2019). The method is based on introducing hydrocarbon-oxidizing microorganisms isolated from the contaminated soils or genetically modified. The biological method also involves the stimulation of indigenous hydrocarbon-oxidizing microorganisms combined with agrotechnical methods (cultivation, fertilizer application, watering etc.) (Heath 1993; Ghazali et al. 2004; Joo et al. 2008; Nilanjana and Chandran 2011). The main advantages of this method are efficiency, profitability, ecological safety, operation flexibility, and lack of secondary pollution (Kireeva et al. 2005).

Bacteria are essential for the purification and remediation of contaminated soil, especially the hydrocarbon-oxidizing strains of genera *Acinetobacter, Agrobacterium, Arthrobacter, Bacillus, Corynebacterium, Enterobacter, Flavobacterium, Microbacterium, Micrococcus, Mycobacterium, Nocardia, Pseudomonas, Rhodococcus,* and *Stenotrophomona* (Myazin and Evdokimova 2012). Microfungi significantly contribute to the self-purification of soil from hydrocarbons (Bilaj and Koval 1980; Field et al. 1992; April et al. 2000; Cerniglia and Sutherland 2001; Tigini et al. 2009; Samson et al. 2010; Khabibullina and Ibatullina 2011; Evdokimova et al. 2013; Korneykova et al., 2019), especially in acidic soil with unfavorable conditions for bacterial growth. The most active hydrocarbon-oxidizing fungi strains mainly refer to the genera *Aspergillus, Penicillium, Fusarium,* and *Trichoderma* (Glyaznetsova and Zueva 2013).

The biological methods for soil remediation can lead to some problems related to the interaction of introduced associations with native soil microbial communities. The increase of species with phytotoxic activity is possible due to rearrangements in the complex of microorganisms. According to Kireeva et al. (2009), the hydrocarbon-oxidizing microfungi are less sensitive to petroleum products, but they can increase soil phytotoxicity. Therefore, the possible microbial toxicosis of petroleum contaminated soils should also be taken into account when using biological preparations.

The main goal of research was to study the influence of biological treatment (with microbial associations) on the rate of remediation of Kola Peninsula soils contaminated with diesel fuel under a field condition.

MATERIALS AND METHODS

Soil

The soil was Hortic Arthrosol on sandy lake-glacial sediments. The samples were collected on each plot at 10-cm depth after 1, 3, 12, 15 months. Stones and root were removed; the soil was passed through a 1 mm sieve and thoroughly mixed for chemical analysis. That is an arable soil with 3.38% organic matter, nitrogen - 0.3%, calcium - 2.26 mg-eq/100 g, magnium - 0.41 mg-eq/100 g and pH 5.5.

Contaminant

The summer diesel fuel was used to contaminate the soil. The diesel fuel brand is L-0.2-62, it meets the requirements of GOST 305-82 (density with 20°C – 835 kg/m^3; viscosity with 20°C – 5.11 mm^2/s; fractional composition, 96% - not more 359°C; cetane number – 47; resin concentration – 4.6 mg/100 cm^3; mass fraction of sulfur – 0.16%).

Microbial associations

At first hydrocarbon-oxidizing bacteria (HOB) (*Pseudomonas fluorescens, P. putida, P. baetica,* and *Microbacterium paraoxydans*) and microfungi (*Penicillium canescens st. 1, P. commune,* and *P. simplicissimum* st. 1) were grown separately. These microorganisms' strains were taken from collection of the INEP KSC RAS. Previously, these strains were isolated from petroleum contaminated soil on Kola Peninsula.The 16S ITS gene regions obtained from those bacterial strains were deposited in the NCBI GenBank database under the registration numbers KM288708, KM288709, and KM 216318. A bacteria was grown in meat-peptone broth in the laboratory fermenter (BIOSTAT® A plus, Sartorius, Germany) under 27°C and aeration for 3 days. Bacterial suspension density was 10_8–10_9 cells/L. The fungal suspension was incubated in Erlenmeyer flasks in Czapek's liquid medium at a temperature of 27°C for 10 days. The number of fungi in suspension was 10_5–10_6 colony-forming units (CFU)/L. To prepare the bacterial-fungal suspension, the bacterial and fungal ones were mixed in equal proportion in meat-peptone broth.

Experiment design

The microfield experiment was performed at the Polar Experimental Station of Apatity Branch of the Vavilov All-Russian Research Institute of Plant Industry (Apatity, Murmansk region, coordinates 67°32'57", 33°22'30"). The size of each experimental plot is 1 m^2. The experiment continued for 15 months: from beginning of June 2018 until the end of September 2019. The experiment design is given in Table 1. Each variant was in triplicate.

Diesel fuel was added once on June. Just after the soil contamination it was amended with a complex mineral fertilizer (N = 16%, P_2O_5 = 16%, K_2O = 16%) in an amount of 60 g/m^2 as well as the microbial associations were inoculated there in the amount of 1.2 L/m^2. The top layer of the soil in all variants was mixed to a depth of 5 cm. After 1 month the soil amendments were repeated.

Determination of the total petroleum hydrocarbons content (TPH) in soil

The content of TPH in the soil was determined by IR spectrometry, using the AN-2 analyzer. The method

Table 1. The experiment design

Soil sample	Treatment	Disel fuel dose, l/m^2	Total amount of inoculated microorganisms, CFU/L	Mixing and fertilizer application	Total $N_{16}P_{16}K_{16}$, (g N,P_2O_5,K_2O/m^2)	
					1st month	2nd month
PS	Background (pure) soil	-	-	+	-	-
DF	Diesel fuel	10	-	+	9.6	9.6
DF+B	Bacteria		10^8–10^9	+		
DF+F	Fungi		10^5–10^6	+		
DF+BF	Bacteria+Fungi		10^6–10^7	+		

is based on the extraction of TPH from the soil with tetrachlorcarbon, separation of oil products from the polar hydrocarbons in the column filled with aluminum oxide, and further spectrophotometric identification of hydrocarbon content, according to absorption intensity of infrared radiation at fixed wavelengths (Drugov and Rodin 2007). The effect of microbial preparations was evaluated through analysis of the residual content of TPH in soil and decomposition rate.

Number and species diversity of culturable soil microfungi

The number of culturable microfungi was determined by plating method on the Czapek's nutrient media with lactic acid (4 ml/L of medium for bacteriostatic effect). Morphological characteristics were evaluated using an optical microscope Olympus CX-41 (Japan) with a camera Jenoptik ProgRes CT3 (Germany). Species were identified according to classical identification guides (Raper and Thom 1968; Klich 2002; Domsh et al. 2007; Seifert et al. 2011). Microfungi names were checked according to CABI Bioscience Databases (http://www.indexfungorum.org).

Phytotoxicity of hydrocarbon-oxidizing microfungi (HOM)

The level of HOM toxicity for plants was evaluated using the seeds of *Triticum aestivum* L. and *Lepidium sativum* L. The HOM were grown in Czapek's liquid medium for 10 days. The cultural liquid was separated from mycelium by filtering. The experimental seeds (30 seeds in triplicate) were placed into a Petri dish with filter paper and 10 ml of a fungi cultural liquid. Instead of fungi cultural liquid, water and sterile nutrient medium was used in the control. The Petri dishes were kept in the thermostat for 24 h at 25–26°C and then the number of germinated seed was counted. The fungi were considered toxic for plants at the reduction of seed germination by 30% in comparison with the control (water) (Bilaj and Koval 1980).

Determination of physical-chemical properties of soil

Soil humidity was measured by drying soil samples at 105°C to a constant weight.

The actual soil acidity was determined by the potentiometric method with a Radelkis OP-300 laboratory pH-meter with a combined pH electrode in the 1:2.5 water extracts from soil.

Statistical analyses

The data were statistically analyzed by the Statistica 6.0 and Microsoft Excel 2007 applied software. The reliability of the calculated coefficients was determined to use Student test.

RESULTS AND DISCUSSION

Influence of microbial associations on physical-chemical properties of soil

A positive effect of biological treatment on soil humidity was noted. This trend was also found at the beginning of the second vegetation period. However, by the end of the second vegetation period, there was no significant difference between the treatments (Fig. 1). The positive impact of biological treatment on the humidity content of contaminated soil will allow using plants for further bioremediation in more favorable conditions.

The microbial associations with mineral fertilizers resulted in a pH decrease of soil by 0.1 to 0.2 units. At the same time, despite using the same number of mineral fertilizers, lower pH values were found with F and B+F treatments. This can be a result of acidifying caused by the active release of metabolites by fungi (Fig. 1).

Influence of the microbial associations on the number of soil microorganisms

The dynamic of soil heterotrophic bacteria, HOB and microfungi in various soil treatments shown on the Fig. 2. The initial number of culturable soil microfungi was 3×10^3 CFU/g. During the first day after the soil contamination with treatment DF and DF+B, their number reduced by 2.4 and 2.8 times, respectively, that can be explained by toxic effect of diesel fuel on indigenous microfungi. At the same time, the number of the microfungi with treatment DF+F and DF+BF were 154×10^3 and 56×10^3 CFU/g respectively after 1 day. To the next year, the number of the soil fungi increased by 3-4 times, that is to 193-226$\times10^3$ CFU/g. These values were about one order of magnitude higher than in the treatment DF and 3-4 times higher than in the treatment B (Fig. 2A).

In contrast to microfungi, the soil contamination with diesel fuel did not inhibit growth either HOB or heterotrophic bacteria. The number of heterotrophic bacteria in the pure soil was $(16.8\pm1.7)\times10^6$ cells/g. During the first day after contamination and fertilizing, their number with

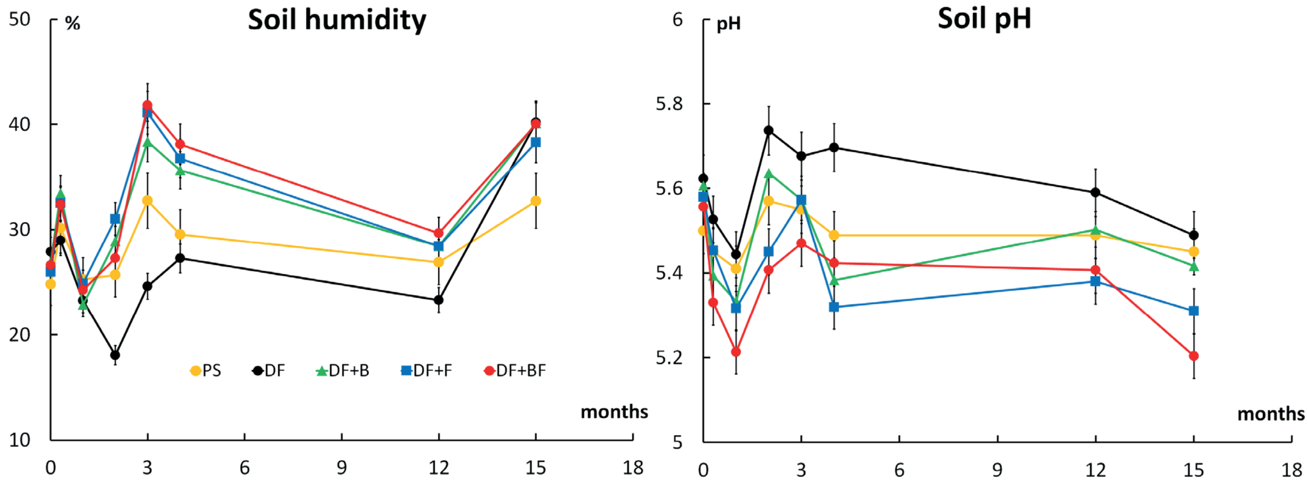

Fig. 1. Dynamics of soil humidity (A) and pH (B) in the background (pure) soil (PS), in diesel fuel contaminated soil (DF) and with association of bacteria (DF+B), fungi (DF+F), mix with bacteria-fungi (DF+BF)

treatment DF and DF+F were increased to (20.5±0.6)×10^6 cells/g. In the next year those values remained increase – (37.5±3.5)×10^6 CFU/g compared to the pure soil. After one day of inoculation the number heterotrophic bacteria in the soil with treatments DF+B and DF+BF were 58.2×10^6 and 31.4×10^6 CFU/g, respectively. Already in 3 months of the soil treatment, their number increased by 6-7 times and remained practically the same till the next year (Fig. 2B).

The dynamic of indigenous HOB in those soils was almost similar. Their number increased from 3.2×10^6 CFU/g in the pure soil to 6.3×10^6 and 11.9×10^6 with treatment DF and DF+F, respectively. The number of culturable heterotrophic bacteria in the soil with treatment DF+B and DF+BF were 30.2 ×10^6 and 12.0×10^6 CFU/g after 1 day, and their number increased by 2-9 times respectively after 12 months treatment (Fig. 2C).

In accordance with the received data, the bacterial preparations supported a high number of culturable heterotrophic and HOB during all term of the observation. The microfungi, which are higher-level organisms than bacteria, are likely to be more sensitive to environmental changes but better able to adapt to a changing environment due to a powerful enzymatic system and abundant sporogenesis (Kireeva et al. 2009).

Influence of the microbial associations on the species diversity of soil microfungi

Soil contamination by diesel fuel reduced fungal species diversity in the soils (from 16 species initial to 11 species at the end of experiment) and changed the structure of the soil culturable microfungal community (Table 2). The fungi of genus *Penicillium* dominated in all soil samples. The increase amount of the fungi *Penicillium* with treatment DF+F and DF+BF from 50% initial to 75% after 3 months of experiment were noted.

The microbial preparations lead to changes in the structure of microscopic fungi complexes both at the beginning of the experiment and after 3 months. Initial the *P. simplicissimum* was the absolute dominant in the fungi community with treatment DF+F and DF+B+F. After 3 months *P. canescens* dominated in the soil with treatment DF+F and DF+B+F. According to previous our research this species is an active decomposer of petroleum products.

Toxicity of microfungi for plants

The biological preparations can influence both microorganisms and higher plants. Because of rearrangement in the species structure of the fungal communities, the toxin-forming microfungi can be dominant in petroleum contaminated soils. This can be considered as the supplementing factor conditioning the high toxicity of petroleum-contaminated soil toward the plants. Therefore, it is necessary to choose groups of microorganisms that have a low hazard effect on the environment.

In our experiment the culture liquid of microfungi (*Penicillium canescens, P. commune, P. simplicissimum*) suppressed the germination of test plant seeds to one degree or another. The maximum degree of phytotoxicity was observed with P. *simplicissimum* St. 1, which inhibits the germination of *Lepidium sativum* by 92% and *Triticum aestivum* by 30%. At the same time, Czapek's sterile medium also reduced the germination of *Lepidium sativum* seeds by 17% and Triticum aestivum seeds by 5% respectively. The lowest degree of phytotoxicity was shown by the species *P. commune*, which inhibited seed germination of plants by 29% for *Lepidium sativum* and 24% for *Triticum aestivum*. According Bilaj and Koval (1980), these fungi species are not toxic for plants and can be used in the biological preparations.

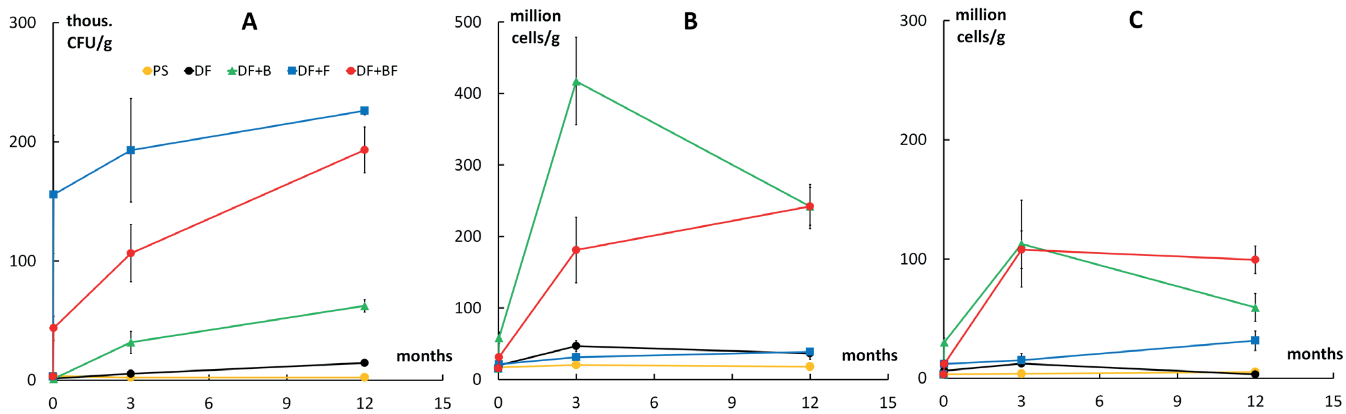

Fig. 2. The dynamics of the number of soils microfungi (A), heterotrophic bacteria (B) and HOB (C) in the soil. The legend is similar to Fig. 1.

Table 2. Dominating species of fungi in initial and after 3 months of experiment

Treatment	Initial	After 3 months
PS	*Sterilia mycelia* (24%), *P. ochrochloron* (24%), *P. janczewskii* (20%)	*P. simplicissimum* 25.3%
DF	*P. ochrochloron* (30%)	*Cephalosporium asperum* 27.5%
DF+B	*Pseudogymnoascus pannorum* (26%) *P. ochrochloron* (26%)	*P. simplicissimum* (30.2%)
DF+F	*P. simplicissimum* (98%)	*P. canescens* (46%)
DF+BF	*P. simplicissimum* (94%)	*P. canescens* (48%)

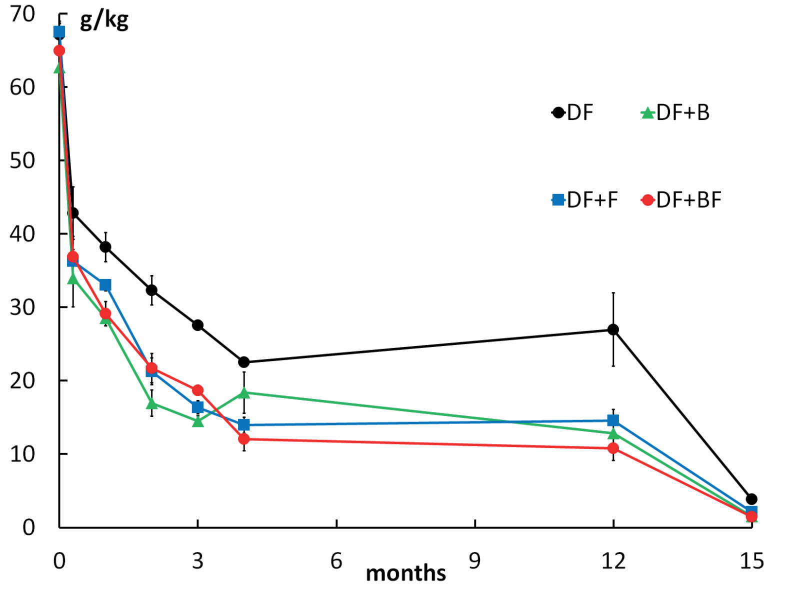

Fig. 3. The dynamics of TPH content in the contaminated soil. The legend is similar to Fig. 1.

Table 3. The rate of petroleum product destruction in soil (g/day)

Variant	Time period, days				
	1-10	10-30	30-60	60-90	90-120
DF	2.43±0.22	0.23±0.02	0.20±0.02	0.16±0.01	0.17±0.02
DF+B	2.87±0.20	0.27±0.02	0.39±0.03	0.08±0.01	0.01±0.01
DF+F	3.12±0.25	0.16±0.01	0.39±0.02	0.16±0.02	0.08±0.01
DF+BF	2.81±0.19	0.39±0.02	0.25±0.02	0.10±0.01	0.20±0.02

Influence of microbial associations on degradation rate of TPH in soil

The results presented on Fig. 3 indicates that all the microbial associations significantly accelerated degradation rate of diesel fuel in the soil compared to uninoculated control.

After 1 month, the petroleum products content with treatment B+F decreased by 57% from the initial and amounted to 29 g/kg. After 120 days the decrease was 82%, that 15% more than with no microbial associations. After 12 months the decrease was 23% more than DF variant. With treatment DF+B and DF+F the content of petroleum products decreased slightly less.

During the first month of the experiment, the petroleum product content reduced quickly due to evaporation (Myazin and Evdokimova 2012). The microbial preparations accelerated oil product decomposition by 10–20%. The rate of petroleum product destruction in soil changed throughout the experiment (Table 3). During the first 10 days, the rate was maximal because of intensive evaporation. Thereafter, the rate of oil product decomposition decreased. The most destruction of petroleum product with treatment DF+B+F was observed between 10 and 30 days of the experiment and for separately treatment DF+B and DF+F was revealed between 30 and 60 days, however the bacterial-fungi community (DF+B+F) maintained its efficiency even after 120 days.

CONCLUSIONS

The microbial associations based on indigenous microorganisms accelerated the decomposition of oil products in the Hortic Arthrosol soil on the Kola Peninsula and can be advised for clearing the environment from oil hydrocarbons. In the field experiment, the bacterial–fungi associations demonstrated a significant effect: the content of oil products reduced by 82% after 120 days that 15% more than with treatment DF (with no microbial associations). After 1 year the decrease was 23% more with treatment DF. The decomposition rate of oil products reached the maximum after 30 and 120 days. Because the soil of the Kola Peninsula is acidic, the efficiency of microbial associations based on fungi will likely be higher than those of bacterial associations. However, the difference between the variants in this field experience is not significant.

At the first period after contamination, the number of microfungi decreased in variants DF and DF+B relative to the control and after 90 days increased in all variants of experiment. Soil contamination by oil products resulted in a reduce in fungal species diversity and change of structure of the soil culturable microfungal community.

The species *Penicillium commune*, *P. simplicissimum*, *P. canescens*, being an active decomposers of oil products, showed almost no phytotoxic effect. They suppressed *Triticum aestivum* seed growth by 24% and *Lepidium sativum* seed growth by 29%. These species may be prospective for the creation of biological preparations and can be advised for the bioremediation of soil contaminated by oil products. However, the use of microbial preparations and phytoremediation have to separated.

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RESEARCH PAPER

RECONSTRUCTION OF OIL SPILL TRAJECTORY IN THE JAVA SEA, INDONESIA USING SAR IMAGERY

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ABSTRACT. Oil spill phenomena in the ocean possess a very serious threat to ocean health. On the ocean surface, oil slicks immediately start to spread and mostly end up in the ecosystem. Furthermore, it could threaten the organisms living in the ocean or impact nearby coastal area. The aim of this research was to investigate the trajectories of oil spill based on a real accident in the Java Sea. Tracking oil spills using satellite images is an efficient method that provides valuable information about trajectories, locations and the spread intensity. The objective of this study was to periodically track the trajectory of the oil spill from the Karawang incident using Sentinel-1 Synthetic Aperture Radar (SAR) images. Pre-processing of the images consisted of radiometric and geometric corrections. After the corrections, SAR images were mapped and plotted accordingly. To understand the oil spill trajectories in relation to the oceanic processes, the ocean current pattern map and surface wind roses were also analysed. The processed images from July to October 2019 show a trajectory dominated by the oil spill layers movement towards the west to northwest from the original location along with a decrease in the detected oil spill area over time. The identified trajectories of the oil spill followed the ocean current pattern and surface winds. Thus, these two parameters were considered to be the main factors responsible for the oil spill drift.

KEY WORDS: The Java Sea, oil spill, satellite SAR imagery, oil spill trajectory, ocean currents, wind

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INTRODUCTION

Oil spills in the ocean are hazardous to the marine ecosystem (Kingston 2002; Paine et al. 1996), they negatively affect the economy (Loureiro et al. 2006; Osmanoğlu et al. 2012), human health and society (Aguilera et al. 2010; Major & Wang 2012) as well as tourism activities (Sulistiyono 2013). Oil discharged in the ocean will immediately start to spread. Moreover, over time, it will get dispersed or degenerated by ocean processes that are collectively called weathering (Akkartal & Sunar 2008). Oil spills will form a layer on the ocean surface due to a difference in density and prevent oxygen transfer from the atmosphere to the water column. Furthermore, if oil accidentally enters marine organisms, it will interfere with the organs and they can be seriously harmed (Almeda et al. 2013; Incardona et al. 2011). Oil pollution in the ocean is challenging to clean and needs a long period to handle and manage, especially if they reach nearby coastal cities (S.E. Chang et al. 2014). With all the damage and impact, real-time information becomes increasingly important for decision-makers. Stakeholders are responsible for cleaning and rescuing the ecosystem as well as human habitat by applying mitigation measures (Fingas & Brown 1997). A study showed that coastal habitats need 20 years to recover from oil spills (Burns et al. 1993).

Previous major oil spills in the world have shown negative impact on the coastal ecosystem and communities. The Deepwater Horizon oil spill in 2010 is one of the more widely known significant oil spills. Studies on the environmental impact of the Deepwater Horizon showed that even several years after the incident, a small number of oil particles remained in the sediments (Barron 2012; Mansir & Jones 2012). A study on the Exxon Valdez oil spill also showed that five years after the incident the oil remained in the sediments, and it was estimated that it takes up to 30 years for oil to return to background levels (S.E. Chang et al. 2014). One of the more recent oil spills in Indonesia is the Karawang oil spill in 2019 in the Java Sea. Information gathered from the rig's company official website[1], showed that the oil spill affected several

[1]Pertamina Hulu Energy (PHE) Website (http://phe.pertamina.com/)

coastal communities in the Karawang and Bekasi Regency. It was also stated that clean-up and other measures to respond to the incident were done. It is crucial to monitor the progress of clean-up actions taken after an oil spill incident, and one of the advanced methods for it is using remote sensing (Brekke & Solberg 2005; Chaturvedi et al. 2019; Filipponi 2019).

To prevent a broader impact of oil spreading, nowadays experts use satellite images on small to large scale cases (Bayramov et al. 2018; Brekke & Solberg 2005; Fiscella et al. 2000; Kolokoussis & Karathanassi 2018; Solberg et al. 2007). Remote sensing data are becoming more accessible recently and some of it can be applied to detect oil spills (Harahsheh 2016). Data from active remote sensing instruments such as Synthetic Aperture Radar (SAR) has a vital role in oil spill detection due to its ability to sense the earth's surface in all weather conditions (Solberg et al. 2007). For example, the new mission satellite, Sentinel-1, which has one of the active sensors developed by the European Consortium, was launched in 2014 (https://sentinel.esa.int). The primary mission objectives are to monitor marine environment including sea ice, ocean waves and oil spills. The research related to detection and mapping of oil spills using SAR from Sentinel-1 satellite has shown that the satellite is capable of detecting oil spills. Prastyani and Basith (2018) explored the data by using an automatic and semi-automatic process to evaluate the oil spreads in Balikpapan Bay (Prastyani & Basith 2018). Chaturvedi et al. (2019) mentioned that SAR Sentinel-1 and other SAR data that have high resolution could be used to detect oil spills in different marine locations (Chaturvedi et al. 2019). Furthermore, Suneel et al. (2019) explored satellite data to identify oil leaks in the Arabian Sea and their correlation with the oceanographic conditions in the area (Suneel et al., 2019). In this context, the objective of this research was to use satellite SAR images to detect trajectories of the oil leakage produced by an oil platform in the Java Sea. Oil leaks (oil spills) were first noted on July 12, 2019, and spread over the sea for several months (PHE, 2019). The surrounding area of the Java Sea is a critical zone as it represents a necessary and prominent location for living, providing a roof for millions of people, fishing catch areas and ensuring the sustainability of coastal ecosystem (Purwanto 2003).

MATERIALS AND METHODS

Geographic Location

The focus area of the research was located near the platform (YYA-1), embedded in the coastal area of the Java Sea (6.09417° S, 107.6257° E). The affected coastal areas are the Bekasi and Karawang Region. The rig is controlled and managed by Pertamina Hulu Energi (PHE), a national oil company. The ocean basin surrounding the Java Sea is mainly shallow, with a depth of about 60 meters (Simanjorang et al. 2018) (Figure 1). These surrounding waters are also affected by Monsoon, tides, and the Indonesian Throughflow current (Purba & Pranowo 2015; Siregar et al. 2017).

The YYA-1 oil rig is located near the coastal area of Java Island, north of Karawang and approximately 10 km off the mainland. From the historical data, the oil leaks were noticed on July 12, 2019, when they were doing the re-entry during the re-perforation activities (PHE 2019). From «Daily Update Sumur YYA-1», it was noted that gas bubbles were the first sign of leakages seen from the YYA-1 rig.

Dataset

The data used in this study are Sentinel-1 SAR images acquired in the Interferometric Wide (IW) mode as Ground Range Detected (GRD) products with vertical-vertical (VV) and vertical-horizontal (VH) polarization[1]. These images can be used as an effective way to map oil spills. Backscattering of the SAR signal over the ocean is mainly due to the sea surface roughness, i.e., a portion of small gravity-capillary waves having a similar radar wavelength scale. Oil film dampens the short gravity-capillary waves on the sea surface and thus the backscatter, which makes spills visible in SAR images as dark spots. In contrast, the surrounding oil-free sea surface appears fairly bright (Topouzelis & Singha 2017).

Based on the European Space Agency (ESA) database, the appropriate satellite SAR images of the area of interest that are downloadable were taken in July (18 and 30), August (11 and 23), September (4, 16, and 28), and October (22). The first step of the process was downloading the data for the specified location and date. The next step was pre-processing, that included radiometric and geometric corrections that were

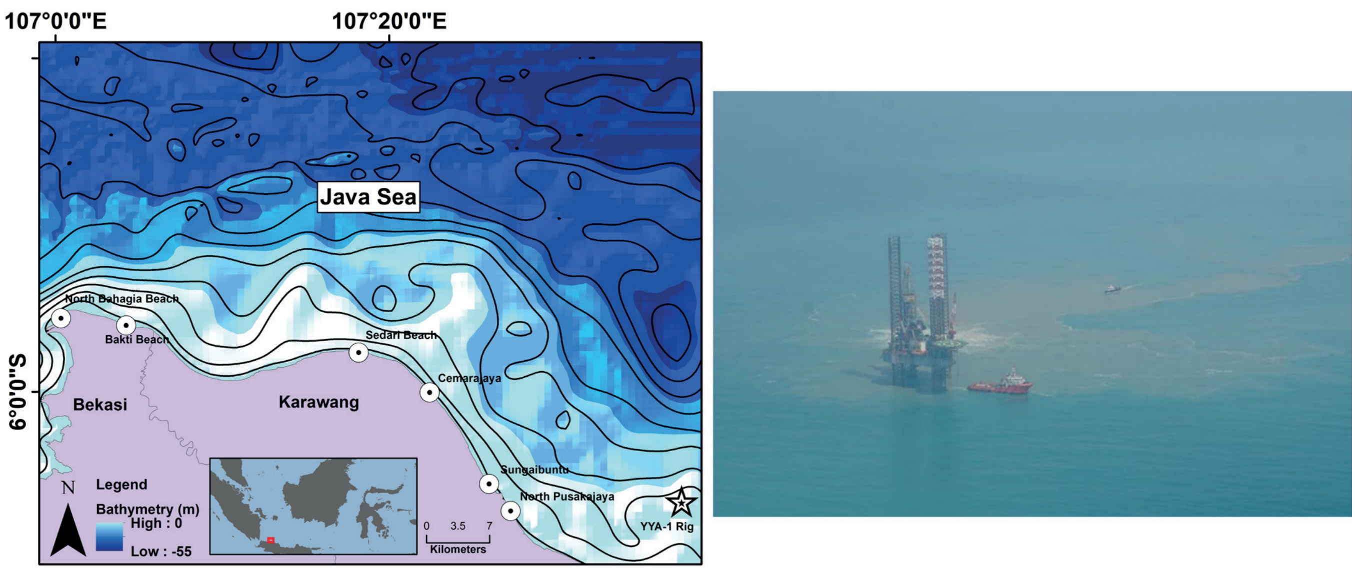

Fig. 1. Left: the geographic area of interest with the YYA-1 oil rig (star), bathymetric map and plots of potentially affected coastal areas; right; situation around the YYA-1 rig after oil leakage (photo by PHE)

[1]Sentinel-1 SAR Images downloaded from https://copernicus.eu

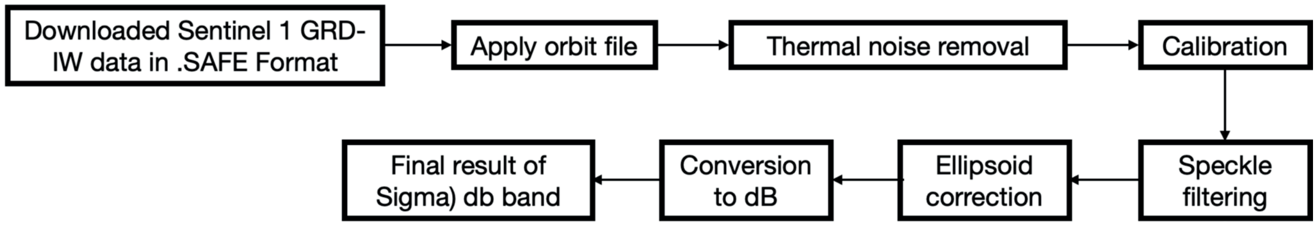

Fig. 2. Workflow for the pre-processing of Sentinel 1 data, adopted from (Chaturvedi et al. 2019; Filipponi 2019)

adopted from (Chaturvedi et al. 2019; Filipponi 2019) (Figure 2). Further information about these processes is accessible through website[1]. We used the Sentinel Application Platform Radar Toolbox (SNAP) from ESA to process the data. The radiometric correction was done using a Gamma MAP filter with a filter size of 3 x 3. The geometric correction was carried with the Ellipsoid Correction-Geolocation Grid to represent the location in the real world. After correction, the VV band from the image was converted to a dB image, which was later analysed. Areas that appear significantly darker than the surrounding waters were interpreted as oil spill areas. The pixel profiles of these areas were analysed as oil spills are marked by the lower pixel values than their clear water surroundings (Prastyani & Basith 2018).

One of the main challenges in detecting and mapping the oil spill areas was distinguishing between oil slick layer and its look-alikes. Look-alikes are areas that also appear to be darker much like oil slick layer (Ivanov 2011). Look-alikes in the tropical waters can appear due to internal waves, shear zones, low wind and rain cells (Espedal 1999). An example profile plot was made (Figure 3) across the area of clear water and oil spill to demonstrate the difference in pixel values (Prastyani & Basith 2018).

Generally, the sea surface that has been polluted by oil would have lower pixel values or appear darker in the image. Based on the graph from Figure 3, the pixels with oil spills have lower values by about 2 to 4 dB than the surrounding clear water.

For ocean current, data from the CMEMS[2] with daily temporal resolution and 0.08 spatial resolution were used. As for wind data (U10), the data from microwave radiometer downloaded from APDRC[3] with a spatial resolution of 0.25° were used. Then, the oil spill trajectories were analysed based on their distance and drift direction from the oil rig. For trajectory analysis, ocean currents and wind data were included for a more comprehensive description. Model data on currents and tides are useful to see the behaviour of the oil spill in the ocean. The two factors were reported to influence oil slick movement and distribution in the ocean (Galt 1994).

RESULTS AND DISCUSSION

Eight satellite SAR images representing the area of interest from July to October 2019 were analyzed. Dark pixels in Figure 4 indicate the oil spreading along and near the shoreline. In general, SAR images show movement and distribution of the oil spill towards the west, along the north coast of Karawang Region. This area is home to numerous residents of coastal cities.

From the SAR images of July, it was seen that the oil spill did not spread far away from the oil rig, reaching as far as Cemarajaya Beach (number 4 in the figure). In August, a small area of the oil spill has reached North Bahagia Beach (number 1 in the figure). This point was the farthest detected oil spill area from the rig. The distance from the rig was about 73.7 km, and the direction was around northwest of the rig (Table 1). In September and October, some oil slick layers were also detected north of the rig. It could have happened because of a change in surface current and wind pattern.

Oil slicks movement in the ocean is driven by many oceanic processes, the major ones are winds and currents as they affect the ocean surface (Daling & StrØm 1999). In the Java Sea, oceanic processes are influenced by many factors, and one of them is the seasonally-shifting monsoonal wind (Sprintall et al. 2014). Winds blow from the dry regions of Australia from June to August (JJA), and from the wetter regions of the Asian continent from December to February (DJF). Other months from the two major seasons are usually referred to as transitional seasons. From the oil spill trajectories shown in Figure 4, it was visible that the monsoonal winds from Australia in the JJA season affected the drift of the oil spill. The oil slick mostly moved westward of the original spill location (YYA-1) in the images from July to August. In September and October, the detected oil spills reduced and were found more northward. This could be due to the clean-up actions and also the transitioning wind pattern. A study in the western part of the Java Sea showed that oil spill trajectories in the Java Sea vary depending on the season (Setyonugroho 2019). The oil spill that occurs in the DJF season will have a more eastward trajectory, and spill that occur in the JJA season will have a more westward trajectory. As shown in Figure 4, the trajectory of the oil spill in this study is more westward in July and August.

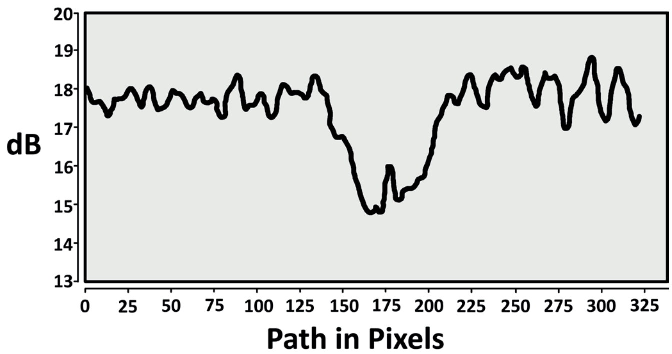

Fig. 3. Profile with an oil slick and clear sea on amplitude SAR image represented in dB

[1]SAR Images (https://sentinel.esa.ints)
[2]Copernicus Marine Environment Monitoring Service, http://marine.copernicus.eu
[3]Windsat v7.01 from the Asia-Pacific Data Research Center http://apdrc.soest.hawaii.edu

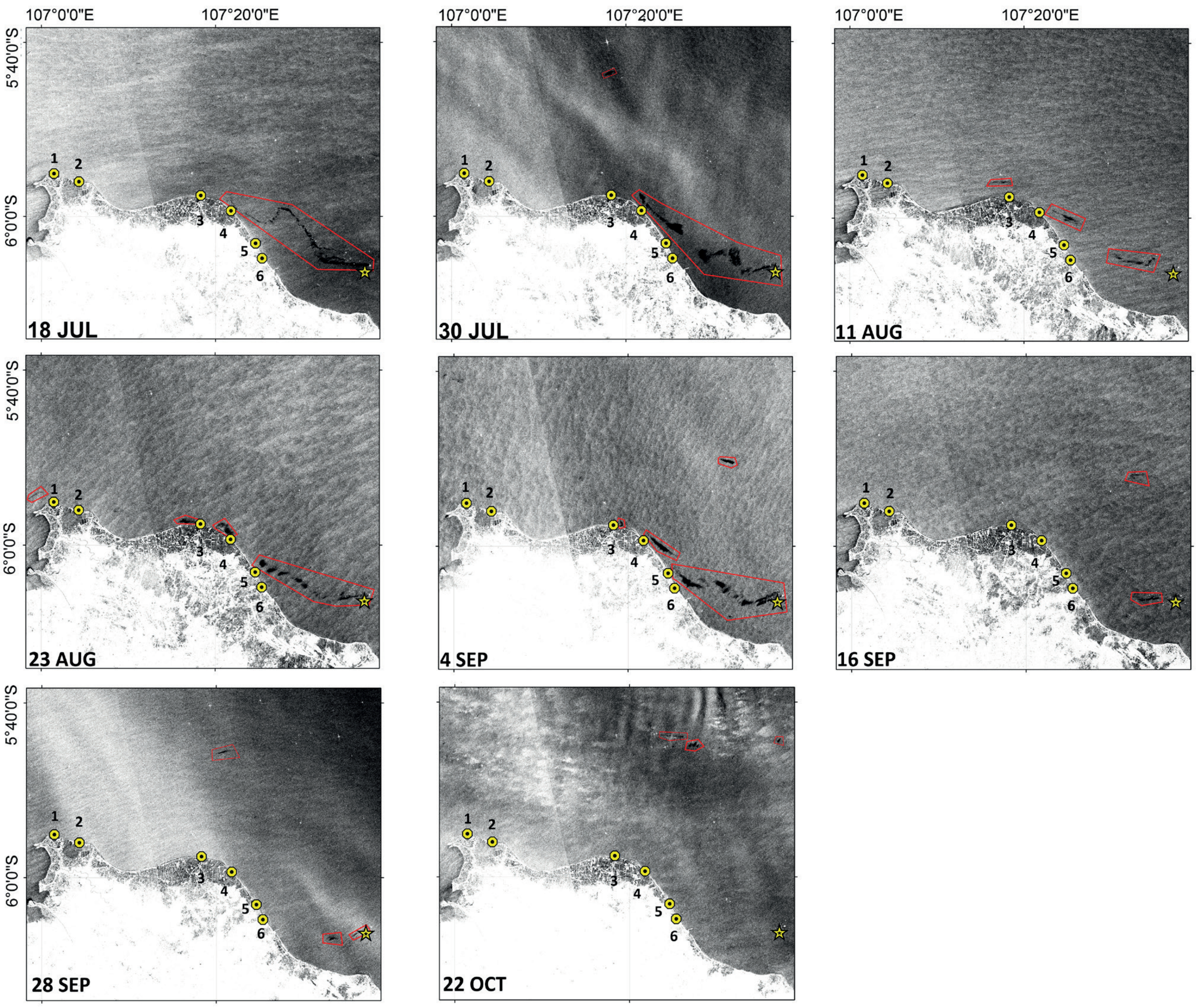

Fig. 4. Oil spills and their trajectories on SAR images and near coastal locations: 1) North Bahagia, 2) Bakti, 3) Sedari, 4) Cemarajaya, 5) Sungai Buntu, 6) Pusakajaya and YYA-1 as rig position; dark patches in the red polygons are interpreted as oil spills

Table 1. Distance and drift direction of oil spills from the rig

Date	July		August		September			October
	18	30	11	23	4	16	28	22
Distance (km)	32.65	33.34	43.16	73.70	37.65	7.97	8.49	48.53
Direction (degree)	299.58	300.11	296.20	287.57	297.28	272.88	261.63	329.58

Table 2. Historical assessment based on PHE reports and satellite image analysis

Date	Historical Assessment	
	PHE	Satellite Image
July, 15th	State of emergency declared	Not acquired
July, 16th	Oil sheen visible at the sea surface	Not acquired
July,18th	Oil sheen starts to spread towards the west of YYA-1 Rig	Oil sheen spread towards the west of YYA-1 Rig
July, 30th	8 villages in Karawang and Bekasi are affected	Oil sheen starts to approach the coastal area of Karawang (Cemarajaya, Sungai Buntu, Pusakajaya)
August, 11th	The oil boom and emergency posts installation along the coastline of six villages, cleaning of the oil spill in the affected villages	Area of oil sheen reduced and a small area of oil sheen detected above Sedari and Cemarajaya
August, 23rd	6,825 meters of shoreline oil boom along Karawang towards Seribu Islands	Oil sheen detected along the coastal area of Sedari, Cemarajaya, Sungai Buntu, Pusakajaya, and a small area around North Bahagia

September, 4th	7,995 meters of shoreline oil boom along Karawang, Bekasi, and Seribu Islands, 9 health services posts in Karawang Regency (Cemarajaya, Tanjung Pakis, Sedari, Pasir Putih, Tambak Sari, Sungai Buntu, PJU Beach, Cicau Sri Jaya, Ciwaru)	Oil sheen detected along the coastal area of Sedari, Cemarajaya, Sungai Buntu, Pusakajaya, and offshore in the Java Sea
September, 16th	9,950 metres of shoreline oil boom along Karawang, Bekasi, and Seribu Islands, cleaning of the oil spill in the affected villages	No oil sheen detected in the coastal areas of Karawang, oil sheen detected near the rig, and also a small area in the open sea
September, 28th	10,185 meters of shoreline oil boom along Karawang, Bekasi, and Seribu Islands, cleaning of the oil spill in the affected villages	No oil sheen detected in the coastal areas of Karawang, oil sheen detected near the rig, and also a small area in the open sea
October, 22nd	8,625 meters of shoreline oil boom along Karawang, Bekasi, and Seribu Islands, cleaning of remaining oil spill in the affected villages	No oil sheen detected around the coastal areas of Karawang and the rig, small areas of remaining oil sheen detected in the open sea

The drift direction of the oil leakage seemed to correspond to the specific direction of ocean currents in the region (Figure 5). According to Figure 4, which shows the evolution of the oil spill from July to September, the oil spills tended to move towards the west, reaching Bekasi and the Seribu Islands. The Java Sea is well known for wind and ocean currents that exist throughout the year. The distribution pattern of the oil spill could be explained by the seasonal wind and current pattern, which around our study period was marked by the north-western current from the lower latitude southeast regions corresponding with the south-eastern monsoon wind, blowing from Australia to the Asian continent (Daruwedho et al. 2016). There was also a decrease in the amount of visible oil slick concentration on the sea surface. This could be due to the actions and cleaning done by the responsible company, oil spills reaching the coast or degradation of oil spill concentration through weathering processes.

As can be seen from the ocean current pattern presented above, there is a steady current flowing towards the west. This could explain a westward distribution pattern which is identified in the processed satellite images. This distribution pattern could be a severe threat to the nearby tourist attraction areas in Karawang, Bekasi, and the Seribu Islands which is a National Park that serves as a home to several crucial ecosystems and protected animals such as sea turtles (Hermawan et al. 1993). The ocean currents at the moment of the spill is probably the most critical factor impacting the distribution of oil. Carls et al. (2001) stated that the tides and currents at the moment of the spill would affect the course of the oil dispersion, while the increased exposure to waves will enhance the mechanical mixing strength (Carls et al. 2001).

In addition to the ocean currents, the direction may be affected by the surface wind pattern. To identify the effect of wind, we analysed wind magnitude and direction around the study area (Figure 6). In June to July, the wind pattern was dominated by winds blowing to the direction of 270° – 285° (north-west) with a speed about 5.7 to 8.8 m/s and an occurrence percentage of about 21%. From July to August, the wind pattern was similar, dominated by winds blowing to the direction of 270° – 285° (north-west) with a speed of about 5.7 to 8.8 m/s and an occurrence percentage of around 25%. From August to September the wind pattern changes slightly and becomes dominated by winds blowing to the direction of 240° – 255° (south-west) with a speed about 5.7 to 8.8 m/s and an occurrence percentage of around 26%. This wind pattern occurs due to the effect of the Australian Monsoon, which causes dry and warm air from Australia to blow to the Asian continent (some also call it East Monsoon season).

On a planetary scale, the Asian Monsoon is powered by differential heating induced by the regular sunrise and geographical asymmetries of the Eurasian plateau, the Pacific and Indian Oceans, and Antarctica (C.P. Chang et al. 2005; Hung et al. 2004; Li & Yanai 1996). This Monsoon typically lasts around three months from June to August, but in September the wind patterns are still similar to the three previous months. This could be demonstrated by the greater thermal inertia of the ocean relative to ground. It triggers the natural transition from the boreal summer to winter when the location of the sun is shifted by a month or two. As a result, the forecast winds from September to November are still in the same direction as the boreal summer monsoon on the east of Java (Purba & Pranowo 2015).

From comparing the windroses with the ocean current patterns, a similarity can be seen between the wind and the ocean current patterns in the surrounding area. The wind blowing over the sea surface generates

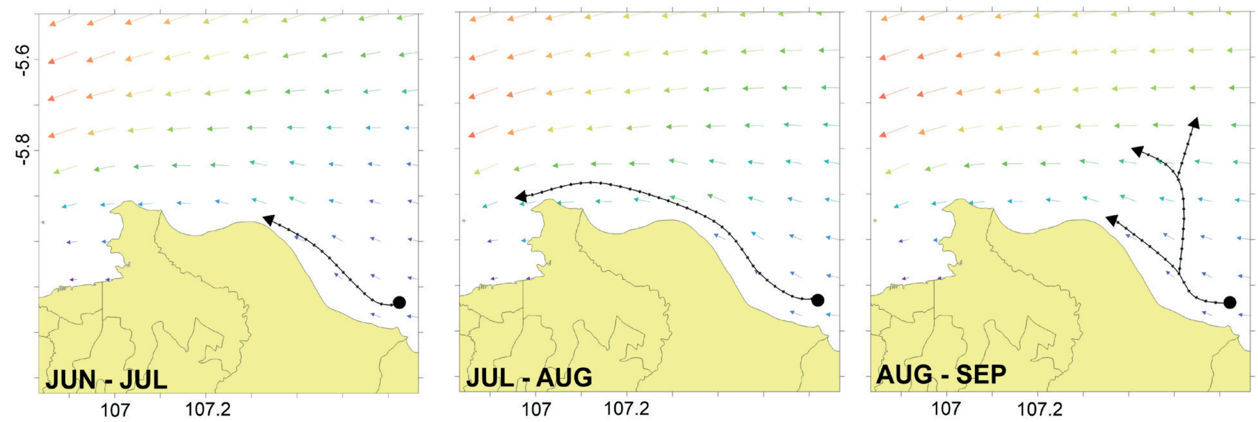

Fig. 5. Ocean current patterns and schematic oil spill trajectories in three months based on the processed SAR images, showing a westward trajectory due to the occurring monsoonal winds from the southeast (Australia)

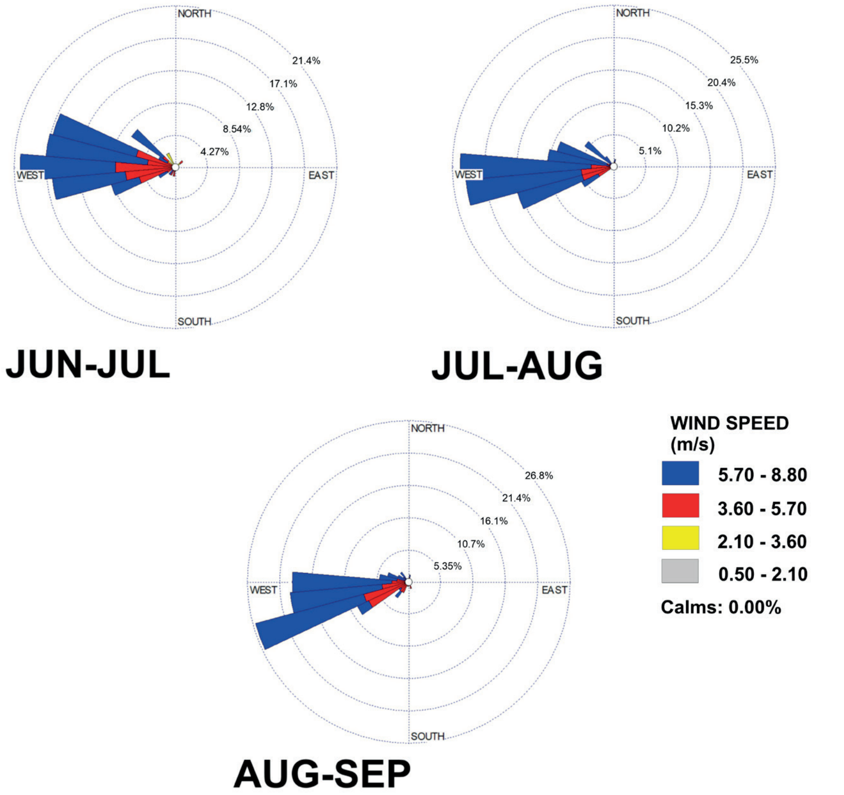

Fig. 6. Windroses of surface wind (at 10 m) for a station near the YYA-1 rig (6.125°S – 107.625°E) from June to September

wind stress and causes sea motion in the horizontal and vertical direction. In the horizontal direction, it generates cyclonic and anticyclonic patterns which are manifested as sea surface current. At the same time, in the vertical direction, a column of water can develop a complex circulation marked by an upward (upwelling) or downward (downwelling) motion (Sisawnto & Suratno 2008). Various factors, particularly the wind, influence physical processes on the sea surface. Monsoonal wind plays a vital role as it generates force for a large scale fluid flow in the Indonesian waters. Because of the unique position – between two continents (Australia and Asia) and two oceans (the Pacific Ocean and the Indian Ocean) – the weather and the climate of this region are influenced by annual monsoons. Also, as an archipelago that is passed by the Indonesian Throughflow current (Purba & Pranowo 2015), Indonesian Region is affected by global phenomenon like the ENSO (El Niño Southern Oscillation), namely El Niño and La Niña, as well as the Indian Ocean Dipole that regulates the air-sea interaction along with the tropical parts of the Indian and Pacific oceans.

CONCLUSIONS

This research was done with a purpose to detect and map the trajectory of the oil spill from the Karawang oil spill incident. The results of our work showed that the satellite SAR images provided valuable information about the oil spill drift trajectories even for several months after the accident happened. Oil spill parts were then found far away from the original leakage site. This spread is affected mainly by wind and ocean currents. Oil spills from the rig moved mainly towards the west to northwest from their original location, along the coastal areas. Their trajectories were similar to the ocean current and surface wind patterns. Furthermore, the satellite SAR images from the Sentinel-1 mission can also be noted as one of the empirical satellite data that can be used to track trajectories of oil spills. However, the accuracy of oil spill detection can still be complicated by factors such as low-wind zones and rains that could produce look-alike regions. Further study to better reduce the noise level of the images is also necessary for more accurate oil spill detection.

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RESEARCH PAPER

CHALLENGES OF FOREST GOVERNANCE IN ADDRESSING REDD+: STATUS, EFFECTS AND PROSPECTS. THE CASE OF BALE ECO-REGION, OROMIA REGIONAL STATE, ETHIOPIA

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ABSTRACT. Reduction of emissions from deforestation and forest degradation (REDD+) is an internationally accepted mechanism for encouraging developing countries to contribute to climate change mitigation by reducing greenhouse gas emissions (GHGs) by preventing forest loss and degradation; and by increasing removal of GHGs from the earth's atmosphere through the conservation, management and expansion of forests. This mechanism, however, has failed to bring the desired results in the Bale Eco-Region. Thus, the purpose of this study is to identify the main challenges of forest governance in addressing the implementation of REDD+ projects. Mixed research approach was employed. Relevant qualitative data were gathered through key informant interviews and focus group discussions. Quantitative data were collected through questionnaires. This study revealed that the community produced a total of 5.5 million metric tons of carbon dioxide equivalent in three years (between 2012 and 2015) as a contribution to the global environment. But, they were not received any economic incentives from the REDD+. Generally, while implementing the REDD+ project, forest governance of the Bale Eco-Region has faced different challenges, such as weak institutional arrangements, continuation of deforestation, low enforcement capacity, low economic benefit of the community, lack of strong coordination with media and research institutes, conflict of interest among sectors over forest land, and lack of adequate budget and logistics to undertake proper monitoring and evaluation. All these challenges have in one way or another contributed to the failure of the REDD+ project in the Bale Eco-Region.

KEY WORDS: Forest Governance Challenges; REDD+; Forest Governance; Bale Eco-Region; Carbon Trade

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INTRODUCTION

Global forest cover is decreasing due to deforestation and forest degradation. FAO estimates that 13 million hectares of tropical forest are being converted to other land uses every year due to deforestation and forest degradation (Vanderhaegen et al. 2015). Deforestation and forest degradation also contribute indirectly to the global greenhouse gas emissions. According to Bluffstone et al. (2013), deforestation and forest degradation are estimated to contribute between 12% and 20% of annual greenhouse gas emissions. To avert this, REDD+ was internationally adopted (Peter et al. 2014). The REDD+ mechanism has been negotiated at the successive United Nations Framework Convention on Climate Change (UNFCCC) Conferences of Parties since 2005 (Vanderhaegen et al. 2015). It comprises of local, national and global actions whose primary aim is to reduce emissions from deforestation and forest degradation and enhance forest carbon stocks in developing countries (Angelsen et al. 2012). While reducing forest-related climate emissions and sequestering more carbon, it aims to financially benefit low-income countries, communities and forest users (Bluffstone et al. 2013). Two approaches for REDD+ implementation have been discussed within the UNFCCC: a project/result-based payment mechanism and country-governed REDD+ programs that could become a part of wider Nationally Appropriate Mitigation Actions (NAMAs) (Mulyani and Jebson 2013). The governance of forests in general and REDD+ in particular is vital for the success of REDD+ because governance deficiencies threaten both the effectiveness and legitimacy of REDD+ (Larson and Petkova 2011).

Ethiopia has limited contribution to the overall greenhouse gas emissions when compared to the developed world. It is estimated that the country's per capita emissions are less than 2t CO_2 e. This is 10 times less when compared to the 20t CO_2 e per capita in the USA and Australia (Zerga and Gebeyehu 2016). In 2010, it was estimated that Ethiopia had a total of 150 million t CO_2 e emissions which accounted for less than 0.3% of global emissions (Ibid 2016). According to the Climate Resilient Green Economy (CRGE) document, out of this, forestry contributed 37% of the emissions (Bekele et al. 2015).

Consistent with the global goals, Ethiopia had its Readiness Preparation Proposal (R-PP) approved in 2011 and officially launched the REDD+ Readiness implementation phase in 2013 (Bekele et al. 2015). Currently, the REDD+ pilot project is being carried out in different parts of the country. For example, REDD+ pilot projects are being carried out in the Bale Mountain Eco-Region, Nono Sele, and Yayu (Ministry of Environment, Forest and Climate Change 2015). However, according to Asfaw et al. (2015), forest governance is facing different challenges such as weak enforcement of forest law and land-use policy, lack of adequate capacity, limited knowledge about the multifaceted advantages of forestry, lack of market access and limited value addition, weak inter-sectorial linkages, and absence of proper institutional arrangements at the regional level. Furthermore, there is a disparity between the participatory forest management institutional principles and the actual local forest management practices on one hand (Ayana et al. 2015), and between the local management practices and the low participation of women in forest governance, on the other (Engida and Mengistu 2013).

For the purposes of this paper, it is relevant to differentiate forest governance from participatory forest management (PFM). Forest governance is broad and inclusive of PFM. Forest governance is a consultative approach in which different actors such as the government, the community, and private sector organizations decide on the overall governance of forests (Arts 2014). On the other hand, PFM is a co-governance approach in which the community and the government jointly manage part of the forests that are under the community organizations. Above all, REDD+ pilot projects themselves are facing various governance challenges. For instance, the Bale REDD+ pilot project has already failed because it has not been successful in bringing sustainable impact on the reduction of emissions from deforestation and forest degradation due to the absence of incentives for the community, which sequestered a certain amount of carbon dioxide initially. Hence, to successfully implement the forthcoming REDD+ projects, it is vital to critically identify the challenges of forest governance in addressing the REDD+ pilot projects and to propose alternative ways of addressing those challenges, because it is widely recognized that the role of governance for the success of REDD+ is important (Larson and Petkova 2011). All of these reasons, together with the absence of adequate literature in the area of REDD+ projects, particularly in the Bale Eco-Region, establish the need for this particular study.

According to the literature, limited studies have been carried out on REDD+ projects in Ethiopia. Bekele et al. (2015) and Beyene et al. (2013) have carried out their studies entitled «The Context of REDD+ in Ethiopia» and «Community Controlled Forests, Carbon Sequestration and REDD+ in Ethiopia» respectively. In addition to having scale differences with the current study, they do not focus on the challenges of forest governance in addressing REDD+. Other studies by Hailemariam et al. (2015) and Devries et al. (2012) have investigated REDD+ implementation at the local level, particularly in the Bale Mountain Eco-Region and Kafa respectively. However, their studies do not emphasize the challenges of forest governance in addressing REDD+. Instead, they stress the implementation of REDD+. Therefore, from the overall assessment, it is clear that the study is necessitated by the existence of forest governance challenges and the absence of literature on them. Thus, the purpose of this study is to identify the main challenges of forest governance in addressing the implementation of REDD+ projects.

METHODS AND MATERIALS

Study Area

This study was undertaken in south-eastern Ethiopia, specifically in the Bale Mountain Eco-Region (BER), which is composed of three zones of the Oromia regional state; namely the West Arsi zone and the East and West Bale zones. From the West Arsi zone, only four districts (Weredas), namely Adaba, Dodola, Kokosa, and Nansabo, are part of the Bale Eco-Region while it covers seven districts (Dalo Mena, Haranna Buluq, Madda Walabu, Goba, Gololcha, Barbare and Agarfa) of the East Bale Zone and Bale Zone (formerly both zones were named together the Bale Zone).

BER is part of the Afromontane biodiversity hotspot, which belongs to the 34 global biodiversity hotspots. Over 40 streams and springs originate from the mountains in the Bale Eco-Region that drain into five major rivers—Wabe-Shebelle, Web, Welmel, Genale, and Dumal. Approximately 12 million people who live in the downstream areas depend on these rivers for their livelihoods. The Eco-Region exhibits a wide range of topography which spans from 1500 to 4377 meters above sea level.

According to the 2007 population census, the total population of the Bale Eco-Region is 1,202,015 (FDRE Population Census Commission 2008). From this, 1,058,665 is classified as rural, while the remaining 143,350 as urban. This means, 88% of the population of the Bale Eco-Region is rural. The Bale Eco-Region receives almost eight months of precipitation (March-October) (Hailemariam et al. 2015). Temperature varies from the lowest of less than 7.5°C at the Sannati Plateau to over 25°C in Dolo Mena (WBISPP 2001: Cited in Hailemariam et al. 2015).

Agriculture is the main economic activity practiced in the Bale Eco-Region. The local population depends primarily on mixed agriculture, both on crop growing and animal husbandry. Generally, the livelihoods of communities in the highland area are predominantly based on a mixed crop-livestock subsistence agricultural system, while communities living in the mid altitude and the lowlands are mainly pastoral and agro-pastoral. Traditional farming is dominantly practiced, but there are some attempts for using mechanized farming. Furthermore, the local inhabitants are also the direct beneficiaries of the forest resource in the area. At present, the local communities are organized into the Forest-Dwellers Associations and community-based organizations, and are authorized to manage the forests. The communities are benefiting from the forests through selling aged trees (mainly by the Forest-Dwellers Associations), receiving compensation when roads are constructed, sharing from trophy hunting, using the forests for house construction and fuel wood.

Fig. 1. Map showing the location of BER

Research Design

Considering the nature of the problem (i.e., challenges of forest governance in addressing REDD+), descriptive research design was employed and mixed research approach was followed. Descriptive research design is used because the nature of the problem requires an in-depth description of the challenges of forest governance in addressing the implementation of REDD+ projects. Similarly, mixed approach is employed with the intention to come up with dependable and reliable data by supporting the qualitative data with the quantitative one. Hence, the study is predominantly qualitative while the quantitative data are used to support the qualitative analysis. While the qualitative data were gathered through interviews and focus group discussions, the quantitative data were gathered through questionnaires.

Sample Size

As can be seen from Table 1, 65 respondents were identified and consulted through purposive and snowball sampling techniques for in-depth interviews and focus group discussions (FGDs). The number of respondents was based on the saturation of the collected data (collection of excess data). The researcher stopped going further when more than the required data were collected.

The quantitative data were collected using a questionnaire as a tool. The questionnaire, which consisted of 11 five-point Likert scale questions, was prepared and distributed to 395 members of the Forest-Dwellers Associations and the community-based organizations. The sample size was determined using Yemane (1967) sample size determination formula. This formula was preferred because the size of the population, i.e., the number of members from both the Forest-Dwellers Associations and the community-based organizations is finite and known. Overall, there are 30,000 members – 5,000 are members of the Forest-Dwellers Associations and 25,000 are members of the community-based organizations in the Bale Eco-Region. From those, 395 respondents were identified using the sample size determination formula. From the 395 respondents, the proportion assigned to the members of the community-based organizations was 329; the remaining 66 were assigned to the Forest-Dwellers Associations. Systematic random sampling technique was employed to select the required sample from the targeted population.

Table 1. Sample size of qualitative data

Categories of respondents	Numbers	Affiliation	Methods of data collection
Environment, Forest and Climate Change Authority	10	Experts	In-depth interview
Oromia Forest and Wild Life enterprises	10	Experts	In-depth interview
NGOs (Farm Africa and SOS Sahel Ethiopia)	5	Experts	In-depth interview
Forest dwellers associations (WAJIBs)	16	Leaders and members	In-depth interview and Focus Group Discussions
Community-Based Organizations	16	Leaders and experts	In-depth interview and Focus Group Discussion
Unions	3	Leaders and members	In-depth interview
Cooperatives	5	Executive committee	In-depth interview
Total	65		

$$n = \frac{N}{1+N(e)^2} = \frac{30,000}{1+30,000(0.05)^2} = 395$$

Where n=designates the sample size the research uses;
N=designate the total members
e=designates maximum variability or margin of error 5 % (0.05)
1=designates the probability of the event occurring

Methods of Data Analysis

Qualitative Data Analysis

The qualitative data was analyzed through descriptive analysis. Discussion guides were prepared and administered for both the interviews and the focus group discussions. The results were recorded using recording materials based on the consent of the respondents. Both interviews and FGDs were undertaken in the local language Afan Oromo (Oromic). Then, the audio was carefully transcribed and afterwards, it was translated into English. Following this, it was repeatedly read, coded and thematic areas were identified. Finally, the interpretation and analysis were carried out.

Quantitative Data Analysis

Descriptive statistics such as percentage and frequencies were used to analyze the quantitative data gathered on the challenges of forest governance in addressing REDD+. SPSS Version 20 was used to analyze the quantitative data. As mentioned earlier, this quantitative analysis was carried out mainly to support the qualitative data.

Analytical Framework

As shown in Figure 2 below, different actors such as the Oromia Forest and Wildlife Enterprise, the Environment, Forest and Climate Change Authority, the local communities and NGOs are contributing their part to the effectiveness of forest governance in the Bale Eco-Region. Despite these contributions, however, forest governance is facing different challenges, such as weak institutional arrangements, continuation of deforestation, low enforcement capacity, low economic benefit to the community due to absence of the expected carbon trade, lack of strong coordination with media and research institutes, conflict of interest among sectors over forest land and lack of adequate budget and logistics to undertake proper monitoring and evaluation, which in turn hamper the effectiveness of the REDD+ project in the Bale Eco-Region.

RESULTS AND DISCUSSION

Overview of Forest Governance and the REDD+ Project in the Bale Eco-Region

The governance of forests in general and REDD+ in particular in the Bale Eco-Region is characterized by the existence of multiple actors that contribute their own part to the sustainable management of forest resources. Government, community, and NGOs are actively taking part in the governance of forests, and hence, in the implementation of REDD+. The government is leading the forest governance through its institution of Oromia Forest and Wildlife Enterprise (OFWE) and the Environment, Forest and Climate Change Authority, while the community is co-governing through its organizations of Forest-Dwellers Associations and community-based organizations (CBOs).

In the Bale Eco-Region, the REDD+ project was carried out for three years, between 2012 and 2015. It was undertaken with the generous support from the NGOs known as Farm Africa and SOS Sahel Ethiopia. These NGOs used the already established community structure to reduce the emissions of carbon dioxide from deforestation and forest degradation. They identified the major causes of deforestation and effectively worked in collaboration with the community organizations, including the CBOs and the Forest-Dwellers Associations to address it. This had become fruitful and hence, effectively reduced a certain amount of emissions from deforestation and forest degradation at least during the project life time. From this, therefore, it is clear that while attempting to address the REDD+ project, forest governance is an interactive effort that invites various actors to play an active role in its governance.

Challenges of Forest Governance in Addressing REDD+

Forest governance is facing different challenges while addressing the REDD+ project. These challenges need to be urgently identified and systematically dealt with. Some of the major challenges are described below.

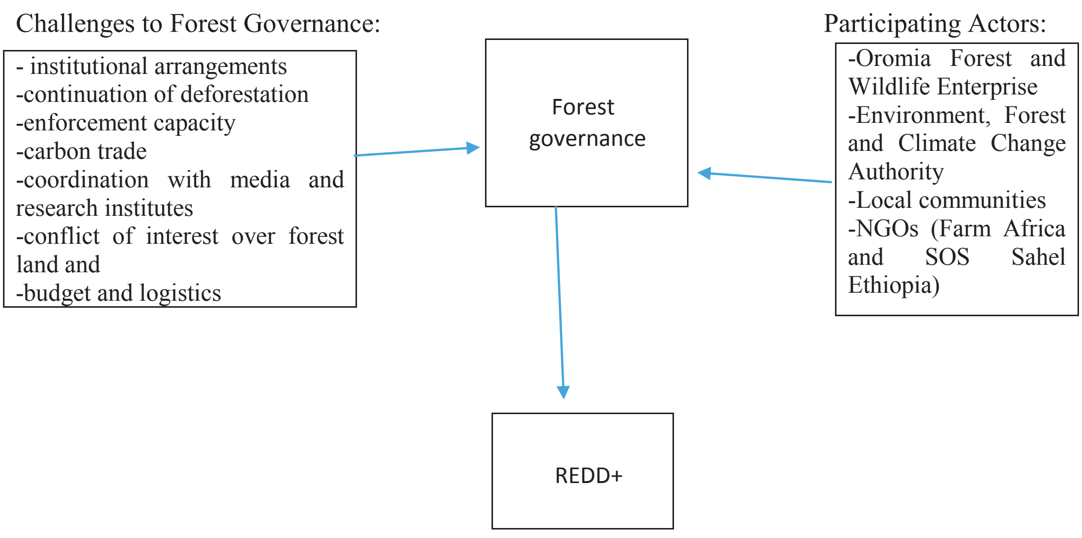

Fig. 2. Analytical Framework for Research

Weak Institutional Arrangements: Institutional arrangements are one of the factors that reduce the effectiveness of forest governance in general, and REDD+, in particular. Why is this a challenge in this case? Because of the lack of a central and responsible authority that continuously follows the activities of every stakeholder and then makes them responsible for their misdeeds. If we examine, for instance, the existing chains of responsibility, we see that the different bodies are responsible to govern the forests differently in their own respective institutions. For instance, the district level Oromia Forest and Wildlife Enterprise office, which concessionally has the authority to govern the forests, reports to their branch offices and the branch offices report to the regional office, which in turn reports to the regional government. Similarly, the community organizations that co-govern the forests, such as the Forest-Dwellers Associations (WAJIB) and the CBOs at Kebele levels (lower levels of government below the district level) report to the cooperative, while the cooperative reports to the district level union, which in turn reports to the cooperative promotional agency. These two institutions—the Forest and Wildlife Enterprise and the community organizations—are benefit-oriented and hence, their main priority is not forest conservation, but rather the benefits that they derive from it.

The other institution working on forest governance is the Environment, Forest and Climate Change Authority. Its offices are also vertically responsible, which means the district Environment, Forest and Climate Change Authority is responsible to the Zone, which in turn is responsible to the Region. The Environment, Forest and Climate Change Authority was actually established as a regulatory body of the forests and the forest products. It is the office that allows the above two offices to transport and sell their legal output to the markets. It is non-profit oriented and it is run by the government. Theoretically, this office is authorized to follow, evaluate, and take corrective measures of the performance of the above two bodies. In practice, the office is facing two major challenges. The first is that there is no clear chain of responsibility that obliges the other two offices to submit their plans and performance reports to this office. The second stems from the recent formation of the office. Because of this, the office does not have enough capacity in terms of financial, material, and human resources. For instance, the Forest-Dwellers Associations were formed in 1998 in Adaba-Dodola. The CBOs were formed starting from 2006 in the West and the East Bale zones and the West Arsi Zone, while the Oromia Forest and Wildlife Enterprise was formed in 2008 in Oromia in general, and the Bale-Eco Region, in particular. These institutions were given the responsibility of managing, conserving, and sustainably utilizing the forest and the forest products. As they are benefit-oriented, they may utilize more resources than they are supposed to utilize. In relation to this, the respondents indicated that the Oromia Forest and Wildlife Enterprise is utilizing more and planting less. As shown below, deforestation also continues inside the Forest-Dwellers Associations and the CBOs. However, the Environment, Forest and Climate Change Authority has not yet made performance evaluations on those institutions, nor taken any corrective measures.

In relation to this, the other problem continuously raised is institutional multiplicity and instability. The key informants and FGD participants stressed that the Environment, Forest and Climate Change Authority and the Oromia Forest and Wildlife Enterprises are more or less working on the same things. Because of this, there is duplication of effort between them. The respondents argued that if both offices are vital, it is better to merge them or otherwise to dissolve one and retain the other. The respondents also stressed that continuous change of the structure of those offices was another challenges of the office in its attempt to realize sustainable management of forest resources.

The Continuity of Deforestation: Deforestation is another challenge that has affected the implementation of REDD+ in the Bale Eco-Region. Actually, tree-planting is also taking place in Ethiopia. For instance, since 2007, the government of Ethiopia has been planning and planting trees every year by mobilizing the communities. However, it is widely believed that deforestation of old-growth forests is much higher than that of recently planted forests. In Ethiopia, conversion of forests to agricultural land and unsustainable use of fuel wood are the two major drivers of deforestation (Forest Carbon Partnership Facility 2018). Similarly, agriculture is the primary driver of deforestation in Latin America and Asia[1].

Contrary to this, however, while experts have attested that deforestation and forest degradation are taking place at high rates in the Bale Eco-Region, different factors, as shown in Table 2, are responsible for the continuation of deforestation. According to the survey respondents, the main ones are illegal use of the forests for construction, uncontrolled conversion to grazing land, settlement, conversion to farm land, and charcoal extraction; in order of their significance respectively. Below, we discuss each one of them.

Table 2. Causes of Deforestation

No.	Questions	Measure	Low	Fair	High
1	Illegal use of forest products for construction	Frequency	60	131	204
		Percent	15.2	33.2	51.7
2	Uncontrolled land conversion to grazing land	Frequency	97	129	169
		Percent	4.5	32.7	42.8
3	Uncontrolled land conversion to settlement	Frequency	143	110	142
		Percent	35.2	27.8	36
4	Uncontrolled land conversion to farm land	Frequency	131	169	94
		Percent	33.4	42.8	23.8
5	Forest land grabbing	Frequency	127	135	133
		Percent	32.2	34.2	33.6
6	Charcoal extraction	Frequency	232	104	59
		Percent	58.8	26.3	15

[1] UN-REDD programme (2013). Legal analysis of cross-cutting issues for REDD+ Implementation. Lessons learned from Mexico, Viet Nam and Zambia. The Programme.

One of the main factors that has contributed to the continuation of deforestation in the Bale Eco-Region is illegal destruction of the forests for construction. As it can be seen from Table 2, the majority of the respondents (51.7%) indicated that the illegal use of forests for construction is «high», while 33.2% and 15.2% defined it as «fair» and «low», respectively. From this, it can be concluded that the illegal use of the forests for construction is the main cause of deforestation in the study area.

Furthermore, conversion to grazing land is the second major factor that mainly contributed for deforestation in the study area. As it can be seen from Table 2, more than 40% of respondents (42.8%) reacted that conversion of forests into grazing lands is «high» in the Bale Eco-Region while 32.7% and 4.5% responded that it was «fair» and «low», respectively. Thus, the quantitative result revealed that conversion to grazing land is high. Actually, using forest land for grazing is allowed to the community particularly after planted trees have reached the age of maturity (after two years). According to the informants, there was an agreement made about this between the community and the government at the time of formation of the participatory forest management organizations. Cattle and other animals live in the forest along with the local community. There were also households having grazing land even before the implementation of PFM. However, grazing land became the cause of deforestation in two ways. First, households that previously had grazing lands were expanding by converting the forests into additional grazing lands. Second, during the dry season, households from the lowlands were moving with their cattle to the Haranna forest—the well-known forest in the Bale Zone—in search of water and grass. Millions of cattle were being moved from the lowland areas and settled in the Haranna forest. This has become the second major cause of deforestation in the study area.

Illegal settlement within the boundaries of the forest is the next major factor that is responsible for the continuation of deforestation in the Bale Eco-Region. As shown in Table 2, more than one-third of the respondents (36%) said that illegal settlement within the boundaries of the forest was «high», while the remaining 35.2% and 27.8% responded that it was «low» and «fair», respectively. It should be made clear that there are two forms of PFM currently being practiced in the study area. These are the capacity-based settlements and the management of forests, which are known as the Forest Dwellers Associations and the CBOs. What is meant by «settlement»?

First, expansion of settlements within the Forest-Dwellers Associations themselves. Considering the capacity of forests, Forest-Dwellers Associations were formed in Adaba-Dodola in 1998. It was analyzed and agreed then that the carrying capacity of each Forest-Dwellers Association would be 360 hectares for 30 households. During the formation process, priority was given to early settlers. Late settlers were obliged to withdraw in places where there were more than 30 households and the government promised to arrange other mechanisms of withdrawal for the new households that would be formed there. After nearly 20 years, however, so many households had emerged and kept settling there, which according to the initial rules of formation, was beyond the carrying capacity of the forests. The youngsters who had not formed their own families at the time of institutional formation, began to form their own families. The government failed to enforce the withdrawal of these new households. Currently, many discussions are going on among the concerned stakeholders on how to address this problem.

Second, there are new settlements from newcomers, coming mainly from outside areas and settling primarily in the Haranna forests. According to PFM, such kind of a new settlement is not allowed and illegal. Through GPS, the boundaries of the forest are known. While it is forbidden to undertake new settlements within the boundaries of the forest, some people move and settle within the boundaries of the forest mainly because of population pressures. According to our informants, while those populations are coming from different areas, they are mainly coming from the Harar of Oromia Regional State and the Sidama from Sidama Regional State. Such kinds of illegal settlements are highly observed in the Bale zone, particularly in the Madda Walabu district, Haranna Buluq district, Dallo Manna, and Barbare districts respectively in order of severity.

The other factor for the continuation of deforestation is the expansion of agricultural lands. As shown in Table 2, the largest percent of respondents (42.8%) said that conversion of forests into agricultural lands was a «medium» reason for deforestation, while 33.4% and 23.8% said it was «low» and «high» respectively. Hence, agricultural land expansion is also contributing its own part for the destruction of forests. In support of this, Beyene et al. (2015) argued that the conversion of forests, woodlands, and shrub lands into agricultural lands is the largest driver of deforestation in Ethiopia. This, however, does not include lands in forests that were formerly converted to farming. The FGD respondents asserted that farmers were allowed to undertake farming on lands in forests which is formerly allowed for agricultural activities.

Low enforcement capacity of forest offices is the third factor that affects the implementation of the REDD+ project. As it can be seen from Table 3 below, the majority of respondents (57.5%) said that the enforcement capacity of the forest offices was «moderate» while the remaining 33% defined it as «low», and only 9.6% defined it as «high.»

Contrary to the survey respondents, the key informant experts argued that the enforcement capacity of the forest offices was low, which is also the researchers' observation. This is because there are so many instances that justify the low enforcement capacity of the forest offices. The first is, according to the informants, when individuals are caught in the act of deforestation, effective measures are not taken in the courts. This is mainly due to the absence of adequate evidence emanating from the witnesses' willingness not to disclose the evidence, as well as the detailed process of evidence gathering. In most cases, the witnesses are willing to report to the office about the deforestation taking place by certain individuals at first. Later on, they either refuse to confirm their statements in front of the court or resolve the issue through elders. This is mainly due to the existence of strong social bonds among them.

The other instances that strengthen the existence of low enforcement capacity in the forest governance of the Bale Eco-Region is that the performance evaluation of both the Oromia Forest and Wildlife Enterprise and the

Table 3. Enforcement Capacity

No.	Questions	Measure	Low	Fair	High	Total
1	How do you rate the enforcement capacity of the forest offices?	Frequency	130	227	38	395
		Percent	33	57.5	9.6	100

PFM organizations has not yet been carried out as per the agreement. They have taken many years after their establishment, but the forest related audit has not yet been done to determine whether they have utilized more of the natural resources or contributed more to the eco-system. Finally, when the Forest-Dwellers Associations were formed, the forest capacity was analyzed and it was determined, based on the carrying capacity of the forests. The government promised to withdraw the households that were above the forest capacity i.e., when it became more than 30 households in one Forest-Dwellers Association. However, due to the demographic pressure, the households within each Forest-Dwellers Association increased and became more than 30. This was because the sons and daughters of the members of each Forest-Dwellers Association grew, formed families and were not willing to withdraw from their Forest-Dwellers Associations, which led to the failure of this capacity-based forest management. The government also failed to enforce the withdrawal of these newly formed households.

In addition to these examples, another example related to the weak government enforcement can be found in forest replanting. The International NGOs FARM Africa and SOS Sahel Ethiopia have trained the community on how to establish nursery sites to plant additional trees and how to manage seeds and seedlings. Furthermore, they provided the community with seeds and different nursery materials. But no nursery sites were established by the community.

Yet another example that strengthens the low performance capacity of the forest offices is the failure of carbon trading on the international markets. The offices initially promised that carbon trading would benefit the local community by securing incentives from the donor organizations or countries through the sale of the produced amount of carbon dioxide equivalent, which was not practically accomplished.

Low direct benefit to the community due to the failure of carbon trade is another factor that has affected the implementation of REDD+ and the sustainable management of the forests. PFM began to be implemented in the Bale Eco-Region starting in 1998 with the intention to reduce deforestation and forest degradation and to achieve the conservation of biodiversity while ensuring the participation of the community and their direct benefit from conservation. As it has been indicated above, different forms of PFM were practiced in the Bale Eco-Region. The first one was the Forest-Dwellers Associations, which have derived direct benefit from the forests and the forest products. The members of the Forest-Dwellers Associations, starting with their formation in 1998, have been benefiting directly from the forests, particularly until 2016. They were selling aged trees both plantation and natural forests under their protection. When they sold such trees, they received 50% from the sale. Furthermore, they were also benefiting from trophy hunting that was legally undertaken by foreigners, paying certain amounts of money. From this, 60% was given to the Forest-Dwellers Associations, while 40% was taken by the Oromia Forest and Wildlife Enterprise. In addition to that, these organizations have also been benefitting from charging park entrance fees and from the compensation given to them during road construction.

The other form of participatory forest management is the CBOs, which primarily works on the protection rather than the benefits. They cannot sell and directly derive benefits from the forests. However, there are situations in which they do derive benefits from the forests. The first is through compensation given during road construction. For instance, when the Adaba-Angetu road was constructed, the Ethiopian Roads Authority paid 10,000,000 Ethiopian birr (equivalent to nearly 400,000 USD) as compensation for the destruction of natural forests. From this amount, 40% was given to three CBOs, which were conserving these natural forests while the remaining amount was taken by the Oromia Forest and Wildlife Enterprises. Furthermore, trophy hunting was also conducted in the forests that were under the control of the CBOs and from this, 60% went to the community. Moreover, when plantation forests conserved and protected by the Oromia Forest and Wildlife were sold, the office gave 5% to the community. However, when asked individually, the members had not received any, or in some instances had received insignificant amounts, directly from the protection and conservation of the forests.

Because of the above reasons, the community in general and the CBOs and Forest-Dwellers Associations in particular had great hopes to benefit from the selling of carbon that has been sequestered. In support of this, Duker et al. (2018) stated that the local communities had high expectations concerning the benefits that they would receive from the REDD+ project, and they were anticipating that they would be compensated for forest conservation. This is because REDD+ is meant to incentivize the forest-dependent communities of developing countries for reducing greenhouse gas emissions from deforestation and forest degradation or for increasing carbon stocks within their forests compared to a reference emissions level (Vanderhaegen et al. 2015). In the Bale Eco-Region, the carbon sequestration work was done under the first phase of REDD+ projects of FARM Africa and SOS Sahel Ethiopia for three years, between 2012 and 2015. During this time, these NGOs identified the major causes of deforestation and effectively worked in collaboration with the CBOs and the Forest-Dwellers Associations. It was identified then that some of the perceived major causes of deforestation in the Bale Eco-Region were the expansion of agriculture inside the forests, illegal logging, illegal settlement, and occasionally, wild fires. Thus, they effectively worked and suppressed the effects of those factors and consequently reduced deforestation and forest degradation. Finally, the CBOs had generated a total of 5.5 million metric tons of carbon dioxide equivalent. With tropical deforestation accounting for up to a fifth of global, anthropogenic carbon dioxide emissions, the storage of this gas is probably the most valuable non-market benefit associated with forest conservation (Groom and Palmer 2012). This was done by 64 CBOs that were established then in the Bale Eco-Region. However, this internationally recognized amount of carbon has not yet reached international markets. Hence, REDD+ has not yet contributed to the improvement of forest-dependent communities' livelihoods. This has greatly discouraged the communities and reduced their trust in the main actors of the issue of carbon sequestration, particularly FARM Africa and SOS Sahel Ethiopia and other international actors.

Regarding the failure of the expected carbon trade, the communities were asked about the existence of well-established channels to access carbon markets. Depending on the question, as shown in Table 4, 82.6% responded that there were «low» established channels to access the carbon markets.

Table 4. Existence of Well-established Channels to Access Carbon Markets

No.	Question:	Measure	Low	Fair	High	Total
1	To what extent do you believe that there are well-established channels to access carbon markets?	Frequency	326	44	25	395
		Percent	82.6	11.1	6.3	100

The key informants also indicated that the certificate of existing results of carbon sequestration had been released on the web site. However, there were no lobbyists in foreign countries to work towards selling the carbon emissions. Hence, the absence of established channels to access the carbon markets might be the reason for not selling this stock of carbon.

Low coordination with Media and Research Institutes is yet another challenge that has affected the effective implementation of the REDD+ project in the Bale Eco-Region. As it can be seen from Table 5, the majority of the respondents (73%) have indicated that the forest offices have «low» cooperation with the media. The key informants also indicated that because of lack of resources, the forest offices were not utilizing media to the expected level. But media plays a vital role in publicizing about REDD+ and educating the citizens about the existing laws of forests, their importance, conservation and the existing destruction.

Similarly, the majority of the respondents (53.9%), as shown in Table 5, indicate that the forest offices had low cooperation with the research institutes. The key informants also confirmed that the research institutes closest to the Bale Eco-Region were Madda Walabu University and Wendo Genet College of Forestry and Natural Resources. From these two institutions, researchers did occasionally come and collect data, but they did not make the results of their studies accessible to the forest offices.

Conflict of interest over forest lands is also another challenge that has affected the implementation of the REDD+ project in the study area. As can be seen from Table 6, the majority of respondents (39.5%) reacted that there was a «fair» share of the conflict of interest among the government sectors over the use of forest land.

In support of the above information, the key informants also confirmed that the local government, the small and micro enterprise offices, and the agricultural offices, at some point had organized the unemployed youths to engage in agricultural activities of the forest land, which led to deforestation and forest degradation. Furthermore, there was also a situation in which small and micro enterprises had licensed the unemployed youths to engage in the home furniture activities in areas where there was no plantation forests. In those locations, the youths were using natural forest resources, which is illegal. Although the Oromia Forest and Wildlife Enterprise and the Environment, Forest and Climate Change Authority oppose those actions, any of their attempts to correct these illegal agricultural expansions and illegal uses of the natural forests, have been futile.

Lack of budget and logistics: Particularly the Environment, Forest and Climate Change Authority of the Weredas (districts) lack adequate budget and logistics to undertake the proper monitoring and evaluation. They do not have vehicles to undertake field visits and to follow the activities of the Forest-Dwellers Associations, the CBOs, and the Oromia Forest and Wildlife Enterprises. Due to the lack of capacity, mainly financial resources, they had not yet carried out forest auditing. According to key informants, the government, besides creating the structure, had not allocated adequate budgets for the Environment, Forest and Climate Change Authority so that it can effectively carry out the responsibilities it had undertaken.

The Effects of Forest Governance Challenges on REDD+

Our study has shown that while attempting to address the REDD+ project, forest governance has faced different challenges, such as weak institutional arrangements, continuation of deforestation, low enforcement capacity, the failure of carbon trade and the consequent low direct benefit of the community, lack of strong coordination with media and research institutes, conflict of interest over forest land, and lack of adequate budget and logistics to undertake the monitoring and evaluation. Other studies have also confirmed these findings. For instance, Asfaw et al. (2015) have revealed that absence of proper institutional arrangements and weak enforcement of forest laws have been observed in other regional states of Ethiopia, particularly in the Southern Nations, Nationalities and Peoples Region. Furthermore, Rahman and Miah (2017) have also argued that the lack of enforcement of forest policies, deforestation, competing interests among government organizations and lack of coordination with academic and research institutes are also some of the problems of forest management observed in the Rema-Kalenga Wildlife Sanctuary in Bangladesh.

These challenges of forest governance have both a direct and an indirect effect on the implementation of REDD+ projects in the Bale Eco-Region. For instance, the continuation of deforestation has a direct effect on REDD+. Since when deforestation continues, the emissions of carbon dioxide from deforestation also continue to grow, which is contrary to the intention of REDD+. Similarly, the failure of carbon trade and the consequent low direct benefit of the community also had a direct effect on REDD+. The intention of REDD+ was to economically support the developing countries in general and the forest-dependent communities in particular for their contribution to carbon dioxide emissions reduction from deforestation and forest degradation. When forest-dependent communities are

Table 5. Coordination of Forest Governance with Media and Research Institutes

No.	Question:	Measure	Low	Fair	High	Total
1	To what extent do you perceive that forest offices cooperate with the media?	Frequency	289	88	16	395
		Percent	73.4	22.3	4.1	100
2	To what extent do you perceive that forest offices cooperate with research institutes?	Frequency	213	134	48	395
		Percent	53.9	33.9	12.2	100

Table 6. Existence of Conflict of Interest Over Forest Land

No.	Questions	Measure	Low	Fair	High	Total
1	To what extent do you believe that there is a conflict of interest among sectors over the use of forest land?	Frequency	140	156	99	395
		Percent	35.4	39.5	25.1	100

not economically supported, they engage in deforestation and forest degradation for their daily livelihoods. This has been observed in the Bale Eco-region. After the end of the REDD+ pilot project in 2015, the registered success of REDD+ has not continued, which has led to further deforestation and forest degradation. The reason for this is the lack of economic benefits, initially promised to the communities via the REDD+ mechanism.

On the other hand, weak institutional arrangements and low enforcement capacity have had an indirect effect on the implementation of REDD+ as well. Because of weak institutional arrangements, there has been a weak chain of responsibility among the Oromia Forest and Wildlife Enterprise, Environment, Forest and Climate Change Authority, and the community organizations. This, in turn, weakens the monitoring and evaluation of the Oromia Forest and Wildlife Enterprises (concessionally holding the power to administer the forests) and the community organizations (authorized to administer the forests under their rule) that in turn worsened deforestation and forest degradation. Similarly, the weak law enforcement capacity of the forest offices, which has been observed in the administrative activities of the forest offices and the courts, has had an indirect effect on the implementation of REDD+. For instance, it has created gaps in establishing nursery sites, building the capacity of the members, and encouraging the illegal deforestation by the local people. These, in turn, have hampered the effectiveness of the REDD+ project even further. Besides those challenges, the lack of strong coordination of the research office with the media and research institutes has also had an indirect effect on the REDD+ project in the Bale Eco-Region. Since the media has been responsible for the low publicity of the achievements so far made regarding the REDD+ project, it has in turn weakened the international community response to the generated amount of carbon dioxide equivalent.

Response to the Challenges of Forest Governance and REDD+

Various research studies and solution attempts have been undertaken to tackle the challenges of forest governance and the problems of deforestation. The study have found that the main factors responsible for the continuation of deforestation are the use of forest outputs illegally for construction, uncontrolled conversion of forests to grazing land, illegal settlement, conversion to farm land and charcoal extraction. For instance, a task force was formed in the Bale Eco-Region to tackle the problem of illegal settlement that caused deforestation. The task force was formed and included nine sectors—the courts, the police office, the justice office, the Environment, Forest and Climate Change Authority, the Oromia Forest and Wildlife Enterprise, the Bale National park, the Woreda administration, the agricultural office, and the land administration. This task force was successful in some districts, mainly in the Haranna Buluq district. In addition, as part of the REDD+ project, NGOs (FARM Africa and SOS Sahel Ethiopia) and community organizations (both Forest-Dwellers Associations and the CBOs) have identified the major causes of deforestation and have effectively tackled them, particularly for three years, between 2012 and 2015. Due to this success, the international organizations had certified them for effectively reducing emissions from deforestation and forest degradation. However, there have been no countries or international organizations that were willing to buy the generated amount of carbon dioxide equivalent, which discouraged the local community and encouraged further deforestation.

Currently the other challenges such as absence of PFM in the forest policy of the country and absence of benefit sharing mechanisms (e.g., what percentage of the benefits should go to the community, to the project developer, and to the government) have been attempted to be addressed. The issue of participatory forest management was addressed by the government and thus, PFM was included in the Forest Development, Conservation and Utilization proclamation 1065/2018. However, regarding the benefit sharing mechanism of REDD+, a clear, dependable and universal benefit sharing system has not yet been developed because this requires a clear definition of what the benefits are, who has rights to them, how will they be allocated and distributed, and who should make these decisions (Ravikumar et al. 2015). Despite this, however, an attempt was made in the Bale Eco-Region to develop an agreed upon benefit sharing mechanism. Through discussions with the government and NGOs, the community had reached consensus on the benefit sharing, which prioritized community benefits. But, contrary to this, in Ghana, the benefit sharing has been biased towards the traditional authorities and local governments, and hence, farmers and forest fringe communities have not been directly included in the benefit sharing, and so they receive few direct benefits (Hansen et al. 2009).

Thus, through long discussions in the Bale Eco-Region, the community has set the following criteria that facilitate the fair assignment of the expected benefits to the community organizations.

1.Deforestation is weighted out at 50%. The CBOs and the Forest Dwellers
Associations that score less on deforestation, will get more benefits
2.The size of the population will be weighted out at 20%
3.Areas will be weighted out at 8%
4.Organizational Capacity Assessment Tools (OCAT) results will be weighted at 22%.

The remaining task has been to decide how the dividend would reach the communities and hence, after many discussions, they have established committees. They have also discussed how to treat grievances and for that, they have established different committees whose members are selected from each district in order to make it more representative. Regardless of the attempt so far made to develop an agreed upon benefit sharing mechanism in the Bale Eco-Region, the benefit sharing mechanism needs further refinement as it is expected to be binding.

Prospects of Forest Governance and Implication to REDD+

It is clear from this study that the forest governance of the Bale Eco-Region has the following prospects. The first is that the existing forest governance has authorized the community, specifically the Forest-Dwellers Associations and the CBOs, to administer parts of the forests. Thus, forest governance is inclusive of the community. The second is that capacity-building training and material support are being continuously given to the members of these organizations by NGOs, such as FARM Africa and SOS Sahel Ethiopia, which is vital for the implementation of REDD+. Furthermore, moderate coordination is created among the government sectors, particularly between the Oromia Forest and Wildlife Enterprise and the Environment, Forest and Climate Change Authority, which can be considered as an opportunity for the implementation of REDD+. This is important because studies have revealed that the lack of coordination among government organizations in the Rema-Kalenga Wildlife Sanctuary in Bangladish (Rahman and Miah 2017) and poor coordination among government ministries and between different levels of government in Indonesia (Mulyani and Jepson 2013) are among the main challenges of REDD+ implementation.

Furthermore, the decision making is inclusive of all critical actors, which is vital to address the interests of stakeholders. The existing community structure — Forest-Dwellers Associations and CBOs — is also another element for the implementation of the REDD+ project in the Bale Eco-Region. Formerly, FARM Africa and SOS Sahel Ethiopia relied on those community structures to carry out the Bale REDD+ project, which was successful in reducing emissions from deforestation and forest degradation. However, the international community was not committed to buy the generated carbon dioxide equivalent. Most likely, this was because prior agreements were not concluded with any international organizations or any interested countries. Currently, however, the Oromia government has concluded an agreement in advance with the World Bank to buy-out a certain amount of carbon dioxide equivalent. The Oromia REDD+ is being carried out throughout the Oromia regional state. However, the Bale Eco-Region is not made part of it. Experts from the district Environment, Forest and Climate Authority and Oromia Forest and Wildlife Enterprise want the inclusion of the Bale Eco-region in the Oromia REDD+. But, the government has not yet decided, probably because the communities are exhausted by the former Bale REDD+ project.

Conclusion and Policy Implications

The Bale REDD+ project was supported mainly by the NGOs FARM Africa and SOS Sahel Ethiopia. Sixty-four (64) community-based organizations, with the support of different sectors and mainly the NGOs, produced a total of 5.5 million metric tons of carbon dioxide equivalent in three years between 2012 and 2015. Regardless of this, however, deforestation and forest degradation have continued in the Bale Eco-Region, especially after 2015.

Forest governance has faced different challenges in an attempt to realize the REDD+ project. Some of the major challenges that have been identified in this study are weak institutional arrangements, continuation of deforestation, low enforcement capacity, the failure of carbon trade and low direct benefits to the community, lack of strong coordination with media and research institutes and lack of adequate budget and logistics to undertake the monitoring and evaluation. Because of these challenges, the REDD+ project of the Bale Eco-Region was not successful in bringing sustainable reduction of emissions from deforestation and forest degradation. Of these challenges, the main one is that the REDD+ project has not brought the expected financial benefit to the local community, which in turn has contributed to further deforestation, particularly after 2015. Immediately after the generation of the estimated carbon dioxide equivalent, the community expected to get financial benefit for their achievement from the international community. But, the absence of an international market for the then produced amount of carbon dioxide equivalent discouraged them, which in turn was responsible for loosening community forest conservation and control that caused further deforestation and forest degradation. From this, it can be learnt that the promise alone to incentivize the community through REDD+ projects, without actually realizing it, has a devastating negative effect on the sustainable reduction of greenhouse gas emission through the REDD+ mechanism. It undermines the legitimacy and effectiveness of the REDD+ approach and the actors involved in its implementation. To overcome this, it is recommended to sign an agreement, in advance, with the interested donor organizations or countries, which are willing to buy the anticipated carbon dioxide equivalent.

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RESEARCH PAPER

THE CHARACTERISTICS OF EXTREME MAXIMUM RUNOFF OF THE RIVERS OF ARMENIA IN THE CONTEXT OF GLOBAL CLIMATE CHANGE

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ABSTRACT. The study concerned the analysis of temporal and spatial variability of floods in the Republic of Armenia (RA). While there are number of reports on flood formation of rivers in RA, the literature lacks results on using nonparametric test results to analyze this disastrous phenomenon. For that purpose, the dynamics of changes in extreme maximum instantaneous runoff, as well as air temperature and precipitation database was evaluated and compared between 1960–2012 for 27 hydrometrical observational and 35 meteorological stations in RA. The Mann-Kendall test with consideration of the autocorrelation function was employed as a non-parametric testto identify any present trends. An increasing tendency of air temperature, decreasing tendency of the atmospheric precipitation and extreme maximum instantaneous river runoff were identified in the studied river-basins. As expected, the warming climate contributed to a gradual melting of accumulated snow in the river-basins in winter, resulting in changes in the extreme maximum instantaneous runoff of the rivers in spring, which significantly reduces the risk of the flood occurrence. Thus, it can be claimed that almost all the river basins of Armenia have a tendency to reduce the risk of floods due to global climate change.

KEY WORDS: maximum runoff, climate change, precipitation, variability, trend, flooding risk

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INTRODUCTION

The 20th century was marked by global changes in the social, political, and economic spheres that impacted the state of the environment, including water bodies. These changes in environmental components have been associated with the increase of greenhouse gas concentration in the atmosphere and the growth of temperature of the sub-surface layer of the atmosphere (Solomon et al. 2007).

Studies showed that from 1929 to 2015 the average annual air temperature increased by 1,030C and precipitation decreased by 10% in Armenia (Armenia's Third National Communication on Climate Change 2015) compared with the baseline period from 1961 to 1990 (adopted by the Intergovernmental Expert Group on Climate Change department).

The negative impact of global climate change on the Earth is evident everywhere, including the RA. It is particularly expressed by the increasing vulnerability of ecosystems, frequent natural disasters, observed extreme climate and hydrologic values, desertification, droughts, and other phenomena and risks (Anthony J. et al. 2009; Zaqaryan et al. 2018). It is challenging to find a sphere unaffected by climate change.

The geographical location of the Republic of Armenia, the variety of relief, the compound geological structure (Physical geography of the Armenian USR 1971; Geology of the Armenian USR 1974), the presence of a seismic zone, and the collisions of various atmospheric fronts create suitable conditions for the occurrence of natural disasters, in particular, for floods formation (Vardanian 2008). Those disasters are becoming more frequent and often result in substantial economic damage and numerous casualties. For example, the financial losses caused by natural disasters in the South Caucasus over the past two decades have exceeded $16 billion (Atlas of Natural Hazards and Risk in Georgia 2012).

Floods have been the most frequent disasters, being much more dangerous than any other natural disaster in the world, as the flood covers significant areas of land, causing numerous human victims and enormous material damage (Transboundary Floods 2005; Anthony J. et al. 2009). Floods formed in the river basins are one of the most common types of floods. Floods are especially dangerous for mountainous regions, because most of the river basins are located in residential areas. Floods causing significant material losses, destruction, human victims, mud runoffs and landslides are frequent and very common in the Republic of Armenia (Vardanyan 2005; Vardanyan 2009). However, unlike other natural disasters, floods are somewhat predictable.

While there are various scientific reports concerning river flood formation in RA (Vardanyan 2005; Vardanian 2007; Anthony J. et al. 2009), little consideration was paid to using nonparametric test results to analyze this disastrous phenomenon. Therefore, the objectives of the present study are (1) to explore and evaluate the characteristics of the flood formation in RA rivers, (2) to analyze their changes in the 1960–2012 period with respect to precipitation and air temperature changes at the same river basins and (3) to identify the impact of climate change on observed extreme maximum instantaneous runoffs of the river basins.

RESEARCH AREA, MATERIAL AND METHODS

Research Area

The Republic of Armenia is located in the northeast of the Armenian Highlands. In the north, Armenia borders Georgia, in the east – Azerbaijan, in the west and southwest – Turkey, and in the south – Iran. The territory of RA is 29743 km^2. RA is a mountainous country: 76.5% of the territory has altitudes of 1000-2500 meters above the sea level (a.s.l.) (Fig. 1), with an average elevation of 1800 m a. s. l. and with extremes ranging from 380 m a. s. l. (Debed River-bed) to 4090 m a. s. l. (summit of Aragats Mt).

Armenia is a country of climate contrasts. Due to a complicated topography and microclimatic particularities, significant climate diversity is observed through neighboring small watersheds. Almost all climatic types starting from arid subtropical to cold high mountainous can be found in Armenia (Nersisyan 1964).

The average annual air temperature is 5.5°C (it is below zero in altitudes above 2500 m), and the highest average annual temperature is 12-14°C. The summer is temperate: the average temperature at the end of July is 16.7°C, while in Ararat valley it ranges between 24-26°C. The recorded absolute maximum temperature is 43.7°C (Scientific Applied Directory on the USSR Climate 1989). Winters are cold, January being the coldest winter month, with an average temperature of -6.7°C and a recorded absolute lowest temperature of -42°C. Winters in the northeastern and southeastern parts of the country are temperate.

The average annual precipitation in RA amounts to 592 mm, where the Ararat Valley and Meghri region are the aridest zones, with annual precipitation of around 200-250 mm and with average summer precipitation of around 32-36 mm in the Ararat valley. The highest precipitation is observed in high mountainous areas: about 1000 mm per year.

The average annual wind speed in RA is unevenly distributed, in the range of 1.0-8.0 m/sec. Mountain winds are quite common for some regions, particularly for Ararat valley. During the summer months, their velocity reaches and exceeds 20 m/sec (Armenia's Third National Communication on Climate Change 2015).

In RA, the rivers belong to the Araks (76.4% of the territory) and the Kur (23.6%) river basins (Fig. 1). These are 380 rivers with a cumulative length of over 10 km in the country (The Hydrography of Armenian SSR 1981).

The hydrometric and hydrological features of the relatively large rivers of the Republic of Armenia are shown in Table 1.

Material

Meteorological and hydrological data taken from Armstatehydromet official observations (Climate Bulletin of the Republic of Armenia 2011), existing scientific sources, as well as climatic and hydrological atlases are used for the implementation of this article (Atlas of the natural conditions of the natural resources of the Republic of Armenia, Hydrology 1990).

The dynamics of changes in the extreme maximum instantaneous runoff of the rivers, air temperature, and atmospheric precipitation data are compared and evaluated

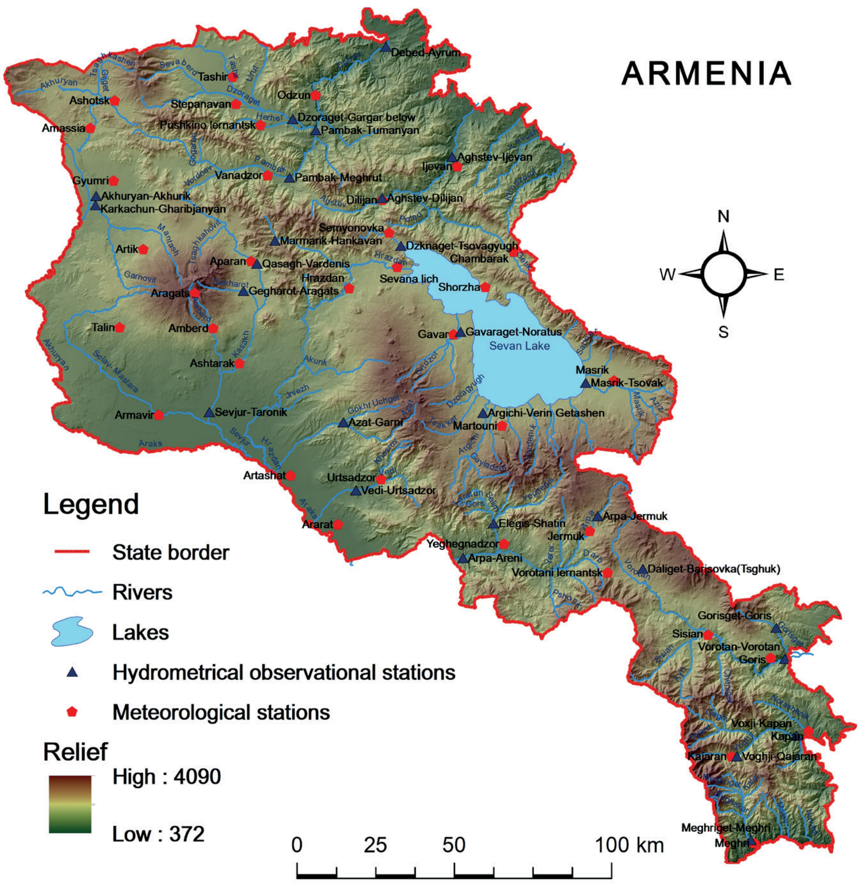

Fig. 1. Geographic distribution of the hydrometrical and meteorological observational stations used in the study

Table 1. The hydrometric and hydrological features of the relatively large rivers of the Republic of Armenia (according to Armstatehydromet data)

N	River – Hydrometric station	Catchment area, km ^{2}	The average height of the catchment area, m	The average annual runoff of river water, m^3 / s	Extreme maximum instantaneous runoff	
					m^3 / s	Monitoring time
1	Debed – Ayrum	3740	1770	33.2	759	19.05.1959
2	Dzoraget – Gargar	1450	1860	15.4	395	19.051959
3	Pambak – Meghrut	1070		7.89	109	14.06.1963
4	Pambak – Tumanyan	1370	1920	10.4	171	23.06.1976
5	Aghstev – Dilijan	303	2000	3.11	53.1	31.05.1978
6	Aghstev – Ijevan	1270	1800	9.54	177	1990
7	Akhuryan – Akhurik	1060	2100	9.93	182	18.04.1968
8	Karkachun – Gharibjanyan	1020	2020	1.04	79.4	27.03.1964
9	Qasakh – Vardenis	441	2300	1.26	151	12.04.1972
10	Gegharot – Aragats	40	3100	0.96	18.7	19.07.1933
11	Sevjur – Taronik	1560	1410	14.37	43.6	06.05.1966
12	Marmarik – Hankavan	94	2430	1.65	31.3	26.04.1960
13	Dzknaget – Tsovagyugh	85	2220	1.1	28.1	06.05.2007
14	Gavaraget – Noradus	467	2430	3.8	49	03.07.1997
15	Argichi – Verin Getashen	384	2470	5.6	171	17.04.1968
16	Masrik – Tsovak	685	2310	4.1	20.3	30.04.1969
17	Azat – Garni	326	2420	4.8	83.9	09.05.1963
18	Vedi – Urtsadzor	329	2090	1.9	53.8	11.09.1974
19	Arpa – Jermuk	180	2790	5.3	91	17.05.1983
20	Arpa – Areni	2040	2110	16.9	340	01. 04.1969
21	Elegis – Shatin	458	2350	6.95	207	30.06.1997
22	Daliget – Borisovka	136	2780	1.37	46.6	14.05.1967
23	Vorotan – Vorotan	2020	2280	22.6	300	18.04.1968
24	Gorisget – Goris	85	2180	0.95	46.4	18.06.1967
25	Voghji – Kajaran	120	2840	3.27	43.9	04,05,21,24.07. 1960
26	Voghji – Kapan	685	2380	11.1	133	15,16.05(2) 2010
27	Meghriget – Meghri	274	2200	3.5	87.5	12.04.1956

for 27 hydrometrical observational and 35 meteorological stations in RA (for the 1960–2012 period). The selected stations' geographic description is given in Fig. 1. The meteorological stations supervised by the Armenian Hydrometeorological center were selected to cover all climatic zones in the country. These locations were chosen according to the following parameters: the data should be reliable, each of them should have acceptable quality datasets, and the data should have adequate record length. In addition to relatively long duration of observation, river observation points with existing meteorological stations were selected. The database consisted of the maximum instantaneous river runoff, average annual air temperatures and atmospheric precipitation for each station in each calendar year.

The rivers were selected based on the principle of having different physical-geographical conditions (Fig. 1): In particular, the different elevations of the relief (average altitudes of the catchment basins range from 2090 to 3100 m), different geological conditions (volcanic and constricted mountains), various types of climate (the lower parts of the selected rivers have arid subtropical climate, while the upper parts have cold high mountainous climate (Nersisyan 1964)). The stations are located within the catchments (Fig. 1 and Table 1), and their areas range from 40 km^2 (Gegharot – Aragats) to 3740 km^2 (Debed – Ayrum).

The elaborated study period (1960–2012) was chosen based on the data availability in terms of record duration and spatial coverage. In addition, results of the current research were compared with similar results obtained elsewhere for European rivers (Blösch G. et al. 2019). The dataset was screened for data errors, and catchments that were known or were identified to have strong human influence (such as reservoirs) on the flood discharges were excluded (for instance, one of the largest rivers in the central part of Armenia was Hrazdan river basin with an area of 2310 km^2).

Methods

This study's methodological approach consists of the following logical steps: the temporal statistical analysis, the spatial statistical analysis, and the identification of extreme maximum instantaneous runoff of the rivers in RA (Fig. 1).

Thus, the main objective of the study is the determination of some hydrometeorological characteristics in Armenia using nonparametric Mann-Kendall (MK) test. This trend analysis is typical in environmental sciences (Mann 1945). The MK test results were obtained using the «Kendall» package in R Studio 3.7 programming language.

MK test is a statistical test widely used to analyze trends in climatologic and hydrologic time series (Yue and Wang 2004). There are two advantages of using this test: First, it is a nonparametric test and does not require the data to be normally distributed. Second, the test has low sensitivity to abrupt breaks due to inhomogeneous time series (Stephens and Ellis 2008). Any data reported as non-detects are included by assigning them a common value that is smaller than the smallest measured value in the data set (Kendall 1975). According to this test, the rejection of the null hypothesis H_0 assumes that there is a trend in the time series, while accepting H_0 indicates no trend detected, and the result is said to be statistically significant.

In order to remove serial correlation from the series, it was suggested pre-whitening the series before applying MK test (Von Storch and Navarra 1995). The critical value of the lag-1 serial correlation coefficient *(r_1)* for a given significance level depends on whether the test is one-tailed or two-tailed (a one-tailed test is used in the current report). The probability limits on the correlogram of an independent series for r can be computed by (Anderson 1942; Salas et al. 1980),

$$r = \frac{-1+1.645\sqrt{n-2}}{n-1} \text{(one tailed-test)} \quad (1)$$

It helps to find out the autocorrelation inside the series and to detect a possible trend. The values must be between -1 and +1. There is a positive correlation if the result is near +1, and there is a negative correlation if it is close to -1. In MK test, if the autocorrelation is r ≥ ± 0,22718, then the members of the series must be recalculated in the following way (Mann 1945),

$$(x_2 - rx_1, x_3 - rx_2 \ldots x_n - rx_{n-1}) \quad (2)$$

The resultant Mann-Kendall test statistic (S) indicates how strong the temperature trend is and whether it is increasing or decreasing (the sign of S indicates the slope of the trend).

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(T_j - T_i) \quad (3)$$

where T_j and T_i are the annual temperature, precipitation and flood values in years *j* and *i, j* > i, respectively, (Jones and Wigley 1986; Kendall 1975) indicates how strong the trend in precipitation is and whether it is increasing or decreasing.

Another statistic obtained on running the MK test is Kendall's tau,

$$\tau = \frac{S}{D} \quad (4)$$

where *D* is the maximum possible value of *S*. Kendall's tau is a measure of correlation and therefore measures the strength of the relationship between the two variables. Kendall's tau is carried out on the ranks of the data (Kendall 1975).

In the case of no relations between two – X and Y series

$$D = \binom{n}{2} \quad (5)$$

The *S* parameter shows the possible trend, and the sign (mins or plus) indicates if the trend is negative or positive. In general, if there are n_x relations with the size of t_i, where *i=1,..., n_x* inside *X* series, n_y relations with the size of t_j, where *j=1,..., n_y* inside *Y*, then

$$D = \sqrt{\left(\binom{n}{2} - T\right)\left(\binom{n}{2} - U\right)} \quad (6)$$

where

$$T = \frac{1}{2}\sum_{i=1}^{n_x} t_i(t_i - 1); U = \frac{1}{2}\sum_{j=1}^{n_y} u_j(u_j - 1)$$

For the time series analysis, it is essential to consider autocorrelation or serial correlation, defined as the correlation of a variable with itself over successive time intervals, prior to testing for trends. Autocorrelation increases the chances of detecting significant trends even if they are absent and vice versa. In order to consider the effect of autocorrelation, a modified MK test applied, which calculates the autocorrelation between the ranks of the data after removing the apparent trend (Khaled at. el. 1998). The adjusted variance is given by:

$$Var(S) = \frac{1}{18} n(n-1)(2n+5) - \frac{n}{nS*}$$
$$\frac{n}{nS*} = 1 + \frac{2}{n(n-1)(n-2)} \sum_{i=1}^{p} (n-1)(n-i-1)(n-i-2) p_s(i) \quad (7)$$

n is the number of observations in the sample, *nS** is the effective number of observations to account for autocorrelation in the data *$p_s(i)$*, is the autocorrelation between ranks of the observations for lag-1, and p is the maximum time lag under consideration.

P≤ 0.05

Significance is set at the 95% level (*α = 0.05*). If the *p-value* is less than the significance level α (alpha), the hypothesis *H_0* is rejected. Rejecting *H_0* indicates a trend in the time series, while accepting *H_0* indicates no trend detected and the result is said to be statistically significant.

For *Z* series having *n* observations data, where *t=1,...,n,* Mann suggested using Kendall's rank correlation for checking monotone changes (Mann 1945). The acceptance of the null hypothesis *H_0* assumes that in *Z* series, where *t=1,...,n,* members are distributed independently:

$$Z = \frac{S-1}{[VAR(S)]^{\frac{1}{2}}} \text{ if } S > 0$$
$$Z = 0 \text{ if } S = 0 \quad (8)$$
$$Z = \frac{S+1}{[VAR(S)]^{\frac{1}{2}}} \text{ if } S < 0$$

Thus, it could be said that the applied method in the article allowed to study the trend in the series and to find out some regularities in them.

Moreover, the Mann-Kendall test for trend analysis, besides the ***'S' Statistic***, relies on another two statistical metrics (Aziz et al. 2003):

√ *The Confidence Factor (CF):* The CF value modifies the S Statistic calculation to indicate the degree of confidence in the trend result, as in *'Decreasing» vs. «Probably Decreasing»* or *«Increasing» vs. «Probably Increasing.»* Additionally, if the confidence factor is quite low, either due to considerable variability in concentrations vs. time or little change in concentrations vs. time, the CF is used to apply a preliminary *«No Trend»* classification, pending consideration of the COV.

√ *The Coefficient of Variation (COV):* The COV is used to distinguish between a *«No Trend»* result (significant scatter in concentration trend vs. time) and a *«Stable»* result (limited variability in concentration vs. time) for datasets with no significant increasing or decreasing trend (e.g. low CF).

Technically, the CF is the measure of confidence for *rejecting* the null hypothesis of «No trend» vs. time. The null hypothesis (H_0) states that the dataset shows no distinct linear trend over time. The probability (*p*) of accepting H_0 is determined from the MK table of probabilities (included in the software), which are based on the number of sample events *n*, and the extreme value of S. Specifically, *p* is the probability of obtaining a value of S equal to or greater than the calculated value for *n* events when no trend is present. In MK test, H_0 is rejected when p < 0.1 (corresponding to $\alpha = 0{,}1$, i.e. below a 90% CF). Here the CF is (*1 – p*) %. The CF is inversely proportional to *p* (higher for lower *p* values) and directly proportional to both *S* and *n* (higher CF for higher *S* and higher *n*). When CF > 95% (p < 0.05), the data demonstrate a strong, either «Increasing» or «Decreasing» trends. When the CF falls between 90 to 95% (0.1 > p > 0.05), the H_0 is rejected, and a trend is indicated; however, due to the lower confidence in the trend, the qualifier «Probably» is applied, as in «Probably Increasing» or «Probably Decreasing.» If the CF is less than 90% (p > 0.1), the H_0 is accepted and either a «No Trend» condition or a «Stable» condition is indicated, depending on the COV, as described below.

Depending on the values of the *S* Statistic and the COV, sampling locations that exhibit a low CF (*CF < 90%*) are designated as either 'Stable' (*S ≤ 0* and *COV < 1*) or 'No Trend' (*COV ≥ 1*) (Table 2).

RESULTS AND DISCUSSION

The trend analysis of temperature series changes

The long-term measurements and observations of air temperature and atmospheric precipitation data taken from the national meteorological services of Armenia were sourced from the chosen 35 meteorological stations located in the studied river basins and were distributed across the whole country (Fig. 1). The average annual air temperature data, atmospheric precipitation and extreme maximum instantaneous river runoff taken from the measuring period of 1960–2012 were used in the study. The presence of trends in annual temperature was assessed by means of MK test and autocorrelation function, a nonparametric test searching for the presence of some trends in the longtime evolution of air temperature, atmospheric precipitation, and extreme maximum instantaneous river runoff.

According to MK test requirements, we have to get autocorrelation results (lag^{-1} serial correlation) for the data series before applying the data. As it was already mentioned, if the autocorrelation coefficient was ≥ |± 0.22718|, then the data series needed to be recalculated, according to Mann test (1945). The analysis was obtained by MK after eliminating the effect of significant lag-1 serial correlation from the time series. Lag-1 was not significant at the 5% level in 10 series out of 35, therefore they were pre-whitened before using in MK test (the others were applied to the original values of the time series).

Autocorrelation plots for the meteorological variables at the ten weather stations are presented in Fig. 2.1.

As shown in Fig. 2, only positive serial correlations were obtained for temperature. The strongest serial correlations were found at Kapan and Urtsadzor stations (below 1000m a. s. l.).

After pre-whitening, according to this test, we had the following results. The Null Hypothesis (H0) was accepted for 14 stations (meaning that no trend is found for these stations), while for 21 remaining stations, it was rejected (there are trends), as shown in Table 3. According to these results, no air temperature decrease was observed in Armenia during the studied periodwhich is an indication of air temperature raise.

There was no trend detected for the remaining 14 stations. According to the test requirements, the confidence of positive or negative changes in the data series were explained by «p-value».

Table 2. Statistical Metrics Used in the Mann-Kendall test (Aziz et al. 2003)

S Statistic	Confidence in Trend	Trend
S > 0	CF > 95%	Increasing
S > 0	95% ≥ CF ≥ 90%	Probably Increasing
S > 0	CF < 90%	No Trend
S ≤ 0	CF < 90% and COV ≥ 1	No Trend
S ≤ 0	CF < 90% and COV < 1	Stable
S < 0	95% ≥ CF ≥ 90%	Probably Decreasing
S < 0	CF > 95%	Decreasing

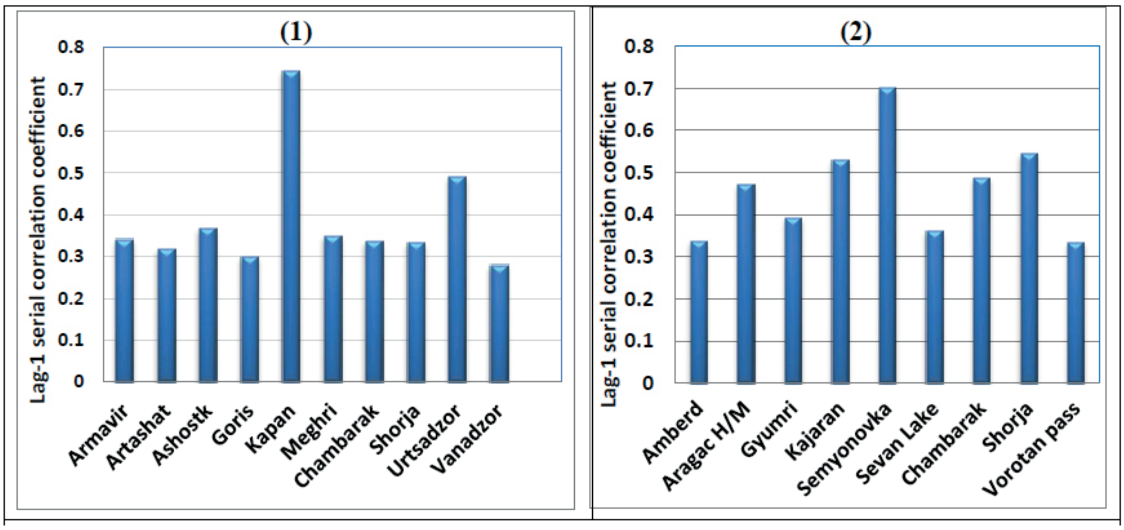

Fig. 2. Lag-1 serial correlation coefficient for the meteorological variables at the weather stations for annual average temperature (1) and atmospheric precipitation (2)

The spatial distribution of weather stations with increasing and no trends for the annual data series during the 1960–2012 period is presented in Fig. 3. As shown, the significant increasing trends in annual temperature were detected at 21 of the observed stations. The strongest significant increasing trend was found for Yeghegnadzor (p = 0.001765, T= 0.343236) and Artashat (p = 0.0036364, T = 0.28966) stations.

Applying MK test and getting results for every station, the schematic map can be created (Fig. 3), where it is possible to notice the detected «Increasing» or «No trend» stations.

Table 3. The «Rejected H_0» test results for annual average air temperature over the period 1960–2012

Name of stations	Z (variation value of S)	P (maximum value of lag)	S (Kandell coefficient)	Tau T(S/D)	D (maximum value of S)	Test interpretation
Amasia	2.2614055	0.0237342	291.0937	0.2195277	1326	Rejected H_0
Aparan	2.2600852	0.023816	249.36763	0.2306824	1081	Rejected H_0
Artashat	2.9080915	0.0036364	340.6402	0.28966	1176	Rejected H_0
Ashostk	1.9768297	0.0480609	246.70418	0.1934935	1275	Rejected H_0
Dilijan	2.8782381	0.003999	362.20774	0.2840845	1275	Rejected H_0
Jermuk	2.0134842	0.0440637	237.58239	0.2020258	1176	Rejected H_0
Yeghegnazor	3.1270847	0.0017655	281.45355	0.343236	820	Rejected H_0
Gavar	1.9715018	0.0486665	247.39479	0.1940351	1275	Rejected H_0
Goris	2.7109032	0.00671	339.72795	0.2664533	1275	Rejected H_0
Gyumri	2.3316821	0.0197174	256.5037	0.2372837	1081	Rejected H_0
Martuni	2.7264622	0.0064017	340.38187	0.2669662	1275	Rejected H_0
Masrik	2.0487062	0.0404909	264.12921	0.1991925	1326	Rejected H_0
Meghri	2.5168019	0.0118425	315.50071	0.2474515	1275	Rejected H_0
Odzun	2.1909045	0.0284587	282.48568	0.213036	1326	Rejected H_0
Sevan Lake	2.626442	0.0086283	338.17727	0.2550357	1326	Rejected H_0
Sisian	2.336992	0.0194396	292.79857	0.2296459	1275	Rejected H_0
Stepanavan	2.2622542	0.0236817	291.77836	0.220044	1326	Rejected H_0
Tashir	2.7121334	0.0066852	349.24533	0.2633826	1326	Rejected H_0
Urtsadzor	2.1209145	0.033929	257.66986	0.2103427	1225	Rejected H_0
Vanadzor	2.8484065	0.0043939	344.96377	0.2816031	1225	Rejected H_0
Vorotan pass	2.6898287	0.0071489	325.82331	0.2659782	1225	Rejected H_0

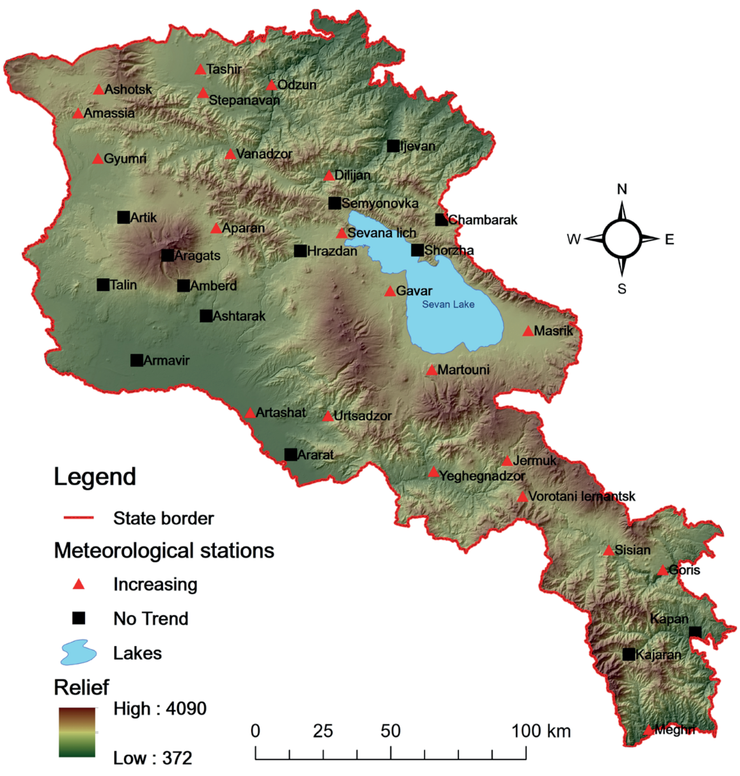

Fig. 3. Mann-Kendall test results for average annual temperature over the period 1960–2012

As it can be seen from Fig. 3, there are twice as many stations with «Increasing» result as stations having «No trend» result. This meant that about 60% of the territory experienced temperature change, and the temperature change had exclusively positive trend (in contrast to precipitation). «No trend» was detected in the south, the west, the southeastern slopes of Aragats mountain, towards south-east from Sevan Lake, Voghji valley, the northeastern and the southeastern parts of the Ararat valley.

It has been an accepted fact that the majority of the territory of Armenia experienced temperature change since 1990's, and the results reported in this study confirm that the global climate change especially began to influence the Armenian climate during the last 2 decades.

According to the overall test results, there was a regional variability in Armenia's annual temperature as a consequence of having complicated relief conditions. Some parts of Armenia experienced a greater increase in temperature, while some parts experienced less increases or no trend.

The trend analysis of precipitation series changes

Similar to air temperature data, the atmospheric precipitation data wasanalyzed as well,the results of which are demonstrated in Fig. 4 and Table 4. In 9 out of 35 series lag-1 was not significant at the 5% level, compared to MK test. Thus we 'pre-whitened' those time series, but the others were applied to the time series's original values. Autocorrelation plots for the meteorological variables at the nine weather stations are presented in Fig. 2.

As shown in Figure 2 only positive serial correlations were obtained for precipitation, which indicates that there is a positive or direct relation inside the series. Similar results were obtained for air temperature series as well. The strongest serial correlations were found in the series of Semyonovka, Shorja and Kajaran stations.

For this test, the Null Hypothesis was accepted for 26 stations (this meant that no trend was seen for these stations), while it was rejected for nine stations (there were trends) (Table 4). It was found that the change in precipitation across

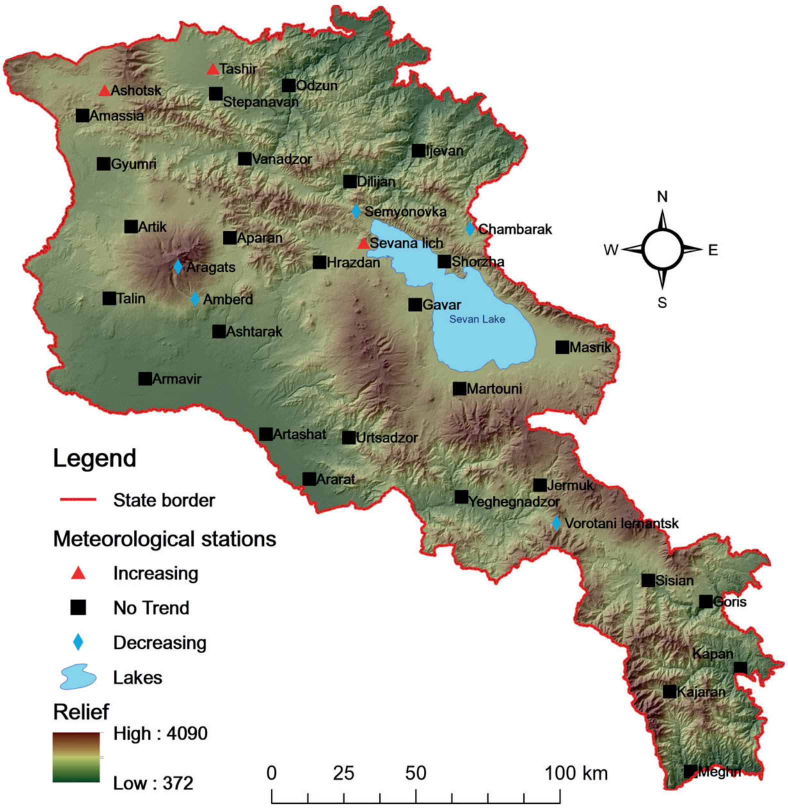

Fig. 4. Mann-Kendall test results for annual average atmospheric precipitation over the period 1960–2012

Table 4. Results of the Mann-Kendall test for annual precipitation over the period 1960–2012

Name of station	Station height, h (m)	Z (variation value of S)	P (maximum value of lag)	S (Kandell coefficient)	Tau T(S/D)	D (maximum value of S)	Test interpretation
Amberd	2071	-3.273	0.001	-403	-0.316	1275	Rejected H_0
Aragats h/m	3227	-3.73	0.000	-430	-0.366	1176	Rejected H_0
Ashotsk	2012	2.967	0.003	376	0.284	1326	Rejected H_0
Ashtarak	1090	2.64	0.022	122	0.301	406	Rejected H_0
Semyonovka	2104	-3.04	0.000	-382	-0.386	990	Rejected H_0
Sevan	1917	3.086	0.002	369	0.301	1225	Rejected H_0
Chambarak	1475	-3.96	0.021	-243	-0.235	1035	Rejected H_0
Tashir	1507	2.103	0.035	259	0.203	1275	Rejected H_0
Vorotan	2387	-3.59	0.021	-228	-0.241	946	Rejected H_0

RA was inconsistent and finding any regularity proved to be challenging.

According to Kendall's tau-based test, four stations had significant annual increasing trends, and five stations had significant negative trends for the annual precipitation, whereas the annual trends for 27 stations were nonsignificant (Table 4). The most significant positive trend was observed in Sevan Lake (p = 0.0020, τ = -0.3012) station, and the most significant negative trends – in Aragats h/m (p = 0.000159, τ = -0.36565) and Semyonovka (p = 0.000136, τ = -0.38586) stations.

Considering the results from Table 4, a schematic map, as shown in Fig. 4, can be plotted, which demonstrates the geographical distribution of MK test results by grouping data obtained from each station. According to the map (Fig. 4), positive changes in precipitation were observed in the north-western regions of RA, in the north of Sevan Lake (at Sevan station).

Negative changes were observed in the southwest of RA, as well as in high-altitude areas of Aragats mountain above 2000 m (at Aragats h/m and Amberd stations). Negative changes were observed in 6 stations from which four stations were located above 1800 m a.s.l.

The trend analysis of floods series changes

The data analysis of long-term extreme maximum instantaneous runoff of the rivers was performed using the above mantioned test. To demonstrate the characteristics of extreme maximum instantaneous runoff of the rivers, as it was already mentioned above, the data taken from the national meteorological services of Armenia (chosen 27 hydrometrical observational stations for 1960–2012 period) were located in the studied river basins and were distributed across the whole country (Fig. 1). To find out the presence of trends in extreme maximum instantaneous runoff of the rivers, nonparametric MK test and autocorrelation function were implemented. At the same time, graphs demonstrating the long-term temporal evolution of flood discharges and their drivers for rivers in RA were created (Fig. 5.1, 5.2)

According to MK test requirements, we had to get autocorrelation results (lag-1 serial correlation) for the data series before applying the data. The analysis was obtained by MK after eliminating the effect of significant lag-1 serial correlation from the time series. Thus, in this case, lag-1 was significant at the 5% level for all stations, therefore they were not pre-whitened before using in MK test (to the original values of the time series were applied for all stations).

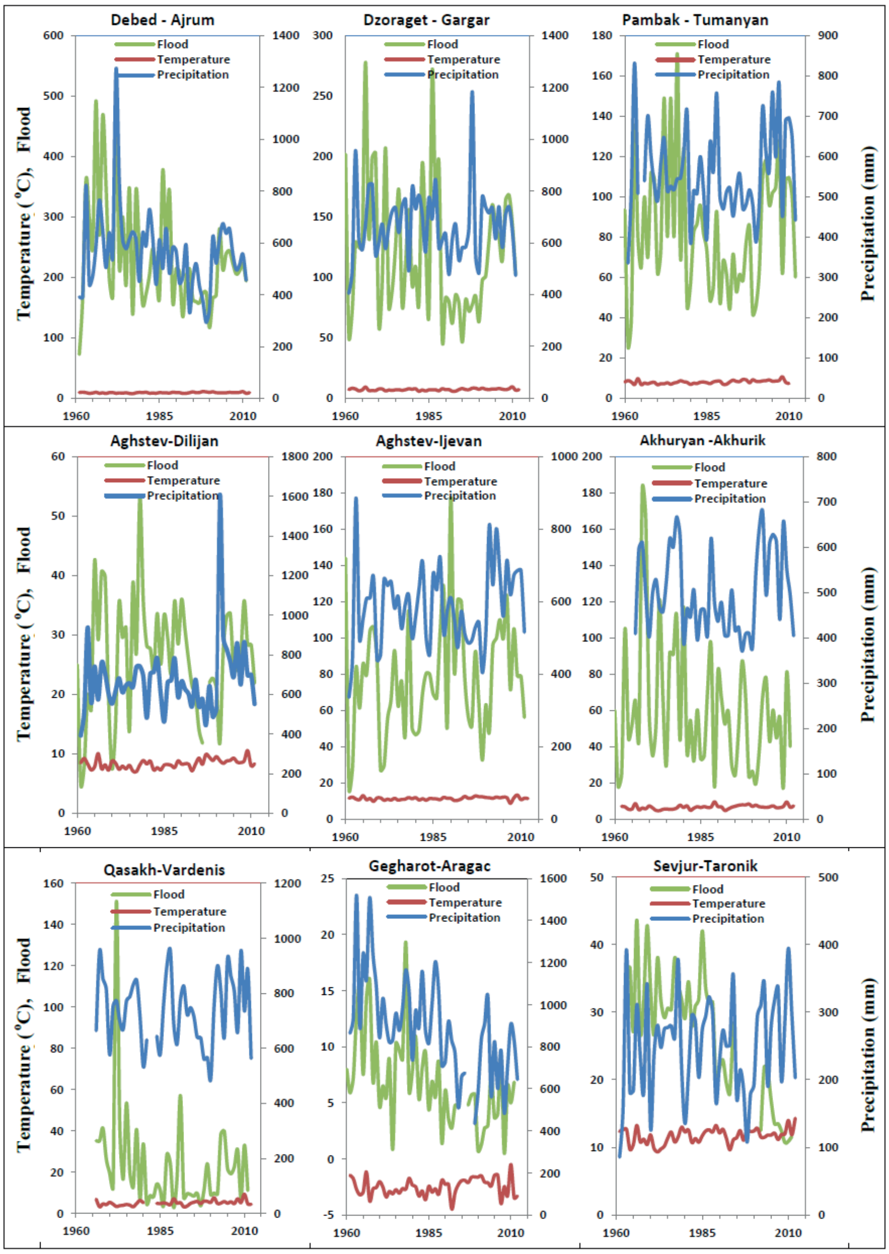

Fig. 5.1. Long-term temporal evolution of flood discharges and their drivers for some rivers in RA

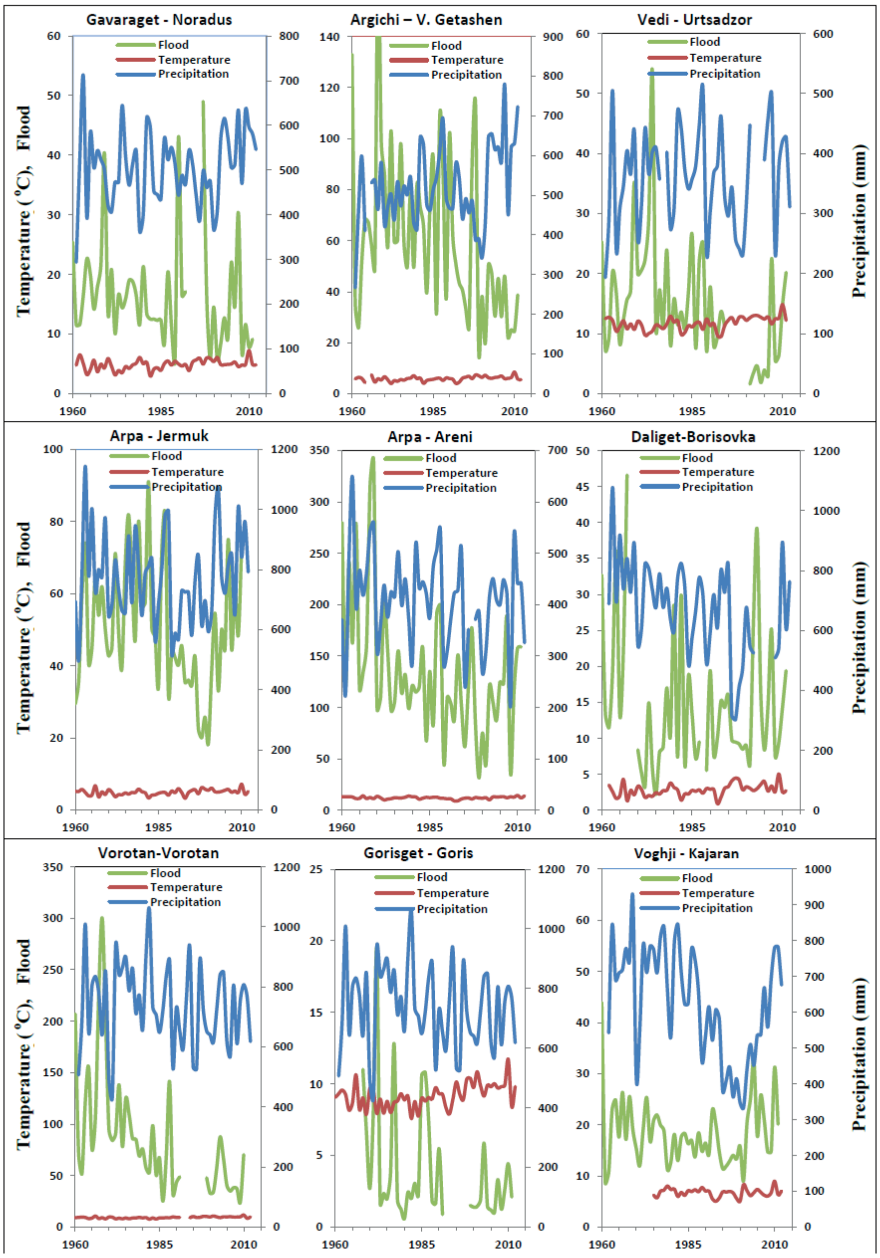

Fig. 5.2. Long-term temporal evolution of flood discharges and their drivers for some rivers in RA

Comparing average air temperature and atmospheric precipitation analyses with the extreme runoff of the rivers reveals more detailed information about the trend detection. Besides finding the increasing and decreasing trends, as well as no trend cases, the stability of the time series can be assessed as well. Thus, the stability during the studied period was investigated for some of the stations. Since the time series were found to be stable, the trend interpretation (the null hypothesis (H0)) was considered accepted.

According to the methodology requirement explained above, to find out if the time series have «No trend» or «Stable» characteristic, it was necessary for some stations to calculate COV,. Since, for 11 stations S ≤ 0 and CF < 90%, COV was compulsory. COV calculation depends on the mean values and standard deviations (as given in Table 5). As the results demonstrate, only in one out of 11 stations «No trend» was detected, whereas for the other stations the extreme maximum instantaneous runoff was stable during the last five decades.

The null hypothesis (H_0) was accepted for 15 stations (this means that «No trend» or «Stable» were observed for these stations), while it was rejected for 12 remaining stations (there were trends) (Table 6). According to these results, during the studied period, extreme maximum instantaneous runoff increase was observed only in one river basin of RA (Dzknaget river basin, which is located from north of Sevan Lake). This is an indication of decline in extreme maximum instantaneous runoff occurrences in RA.

The spatial distribution of hydrometrical observational stations with decreasing, increasing, stable, and no trend results for the annual data series during the period 1960–2012 are presented in Fig. 5.1, 5.2, and 6. As shown, significant decreasing trends were detected in extreme maximum instantaneous runoff at ten of the observed stations. Moreover, the extreme maximum runoff was detected to have a «Probably decreasing» trend only in one river basin (in the northeastern edge of RA, for Debed river basin).

The strongest significant decreasing trend was found in Vorotan-Vorotan (p = 0 , T = -0.64058), Karkachun-Gharibjanyan (p = 0, T = -0.51170) and Sevjur-Taronik (p = 0, T = -0.57791) stations.

Applying MK test results for every station, the schematic map can be plotted (Fig.6), where three major regions can be identified (with minor regions being «Increasing», «Probably decreasing» and «Not studied» areas). Those major regions are: «No trend» area, where the extreme maximum instantaneous runoff of the rivers did not change, «Stable» area, where they were considered stable during the studying period and «decreasing» area, where the extreme maximum instantaneous runoff of the rivers decreased. It can also be seen that there is a small northeastern edge marked «increasing» area (the word «area» represents the river basins). It can be visually

Table 5. The Coefficient of Variation of extreme maximum instantaneous runoff of the rivers for eleven stations

River Stations	Mean	Standard deviation	COV	CF %	Trend
Dzoraget – Gargar	119.1	57.1	0.5	21.2	Stable
Aghstev – Dilijan	26.3	9.6	0.4	12.9	Stable
Akhuryan – Akhurik	61.5	36.5	0.6	79.6	Stable
Qasakh – Vardenis	23.1	23.8	1.0	86.5	No Trend
Marmarik – Hanqavan	16.7	6.1	0.4	69.6	Stable
Masrik – Tsovak	9.8	4.0	0.4	8.6	Stable
Azat – Garni	34.4	17.7	0.5	20.9	Stable
Arpa – Jermuk	49.3	17.2	0.3	86.8	Stable
Daliget – Barisovka	14.7	10.0	0.7	11.7	Stable
Voghji – Qajaran	18.4	6.4	0.3	40.3	Stable
Meghriget – Meghri	17.0	9.1	0.5	87.33	Stable

Table 6. Results of MK test for extreme maximum instantaneous runoff of the rivers over 1960–2012 period

River – Station	Z	p-value	S	varS	tau	CF %	Trend	Test interpretation
Debed – Ajrum	-1.89	0.058	-234	15155.3	-0.18	94	Probably Decreasing	Rejected H_0
Karkachun – Gharibjanyan	-5.34	0.000	-678	16057.3	-0.51	100	Decreasing	Rejected H_0
Gegharot – Aragats	-3.71	0.000	-444	14290.7	-0.36	100	Decreasing	Rejected H_0
Sevjur – Taronik	-5.38	0.000	-497	8512.3	-0.58	100	Decreasing	Rejected H_0
Dzknaget-Tsovagyugh	2.17	0.030	260	14286.7	0.21	97	Increasing	Rejected H_0
Gavaraget – Noradus	-2.45	0.014	-277	12651.0	-0.25	99	Decreasing	Rejected H_0
Argichi – V. Getashen	-3.46	0.001	-440	16059.3	-0.33	100	Decreasing	Rejected H_0
Vedi – Urtsadzor	-2.58	0.010	-273	11155.0	-0.26	99	Decreasing	Rejected H_0
Arpa – Areni	-2.68	0.007	-340	16052.7	-0.26	99	Decreasing	Rejected H_0
Vorotan – Vorotan	-6.27	0.000	-663	11155.0	-0.64	100	Decreasing	Rejected H_0
Gorisget – Goris	-2.28	0.023	-175	5845.0	-0.26	98	Decreasing	Rejected H_0
Voghji – Kapan	-2.33	0.020	-194	6832.7	-0.26	98	Decreasing	Rejected H_0

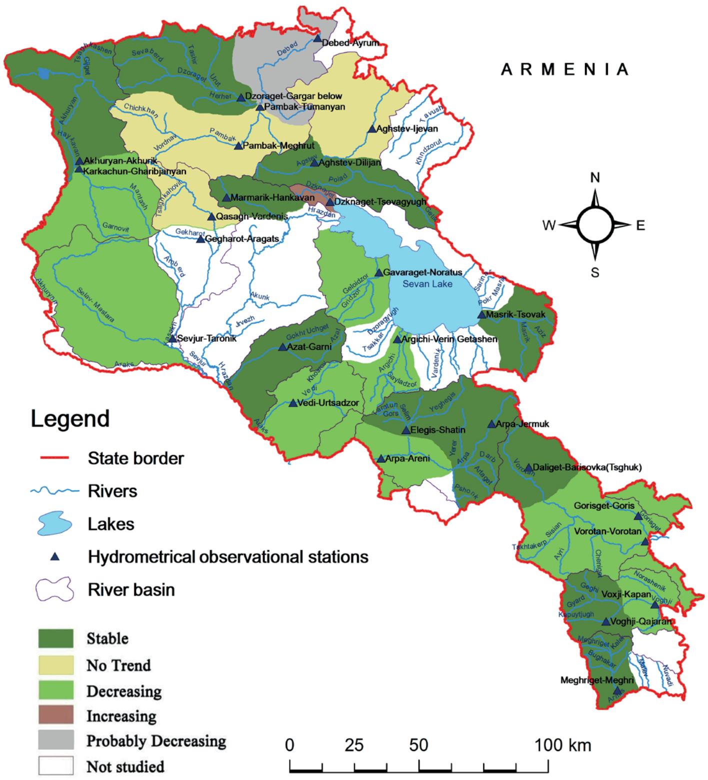

Fig.6. Mann-Kendall test results for extreme maximum instantaneous runoff of the rivers over the period 1960–2012

seen from Fig. 6 that the «Decreasing» area is twice as large as «No trend» and «Stable» areas. «No trend» was detected in Pambak river basin, the middle course of Aghstev river, and the upper course of Qasakh river basins. The extreme maximum instantaneous runoff «Decreasing» areas were identified in the following regions: the west of Ararat valley and the southern, south-western and north-western slopes of Aragats mountain (lower course of Qasakh river, Amberd, Gegharot, Mastara river basins), the lower course of Arpa and Vedi river basins, from Sevan Lake basin Gavaraget and Argichi river basins, in the south of the country, mainly in the lower course of Voghji and in the middle course of Vorotan river basins.

«Stable» extreme maximum runoff was detected especially in the upper course of of Akhuryan, Dzoraget river (in the north-west of RA), the upper courses of Aghstev, Arpa, Eghegis, Vrotan and Voghji river basins (from north to south), from Sevan Lake basin only Masrik river basin, in the south edge was Meghri river basin and in the central part of RA was Azat river basin.

In fact, the «decreasing» extreme maximum instantaneous runoff (observed last five decades over the most territory of Armenia) was mainly influenced by global climate change, which had its effects almost everywhere. As it was shown above, the average temperature increased, and the precipitation decreased during the same period, which had a significant influence on the formation of the extreme maximum instantaneous runoff of the rivers.

Similar studies in Europe demonstrate that the climate change both increased and decreased the flooding risks in different river basins of the continent (Blösch G. et al. 2019). Analyzing the long-term temporal evolution of flood discharges and their drivers (temperature and precipitation) for seven hotspots in four regions (Northern Iberia, Central Balkans, Southern Finland and Western Russia) in different parts of Europa (Blösch G. et al. 2019), it was found, that flood and temperature changes were similarl to what was discussed above for RA. Moreover, the discussed three parameter (including precipitation) changes had a similar pattern as in RA only in Northern Iberia and Central Balkans. Considering the last statement, it is difficult to identify any flood formation factor, which would be the same for all regions, except climate change. Therefore, it can be argued that climate change is the primary factor of these changes.

According to our calculations, 60-70% of the average annual river runoff in RA passed during the overflow season (spring), and the rivers became low-water in summer and winter (Vardanyan 2006). The maximum instantaneous river runoffs were on average 25-30 times higher than the annual norm (Table 1), and in some cases, they were more than a hundred times (for Qasakh – Vardenis it was 120 times more) in the case of dominance of underground alimentation of the rivers.

For all studied rivers, the extreme maximum instantaneous runoff during the 1960–2012 period was calculated and compared with average values over the last years (expressed in m3 and percent) using trend equations (Table 7).

Table 7. The change characteristics of extreme maximum instantaneous runoff of the relatively major rivers of RA

N	River – Hydrometric station	Trendline equation	The correlation coefficient (R)	Extreme maximum runoff norm, m^3 / s	Runoff change	
					m^3 / s	%
1	Debed – Ajrum	y = -2.135x + 4474.7	- 0.35	234.1	- 54.8	- 23.4
2	Dzoraget – Gargar	y = -0.560x + 1233.3	- 0.16	121.3	- 15.5	- 12.8
3	Pambak – Meghrut	y = 0.033x - 7.6	0.02	57.6	0.65	1.1
4	Pambak – Tumanyan	y = -0.045x + 172.0	- 0.02	82.7	- 0.95	- 1.1
5	Aghstev – Dilijan	y = 0.019x - 11.7	0.03	26.3	0.56	2.1
6	Aghstev – Ijevan	y = 0.364x - 644.6	0.21	78.2	8.6	11.0
7	Akhuryan – Akhurik	y = -0.585x + 1222.5	- 0.25	60.2	- 15.8	- 26.2
8	Karkachun – Garibjanyan	y = -0.383x + 769.5	- 0.50	9.03	- 5.1	- 56.5
9	Qasakh – Vardenis	y = -0.484x + 984.9	- 0.27	23.1	- 11.1	- 48.1
10	Gegharot – Apagats	y = -0.134x + 272.1	- 0.52	6.9	- 3.4	- 49.6
11	Sevjur – Taronik	y = -0.523x + 1065.1	- 0.83	27.1	- 14.1	- 52.0
12	Marmarik – Hankavan	y = -0.068x + 150.9	- 0.17	16.7	- 1.9	- 11.4
13	Dzknaget – Tsovagyugh	y = 0.150x - 284.6	0.37	13.7	3.7	27.0
14	Gavaraget – Noradus	y = -0.101x + 216.4	- 0.17	16.5	- 2.8	- 17.0
15	Argichi – Verin Getashen	y = -0.927x + 1900.8	- 0.44	60.5	- 23.5	- 38.8
16	Masrik – Tsovak	y = -0.027x + 6..0	- 0.09	9.8	- 0.7	- 7.1
17	Azat – Garni	y = -0.030x + 94.2	-0.03	34,4	-0.8	-2.3
18	Vedi – Urtsadzor	y = -0.246x + 503.4	- 0.39	15.0	- 7.0	- 46.7
19	Arpa – Jermuk	y = -0.227x + 501.3	- 0.20	50.2	- 6.3	- 12.6
20	Arpa – Areni	y = -1.983x + 4072.4	- 0.46	135.2	- 51.6	- 38.2
21	Elegis – Shatin	y = -0.425x + 905.3	- 0.18	61.7	- 11.2	- 18.2
22	Daliget – Borisovka	y = -0.086x + 185.4	- 0.13	14.7	- 2.2	- 15.0
23	Vorotan – Vorotan	y = -2.240x + 4529.0	- 0.59	86.6	- 63.3	- 73.1
24	Gorisget – Goris	y = -0.117x + 237.5	- 0.39	4.1	- 2.46	- 60.0
25	Voghji – Kajaran	y = -0.033x + 84.2	- 0.08	18.4	- 1.0	- 5.4
26	Voghji – Kapan	y = -0.895x + 1836.1	- 0.50	58.4	- 23.5	- 40.2
27	Meghriget – Meghri	y = -0.122x + 258.9	- 0.20	17.1	- 3.2	- 18.7

As it can be seen from Table 7, only in four stations out of the studied 27 stations, the extreme maximum instantaneous runoff had a positive tendency (it increased), while it decreased for the remaining stations. A relatively high value (27 %) was observed in Dzknaget, while it was very insignificant (1-2%) in two other stations. The reasons for the «increasing» tendency is not explained yet, especially, in Dzknaget river basin, where temperature increas was observed. In contrast to other studied river basins, Dzknaget river basin is considered the smallest one (85 km2), hence local factors may skew the results. Relatively high values of extreme maximum instantaneous runoff (more than 50%) were obtained for four rivers (Sevjur-52 %, Karkachun-56.5%, Gorisget-60%, and Vorotan-73.1%). On the other hand, the extreme maximum instantaneous runoffs decreased in 9 river basins (20-50%). For the other river basins, the changes were negligible, and in some cases, the changes could be 1-2% (Table 7).

In our opinion, the downward trend in the extreme maximum instantaneous runoff was mainly due to air temperature increase and precipitation decrease at these areas, which were almost certainly due to global climate change. Still, there may be some local factors that may require further attention. Comparing the observed extreme maximum instantaneous runoff of the rivers with long-term air temperature changes in the same river basins during the same period, it was clear that the temperature increased for almost all river basins (Fig. 5.1-2). The average annual air temperature compared with 1961–1990 baseline period (adopted by IPCC) increased by 1.03°C (Armenia's Third National Communication on Climate Change 2015; Galstyan et al. 2017). As a result, the snow can not accumulate in many river basins as it melts due to increasing air temperature in winter (Vardanian 2017). Starting early spring, it gradually melts, and the possibility of an extreme maximum instantaneous runoff in late spring decreases or completely disappears, therefore, the risk of the flood occurrence disappears as well.It can be concluded that the extreme maximum air temperatures contributed to the runoff reduction of rivers, resulting in decline in the risk of possible flood occurance.

CONCLUSIONS

This paper provided the review of characteristics of extreme maximum runoff of the rivers RA in the context of global climate change. The temporal and spatial distribution of the extreme maximum instantaneous runoff, as well as air temperature and precipitation database was evaluated and compared. There was a clear reduction in extreme maximum instantaneous runoff potential in almost all the investigated riversas a consequence of increase of the average annual air temperature and decrease in precipitation during the same period. Based on the results presented, it can be claimed that the degree of flooding risk in the river basins drastically reduced due to the increase in average annual air temperatures, which prevents the snow accumulation in many river basins, since it melts due to increasing air temperature in winter. From early spring, it gradually melts, and the possibility of an extreme maximum instantaneous runoff in late spring decreases or completely disappeares, reducing the risk of the flood occurrence.

In conclusion, it can be claimed that because of the global climate change, almost all the river basins of RA have a tendency to reduce the risk of floods. ■

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RESEARCH PAPER

RAINFALL AND DROUGHT TENDENCIES IN RAJSHAHI DIVISION, BANGLADESH

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ABSTRACT. Insufficient rainfall results in water shortage and eventually leads to drought. This research has investigated drought by utilizing standardize precipitation index in monthly mean rainfall data for 30 years from 1988 to 2017 in Rajshahi division, a region in the northwestern part of Bangladesh. Estimated indices have identified that the years 1992, 1994, 2006, and 2012 experienced moderate to severe droughts, and the year 2010 suffered from extreme drought. Non-parametric and linear trend analyses have shown that the number of draughts in the study area has been growing. The study area is thus judged as moving forward to experience more droughts from lack of water due to rainfall deficit, especially during monsoon. This region has already started to experience a shortage of rainwater, approximately 18%, in the monsoon season. This shortage is likely to affect the volume of surface water and thus the groundwater recharging, which would distort irrigation for agriculture in the region. This work would therefore assist in policy-making addressing the watering system of the region to ensure smooth agricultural production.

KEY WORDS: Drought, Rainfall, Trends, Rajshahi, Bangladesh

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INTRODUCTION

Drought is the deficiency of precipitation that results in a disturbance of water cycle and thereby water shortage. The agriculture sector suffers the most due to lack of precipitation and subsequent serious hydrological imbalance, making drought one of the most complex natural hazards (Heim 2002). Bangladesh experiences dry weather because of low precipitation for a period of six months from November to April, and many parts of the country have already experienced an increasing number of droughts with varying severity in recent years (Uddin et al. 2020; Alamgir et al. 2020; Hoque et al. 2020; Adhikary et al. 2013). The northwestern part of the country is highlighted as a severely drought-prone area because of irregularity and high variability in rainfall (Rahman et al. 2020; Uddin et al. 2020; Rahman et al. 2019; Shahid and Behrawan 2008). Agricultural production in the northwest part plays a pivotal role in the overall economy of the country. Most of the surface water bodies including swamps, beals, rivers and canals dry up during the dry season. To meet irrigation approximately 75% of water demand were sourced from groundwater which led to a sharp rise in the ratio of surface to groundwater, as previous literature identified (Shahid and Hazarika 2010; Rahaman et al. 2016; Bari and Anwar 2000), which was not sustainable from both environment and climate change perspectives. A paradigm shift towards a cross-sectoral water management regime is yet to be achieved (Islam et al. 2020), where additional knowledge about the influence of climate variables would play a key role.

The drought of Bangladesh, especially in the northwestern part, has already attracted numerous researchers. Many studies during the last decade have projected that the northwestern part of Bangladesh would become more vulnerable to droughts (Shahid 2011; Shahid and Behrawan 2008). Although there is an agreement about greater agricultural losses from droughts (Ahammed et al. 2020; Alauddin and Sarker 2014; World Bank 2013; Alam et al. 2012), various contributions show different opinions about recent droughts in the region (CEGIS 2013; Miyan 2015; Nury and Hasan 2016), which creates a room for further investigation.

Investigations have been conducted to assess drought severity, vulnerability, historical trend and also to predict using for instance Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index, and analytical hierarchical process (Alamgir et al. 2020; Uddin et al. 2020; Hoque et al. 2020; Ahammed et al. 2020; Miah et al. 2017), However, use of statistical tools is hardly found in the existing literatures, particularly focusing Bangladesh.

SPI, designed by McKee et al. (1993), for the above purposes is relatively simple, can describe drought through water supply condition, and is based on rainfall data alone. It has the strength to be employed for a variety of timescales. SPI is a tool to monitor short-term water supplies to observe soil moisture, which is important for agricultural production, and also to observe groundwater supplies and streamflow in the long run (Hayes et al. 1999). Researchers from several countries including Argentina, Canada, China, Hungary, India, Korea, Spain, Turkey, and the USA, and are using this index to monitor droughts (Nury and Hasan 2016; Quiring and Papakryiakou 2003; Hayes et al. 1999; Wilhite et al. 1985). While several pieces of research utilized SPI, most of the studies have not considered the whole water cycle, instead considered groundwater extraction for irrigation (Rahaman et al. 2016). The amount of water required has rarely been addressed in water management.

In this backdrop, this research, in addition to rainfall, the primary factor in governing drought phenomena (Edossa et al. 2014), intends to investigate the shortage of water supply in northwest Bangladesh. Since rainfall is one of the basic natural resources in the study area, this work reinvestigates recent droughts, trends, and shortage of water from rainfall with the estimation of drought indices using the statistical tools.

MATERIALS AND METHODS

Study area

The study area is Rajshahi division, which is located in the northwestern part of Bangladesh (Fig. 1). Most of the region is low-lying plain land except the uplifted and undulated Barind Tract. It is surrounded by India in the west, Rangpur division in the north, Dhaka division in the east, and Khulna division in the south. The area is lying at the west of the river Jamuna and the north of the river Ganges.

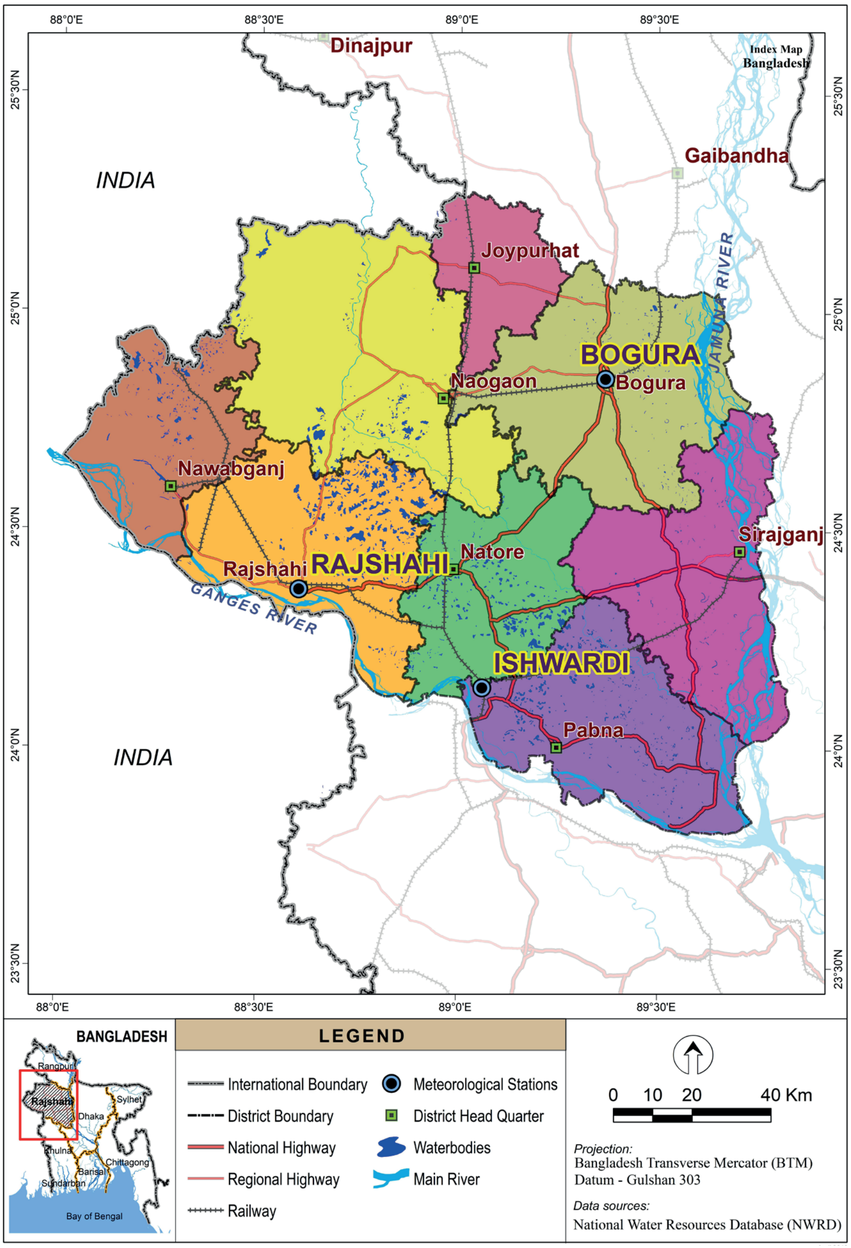

Fig. 1. Location map of the study area

MATERIALS

Daily rainfall data for 30 years from 1988 to 2017 recorded in three meteorological stations in the region namely Rajshahi, Ishwardi, and Bogura (Fig. 1) by the Bangladesh Meteorological Department (BMD) have been used for the analysis.

METHODS

Standardized Precipitation Index (SPI)

SPI conveys the rainfall departure with respect to the rainfall probability distribution function. SPI computation requires long-term rainfall data to determine the probability distribution function which is then transformed to a normal distribution with mean zero and standard deviation of one (Edwards and McKee 1997). It is the fitting of a gamma probability density function and the gamma distribution, g(x) can be written as shown below.

$$g(x) = \frac{x^{a-1}e^{\frac{-x}{\beta}}}{\beta^a \Gamma(a)} \qquad x, a, \beta > 0 \tag{1}$$

where,

$$logmean = \overline{X}_{ln} = \ln(X)$$

$$U = \overline{X}_{ln} - \frac{\sum \ln(X)}{N}$$

$$\beta = \frac{1+\sqrt{1+\frac{4U}{3}}}{4U} \; and \; a = \frac{\overline{X}}{\beta}$$

The cumulative probability is then can be written as:

$$G(x) = \int g(x)dx \tag{2}$$

Since Equation 1 is undefined at x = 0 (no rainfall event), the cumulative probability can be modified further as written below:

$$H(x) = q + (1-q)G(x) \tag{3}$$

where, q is the probability of zero or for no rainfall.
The cumulative probability H(x) is then transformed to the standard normal random variable Z with mean zero and variance of one. Transferred Z is said to be SPI (Edwards and McKee 1997). Such approximate conversion given by Abromowitz and Stegun (1965) is as shown below:

$$Z = SPI = -\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) 0 < H(x) \le 0.5 \tag{4}$$

$$Z = SPI = +\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) 0.5 < H(x) \le 1 \tag{5}$$

$$t = \sqrt{\ln\left(\frac{1}{H(x)^2}\right)} \quad 0<\mathrm{H(x)} \le 0.5$$

$$t = \sqrt{\ln\left(\frac{1}{(1.0 - H(x))^2}\right)} \quad 0.5<\mathrm{H(x)} \le 1$$

where,
C_0=2.515517; c_1=0.802583; c_2=0.010328; d_1=1.432788; d_2=0.189269 and d_3=0.001308 (Abramowitz and Stegun 1965).
With the estimated Z or SPI values drought status can be classified as shown in Table 1.

Mann-Kendall Test

The Mann-Kendall (MK) test is used for determining monotonic trends and is based on ranks (Helsel and Hirsch 2002). This is a test for correlation between a sequence of pairs of values. The significance of the detected trends can be obtained at different levels of significance (generally taken as 0.05). It has been suggested by the World Meteorological Organization (WMO) to determine the existence of statistically significant trends in climate and hydrologic data time series. The MK test statistic and the sign function are calculated using the below formula:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(x_j - x_i) \tag{6}$$

$$sign(x_j - x_i) \begin{cases} +1 x_j > x_i \\ 0 x_j = x_i \\ -1 x_j < x_i \end{cases} \tag{7}$$

where *n* is the number of data, *x* is the data point at times i and j (*j* > *i*). The variance of S is as follows:

$$\mathrm{var}(S) = \left[n(n-1)(2n-5) - \sum_{i=1}^{m} t_i i(i-1)(2i+5)\right]/18 \tag{8}$$

Where t_i is the number of ties of extent *i*, and *m* is the number of tied groups. For *n* larger than 10, the standard test statistic *Z* is computed as the MK test statistic as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\mathrm{var}(S)}} if \; S > 0 \\ 0 \; if \; S = 0 \\ \frac{S+1}{\sqrt{\mathrm{var}(S)}} if \; S < 0 \end{cases} \tag{9}$$

The presence of a statistically significant trend is evaluated using the *Z* value. Positive values of *Z* indicate upward trends, while negative values show downward trends. To test for either an increase or decrease in monotonic trend (a two-tailed test) at a level of significance, H_0 should be rejected if the $|Z| > Z_{1-\frac{a}{2}}$, where $Z_{1-\frac{a}{2}}$ is obtained from the standard normal cumulative distribution tables. For example, at the significance level, the null hypothesis is rejected if IZI>1.96. A higher magnitude of *Z* value indicates that the trend is more statistically significant.

Spearman's Rho Test

Similar to MK, the Spearman's Rho (SR) is another rank-based non-parametric statistical test that can also be used to detect a monotonic trend in a time series (Yue et al. 2002; Yenigun et al. 2008). It is a simple test to determine whether a correlation exists between two classifications

Table 1. Drought category according to SPI (McKee et al. 1993)

SPI	Drought category
0 to - 0.99	Mild drought
– 1.00 to -1.49	Moderately drought
– 1.50 to -1.99	Severely drought
– 2.00 to less	Extremely drought

of the same series of observations. The Spearman's Rho Test statistic, r_s, and the standardized test statistic, Z_{SR} are calculated as follows (Sneyers 1990).

$$r_S = 1 - \frac{6\left[\sum_{i=1}^{n}(R(x_i)-i)^2\right]}{(n^3-n)} \quad (10)$$

$$Z_{SR} = r_S\sqrt{\frac{n-2}{1-r_{S^2}}} \quad (11)$$

Where $R(X_i)$ is the rank of the i^{th} observation X_i in the time series, and is the length of the time series. Positive values of Z_{SR} indicate an increasing trend, while negative Z_{SR} indicates decreasing trends in the time series. For example, at the significance level, the null hypothesis is rejected if |Z|>1.96. A higher magnitude of Z value indicates that the trend is more statistically significant.

The Mann-Kendall and Spearman's Rho tests are non-parametric tests to be applied for the detection of trends because the tests do not require the data to fit any particular probability distribution.

RESULTS AND DISCUSSION

SPI is a probability of rainfall at a location computed from rainfall records at any number of timescales from 1 to 48 months or longer. The time scales 3M (three-month) and 6M (six-month) are applied in the estimation since the mentioned scales are agreed to be the right options to address basic drought and the resulting impact on agriculture in a region (WMO and GWP 2016). Figures 2-4 show the estimated SPIs for the stations: Rajshahi, Ishwardi, and Bogura, respectively. Results show that Rajshahi region has suffered from drought in the years 1992 and 2010. The indices in most of the months in 1992 have obtained a value as less than -1.0 [Fig. 2(a)] indicating that the year 1992 experienced moderate to severe drought. The value of indices has even gone below -2.0 in the year 2010 as shown in Fig. 2(b), which indicates that the area suffered from extreme drought. Similarly, Ishwardi region experienced moderate to severe drought in the years 1992, 1994, and 2012, and extreme drought in the year 2010 (Fig. 3). It is also notable that the estimated indices for the month of January with 6M

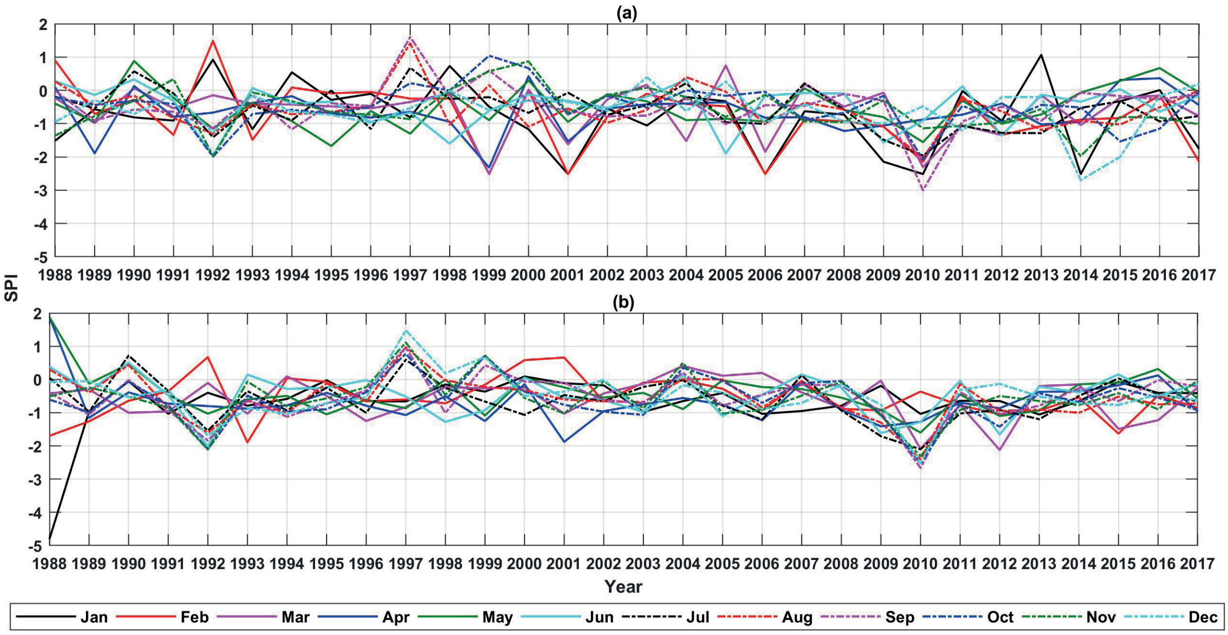

Fig. 2. Estimated monthly SPIs for the duration from 1988 to 2017 at Rajshahi, using 3M time-scale (a), and 6M time-scale (b)

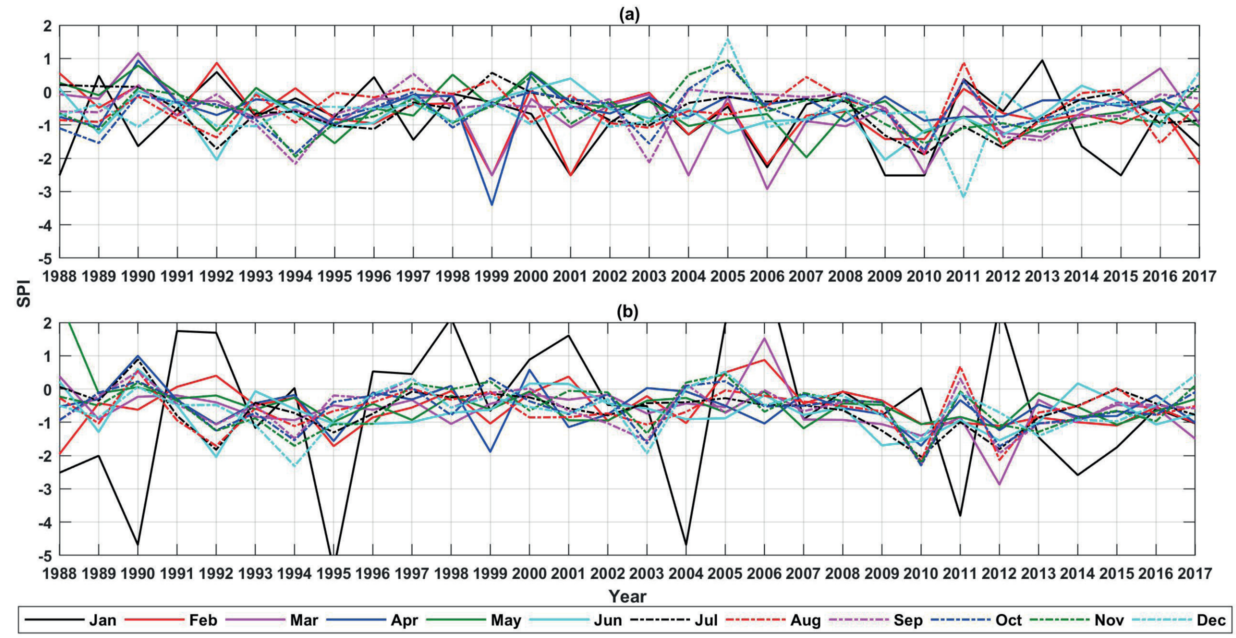

Fig. 3. Estimated monthly SPIs for the duration from 1988 to 2017 at Ishwardi, using 3M time-scale (a), and 6M time-scale (b)

time scales were found to be overestimated, and hence were not considered in later analyses to assess drought in this work. In contrast, most of the estimated SPIs in Bogura are found greater or close to -1.0 as shown in Fig. 4. However, the years 2006 and 2012 experienced moderate to severe drought.

According to the investigation made by the Center for Environmental and Geographic Information Services (CEGIS) (2013) based on rainfall data for the duration 1982–2008, Rajshahi experienced severe drought in the years 1995 and 1996. In contrast, this study finds that the years 1995 and 1996 experienced mild drought, or mostly enjoyed normal condition. Drought severity in the year 1992 for Rajshahi region is found well aligned with the findings of Miyan (2015), Adnan (1993) and Hossain (1990). Besides, this study resembles the findings of Nury and Hasan (2016), where the authors found extremely dry events in the years 1992, 1999, and 2010 in Rajshahi.

This study has estimated the trends using Mann-Kendall and Spearman's Rho tests as shown in Tables 2-4 over the estimated SPIs as shown in Figures 2-4. The months July and August in Rajshahi; March, May, and July in Ishwardi; and July to November in Bogura are showing strong negative trends (Tables 2-4). The months June, July, and August are the rainy or monsoon season all over Bangladesh (Banglapedia 2014), while March to May and September to November are pre- and post-monsoon seasons (Syed and Amin, 2016). Trend analyses show that the months June to November have strong negative trends in the estimated indices. Whereas, the months July and August or the monsoon season are approximated to be common in all three stations having stronger negative trends. In addition, this work has also included the month of June as one of the monsoon months to estimate the shortage of water during the whole monsoon season to be explained in a later section. The yearly maximum and minimum indices along with linear trends are shown in Figures 5-6. In the yearly maximum in both 3M and 6M analyses, linear trends are found to be negative for the whole study area with a significant slope of -0.03 in 6M analyses. On the other hand, in the yearly minimum in 3M analyses, the whole study is showing a negative trend with a slope of -0.02, while 6M analyses are also showing a negative trend, except the case of Rajshahi station which has shown a tiny positive trend. Results are indicating that Rajshahi division is likely to suffer more in the coming years than those of the past from drought.

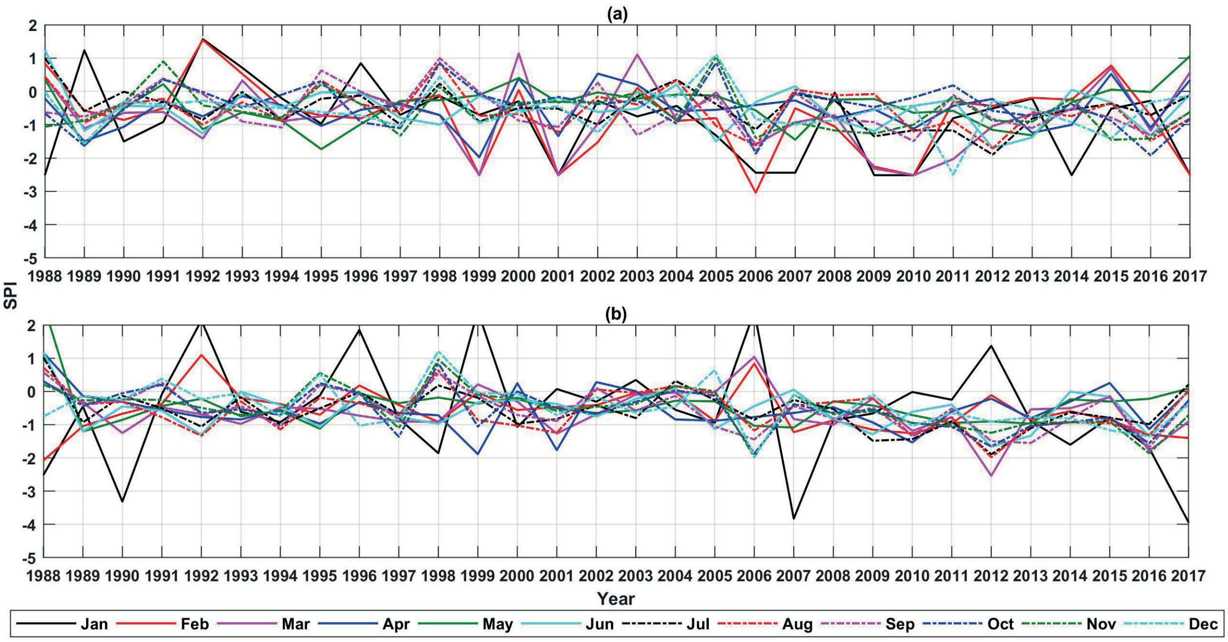

Fig. 4. Estimated monthly SPIs from 1988 to 2017 at Bogura, using 3M time-scale (a), and 6M time-scale (b)

Table 2. Trend estimations using Mann-Kendall and Spearman's Rho tests in SPIs estimated for Rajshahi station

Month	Using 3M Time Scale SPI			Using 6M Time Scale SPI			Remarks
	MK test	SR test	Trend	MK test	SR test	Trend	
January	-0.0	0.1	-/+	1.6	1.7	+	
February	-1.3	-1.3	-	0.0	0.0	+	
March	-0.4	-0.5	-	0.1	-0.0	+/-	
April	-0.2	-0.2	-	0.2	0.2	+	
May	1.3	1.3	+	0.6	0.8	+	
June	-0.1	-0.2	-	-0.7	-0.6	-	Both -
July	-2.1	-2.3	-	-1.1	-1.2	-	Both - and stronger
August	-1.0	-1.0	-	-1.9	-1.9	-	Both - and stronger
September	0.5	0.5	+	0.4	0.5	+	
October	-1.0	-0.9	-	-0.1	-0.1	-	Both -
November	-1.9	-1.7	-	-0.7	-0.7	-	Both -
December	0.0	0.0	+	-0.8	-0.9	-	

Table 3. Trend estimations using Mann-Kendall and Spearman's Rho tests in SPIs estimated for Ishwardi station

Month	Using 3M Time Scale SPI			Using 6M Time Scale SPI			Remarks
	MK test	SR test	Trend	MK test	SR test	Trend	
January	-0.9	-0.7	-	-0.3	-0.2	-	Both -
February	-1.6	-1.6	-	-0.7	-0.8	-	Both -
March	-1.5	-1.6	-	-1.2	-1.2	-	Both - and stronger
April	0.1	0.2	+	-0.9	-0.9	-	
May	-2.4	-2.8	-	-1.5	-1.5	-	Both - and stronger
June	-0.5	-0.5	-	-0.9	-1.0	-	Both -
July	-1.2	-1.4	-	-1.6	-1.5	-	Both - and stronger
August	0.1	0.1	+	0.4	0.3	+	
September	0.2	0.1	+	-1.0	-1.1	-	
October	1.2	1.3	+	-0.7	-0.8	-	
November	-0.8	-0.9	-	-0.6	-0.5	-	Both -
December	0.4	0.5	+	0.0	-0.1	-	

Table 4. Trend estimations using Mann-Kendall and Spearman's Rho tests in SPIs estimated for Bogura station

Month	Using 3M Time Scale SPI			Using 6M Time Scale SPI			Remarks
	MK test	SR test	Trend	MK test	SR test	Trend	
January	-1.6	-1.3	-	-0.9	-0.8	-	Both -
February	-0.4	-0.5	-	-1.6	-1.4	-	Both -
March	-0.5	-0.5	-	-0.0	-0.0	-	Both -
April	0.4	0.4	+	-0.2	-0.0	-	
May	0.9	0.9	+	0.8	1.0	+	
June	-0.8	-0.7	-	-0.3	-0.3	-	Both -
July	-1.8	-1.8	-	-1.7	-1.7	-	Both - and stronger
August	-1.5	-1.6	-	-1.5	-1.5	-	Both - and stronger
September	-1.8	-2.0	-	-2.7	-2.8	-	Both - and stronger
October	-1.1	-1.0	-	-2.7	-3.2	-	Both - and stronger
November	-1.5	-1.7	-	-3.0	-3.7	-	Both - and stronger
December	-0.7	-0.5	-	-2.3	-2.6	-	Both -

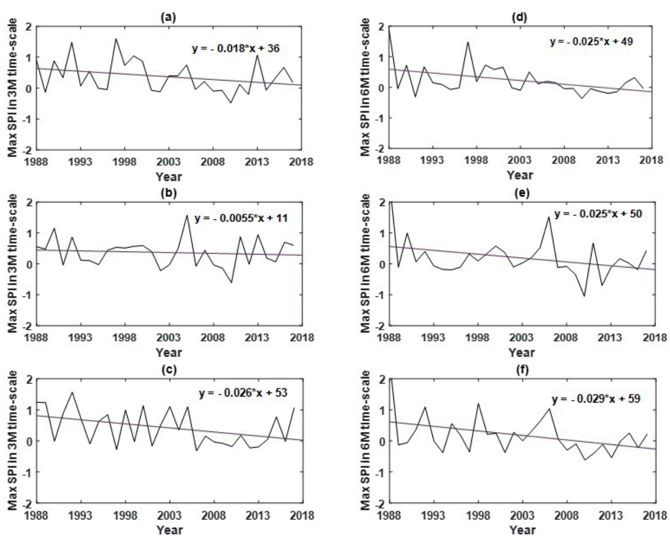

Fig. 5. Yearly maximum index for the duration from 1988 to 2017, in 3M time-scale analyses Rajshahi (a), Ishwardi (b), and Bogura (c); in 6M time-scale analyses Rajshahi (d), Ishwardi (e), and Bogura (f)

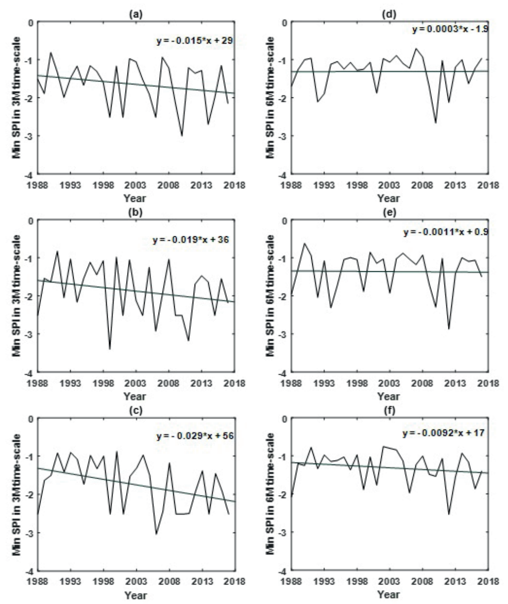

Fig. 6. Yearly minimum index from 1988 to 2017, in 3M time-scale analyses Rajshahi (a), Ishwardi (b), and Bogura (c); in 6M time-scale analyses Rajshahi (d), Ishwardi (e), and Bogura (f)

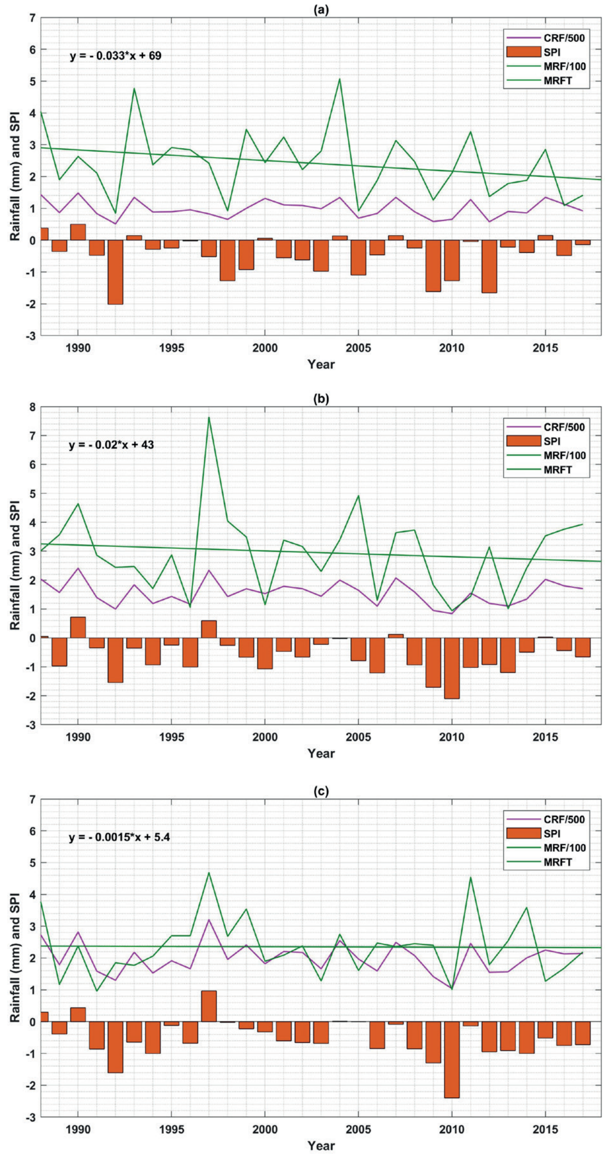

Fig. 7. Monthly rainfall (MRF), cumulative rainfall (CRF), and SPIs with the 6M time-scale along with monthly rainfall trend (MRFT) for the months June (a), July (b), and August (c) at Rajshahi

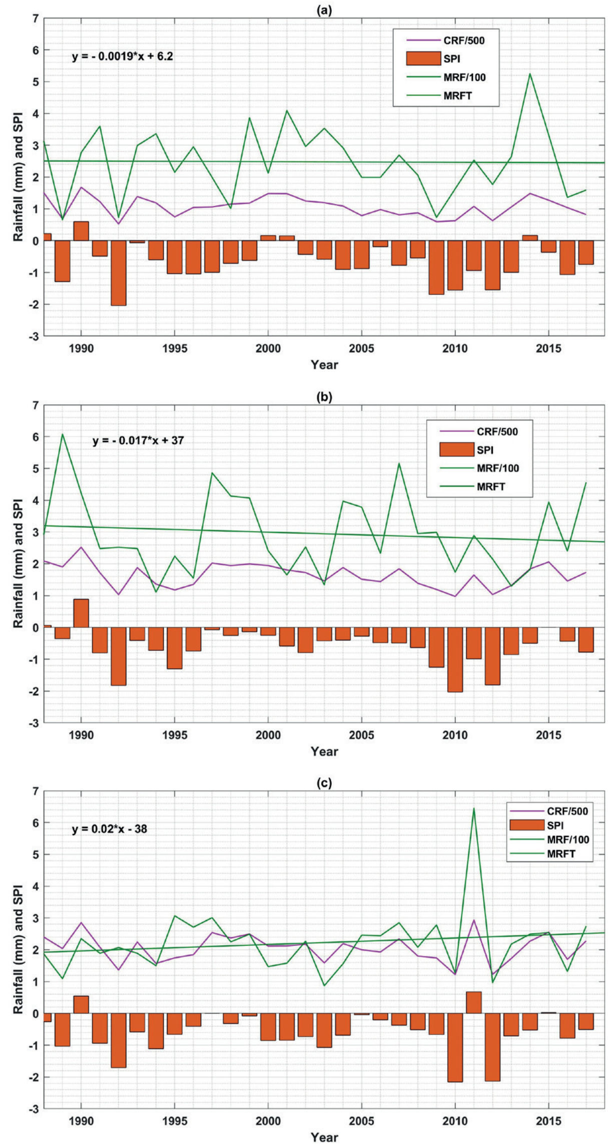

Fig. 8. Monthly rainfall (MRF), cumulative rainfall (CRF), and SPIs with the 6M time-scale along with monthly rainfall trend (MRFT) for the months June (a), July (b), and August (c) at Ishwardi

MK and SR tests (Tables 2-4), along with maximum indices (Figure 5) have attributed that the months June, July, and August are showing stronger negative trends. With a little slope yearly minimum indices (Figure 6) also show the negative trends. As the months June, July, and August belong to the monsoon season and are showing stronger negative trends in the estimated drought indices, the following section is appended to show detailed rainfall along with estimated SPIs for the monsoon season. Monthly rainfall, cumulative rainfall through which the indices are estimated, and indices estimated using a 6M time scale are shown in Fig. 6-8 for the rainfall recorded at Rajshahi, Ishwardi, and Bogura for the months June, July, and August. Here, the 6M time scale is applied since the scale is suggested for investigating agricultural impacts from drought.

Monthly rainfall in the monsoon season in Rajshahi region shows negative trends with the slopes -0.03, -0.02, and -0.002 for June, July, and August, respectively (Figure 7). The month of August shows that the difference between monthly rainfall and cumulative rainfall is minimum, and this minimum difference indicates that the months June and July are experiencing less rain than that of the month August.

Similarly, the monthly rainfall in the monsoon season in Ishwardi shows negative trends with the slopes -0.002 and -0.02 for June and July, respectively (Figure 8). The month of August shows a positive trend with a slope of 0.02. Estimations once again indicate that the months June and July lack rainwater than that of the month August.

Monthly rainfall in the monsoon season in Bogura shows a stronger negative trend with the slopes -0.05 and -0.07 for June and July, respectively (Figure 9). The month of August showing positive trends with the slope of 0.02 indicates a similar pattern that the months June and July lack rainwater compared to that during the month of August. However, the positively trended rainfall in August in all regions do not show better indices (Fig. 2-4), since many of the slopes are found to be close to -1.0 or less.

The above findings interpret that during the monsoon season the whole study area lacks rainwater, whereas rainwater is the most important agent for keeping better agricultural production. If the amount of rainwater becomes scarce, the area is likely to face a shortage of agricultural productivity. Initially, groundwater may be used for agriculture to replenish the productivity gap, but the overall climate of the region would deteriorate. An overall water deficiency in percentage is estimated

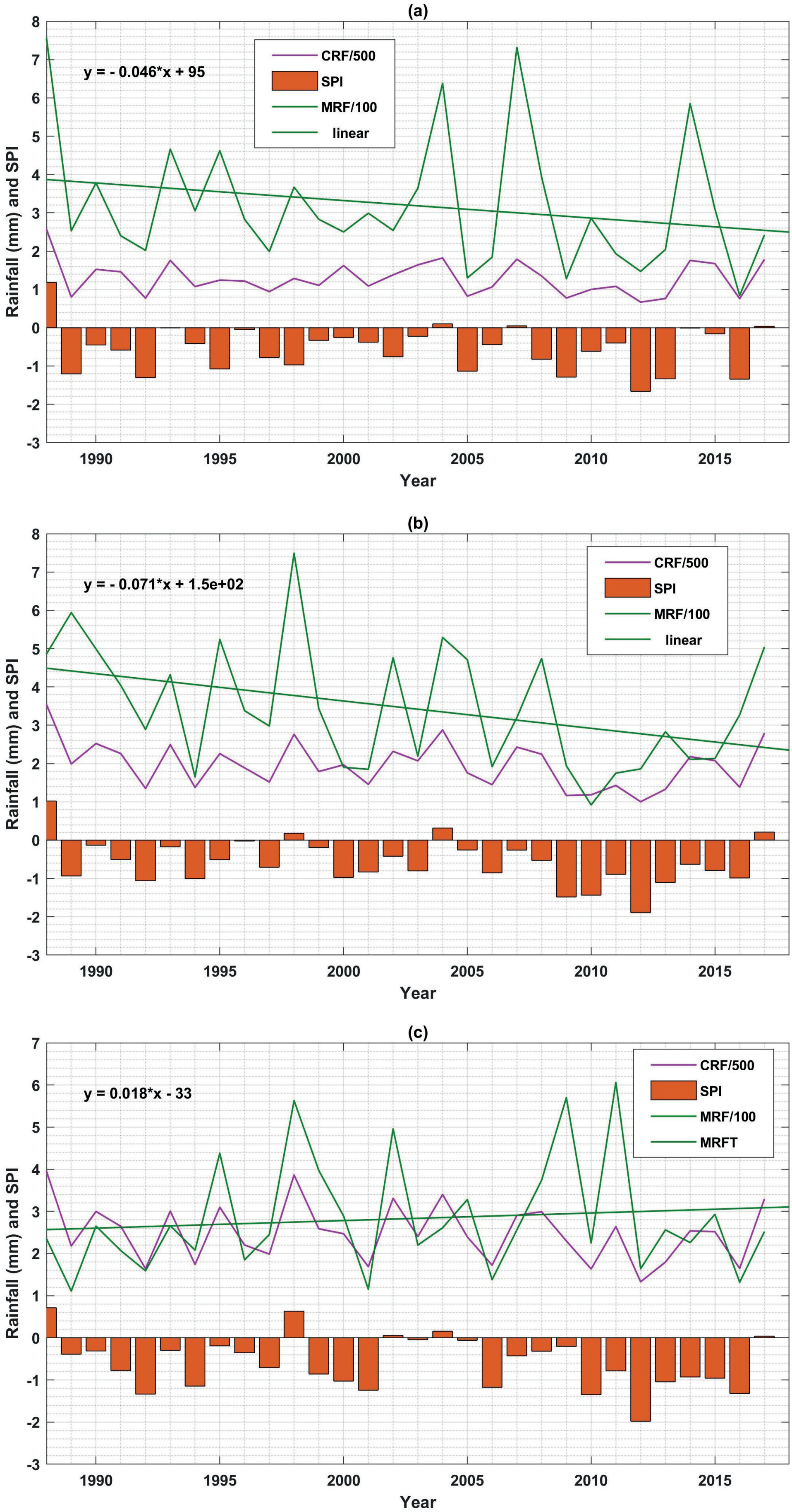

Fig. 9. Monthly rainfall (MRF), cumulative rainfall (CRF), and SPIs with the 6M time-scale along with monthly rainfall trend (MRFT) for the months June (a), July (b), and August (c) at Bogura

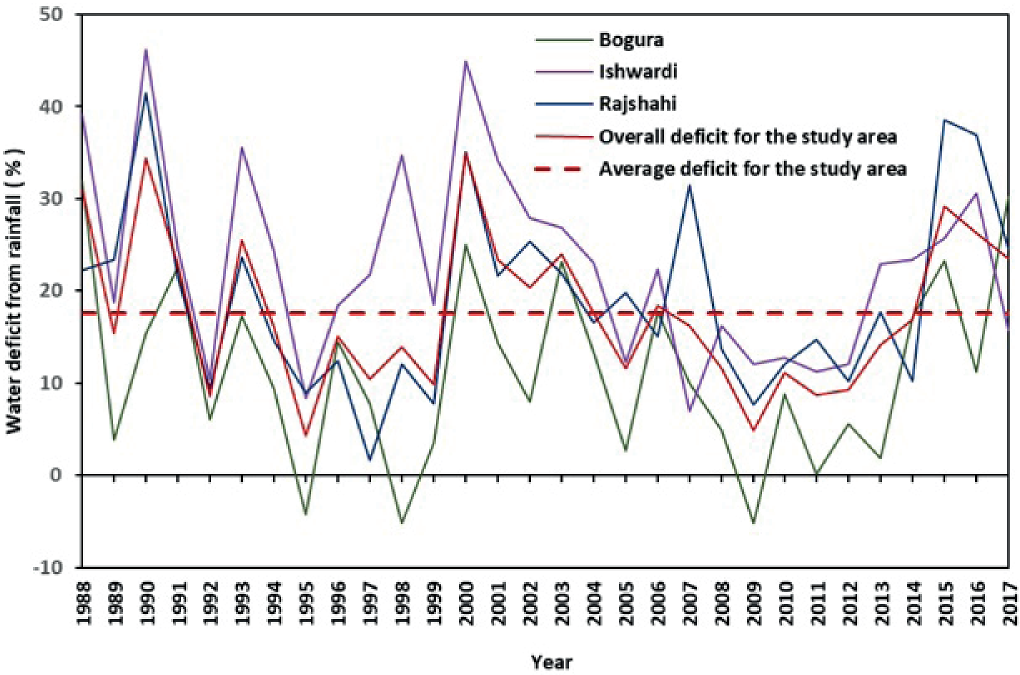

Fig. 10. Overall water deficit from rainfall in monsoon for the months June, July, and August in the study area

using rainfall data during monsoon. This is done from the differences of converted monthly rainfall and cumulative rainfall to a unique scale for Rajshahi division (Figure 10). Results show that Bogura experiences the least water deficit in the region, while Ishwardi experiences the most. Overall water deficit ranges from 4% to 35% in different years, and the average water deficit is found to be 18% for the whole study area. Hence, Rajshahi division has to increase the supply of water from alternative sources for agriculture to maintain the current level of production.

CONCLUSIONS

Rajshahi division, part of northwestern Bangladesh, is highlighted as one of the most drought-prone areas in southeast Asia. This research has reinvestigated the recent drought status of Rajshahi division with the estimation of SPI using rainfall data from 1988 to 2017 and has found discrepancies in past drought years. This work has identified that the years 1992, 1994, 2006, 2012 have experienced moderate to severe drought, while the year 2010 has suffered from extreme drought. Drought trends have figured out a shortage of water in the study area using the estimated SPIs. Most of the estimated yearly maximum and minimum indices have attributed negative trends with a diverse slope from -0.001 to -0.029 except Rajshahi having a very small positive trend with a slope of 0.0003 in minimum indices with 6M analysis. Mann-Kendall and Spearman's Rho tests have identified strong negative trends for the monsoon season, i.e. the months of June, July, and August. Findings have interpreted that the study area is experiencing a roughly 18% of shortage in rainwater during the monsoon season. It has been observed that the cumulative monthly rainfall is always higher than the monthly rainfall. As a result, most of the estimated indices have been found below zero. Water from rainfall replenishes water bodies on the surface and recharges groundwater, and shortage of water obstructs sustainability and overall irrigation. The estimation of rainwater deficit would therefore help to identify the water requirement to replenish water sources in the study area to continue irrigation for smooth agriculture. This research may be replicated and/or extended to other regions to assess the trend in rainfall.

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RESEARCH PAPER

DAILY VARIATIONS IN WET DEPOSITION AND WASHOUT RATES OF POTENTIALLY TOXIC ELEMENTS IN MOSCOW DURING SPRING SEASON

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ABSTRACT. For the first time, the wet deposition and washout rates of soluble forms of potentially toxic elements (PTEs) were estimated in rains during the spring AeroRadCity experiment in Moscow. Rains are an important factor in reducing atmospheric pollution with PTEs in Moscow. Due to the resuspension of contaminated particles of road dust and urban soils, industrial and traffic impact, waste and biomass burning, rainwater is highly enriched in Sb, Pb, Se, Cd, and S, and less enriched in P, Ba, As, W, Mn, Sn, Na, Co, Ni, and Be. Significant wet deposition (μg/m^2 per event) and washout rates (μg/m^2 per hour) of PTEs were revealed during the public holidays in May which corresponded to the elevated aerosol content due to predominant air advection from southern and south-western regions in this period. During continuous rains, the level of PTEs wet deposition sharply decreases on the second and subsequent days due to the active below-cloud washout of aerosols during the initial precipitation events. We show that the length of the dry period and aerosol content before the onset of rain determines the amount of solid particles in rainwater, which leads to an increase in rainwater pH, and strongly affects wet deposition and washout rates of PTEs of mainly anthropogenic origin (W, Zn, Bi, Cd, Sb, Ni, B, S, K, and Cu). At the same time rainfall intensity contributes to an increase in wet deposition and washout rates of Se, As, B, Cu, Sb, S, Cd, Ba, Rb, and K. The obtained results provide a better understanding of atmospheric deposition processes and can be useful in assessing the urban environmental quality.

KEY WORDS: wet deposition; washout rate, urban environment; contamination of precipitation; soluble forms of chemical elements

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INTRODUCTION

The study of the chemical composition of atmospheric precipitation makes it possible to assess the washout rates of potentially toxic elements (PTEs), particulate matter, organic pollutants and ions (such as sulfates, nitrates, ammonium, etc.) from the atmosphere and to evaluate wet deposition fluxes on the Earth's surface (Al-Momani 2008; Cizmecioglu and Muezzinoglu 2008; Bayramoğlu Karşı et al. 2018; Talovskaya et al. 2018, 2019; Ma et al. 2019; Tian et al. 2020; Cherednichenko et al. 2020; Park et al. 2020; Loya-González et al. 2020; McHale et al. 2021). PTEs usually include a large number of elements, e.g. carcinogenic As, Cd, Pb, Cr, Be, Ni, and Co, as well as causing general toxic damage to the body or individual organs and systems Sb, Zn, Cu, Mo, W, Sn, Se, Ba, Mn, and others (R 2.1.10.1920-04 2004; U.S. EPA 2020). Atmospheric precipitation is the most important factor in the self-purification of atmospheric air during the warm season (Ouyang et al. 2019; Long et al. 2020; Orlović-Leko et al. 2020). Wet deposition compared to dry one is more efficient in removing PTEs from the atmosphere and causes higher pollutants input into terrestrial or aquatic systems (Ouyang et al. 2015). Although estimates of wet deposition of PTEs over long periods of time (one-year or long-term) are carried out quite often, short-term changes in the chemical composition of rainwater are still poorly investigated (Pan et al. 2017).

The elemental composition of atmospheric precipitation has been studied in detail in many cities around the world. In Russia, the main attention is paid to the analysis of the individual chemical elements distribution in the rains, but those are usually snap-shot observations (Elpat'evskii 1993; Golubeva et al. 2005; Chudaeva et al. 2008; Udachin et al. 2010; Yanchenko and Yaskina 2014; Semenets et al. 2017; Svistov et al. 2017; Kuderina et al. 2018; Bufetova 2019). In Moscow – the largest megacity in Europe – complex meteorological observations are being carried out since the mid-1950s (Chubarova et al. 2014) at the Meteorological Observatory of the Lomonosov Moscow State University (MO MSU). Since 1982, these observations have been supplemented with monitoring of the physicochemical properties and macrocomponent composition of atmospheric precipitation (Eremina 2019). The atmospheric air pollution in Moscow with particulate matter (PM) and gaseous pollutants, especially sulfur dioxide due to the use of natural gas by electric and thermal power plants, is lower than in other megacities (Elansky et al. 2018). In Moscow, research on the individual rain samples pollution with organic compounds was carried out (Polyakova et al. 2018). Our previous study of the solubility and partitioning of PTEs during spring rains in Moscow showed that anthropogenic sources contributed significantly to the concentration of soluble PTEs; for the insoluble PTEs, crustal materials were the important contributors (Vlasov et al. 2021a). The spring period was chosen because of the largest variety of meteorological conditions, typical for both cold and warm seasons, and emissions of pollutants into the atmosphere from various sources that were previously observed during spring months (Chubarova et al. 2019; Elansky et al. 2020; Popovicheva et al. 2020a). However, studies of the intensity of soluble PTEs washout from the atmosphere by rains within the city have not been previously conducted. Therefore, the aims of this study are to estimate wet deposition of soluble PTEs forms and to identify the rain parameters that affect PTEs washout from the atmosphere during the spring period.

MATERIALS AND METHODS

The study of the rainwater chemical composition was carried out in April-May 2018 at the MO MSU during the AeroRadCity experiment (Chubarova et al., 2019). The MO MSU is located in the southwestern part of the city at the territory of the MSU Botanical Garden, far from industrial sources of pollution and major highways; and therefore is considered as a background city station (Fig. 1). Rain samples (n = 15) were taken at a height of 2 m from the ground surface using a vinyl plastic funnel 80x80 cm in size and a white plastic bucket. Each rainfall event was analyzed from its beginning to the end on the current or adjacent days, that is, individual rainfall events: on April 6–7, 10–11, 17–18, 18–19, 21, 21–22, 25, 26, and May 1, 2, 4, 5–6, 17–18, 18–19, 19–20.

The pH and electrical conductivity (EC, μS/cm) were measured in rainwater samples by potentiometric and conductometric methods, respectively. To isolate soluble forms of PTEs, samples were filtered through Millipore© filters with a pore diameter of 0.45 μm. According to the mass of suspension on the filter, the content of solid particles in rainwater (*S*, mg/L) was estimated as $S = m / V$, where *m* is the mass of particles on the filter, mg; *V* is the volume of filtered rainwater, L. Concentrations of Al, As, B, Ba, Be, Bi, Ca, Cd, Co, Cr, Cu, Fe, K, Mn, Mo, Na, Ni, P, Pb, Rb, S, Sb, Se, Sn, W, and Zn in the filtrate were determined using mass spectral (ICP-MS) and atomic emission methods (ICP-AES) with inductively coupled plasma on the mass spectrometer «iCAP Qc» (Thermo Scientific, USA) and atomic emission spectrometer «Optima-4300 DV» (Perkin Elmer, USA) in the laboratory of the

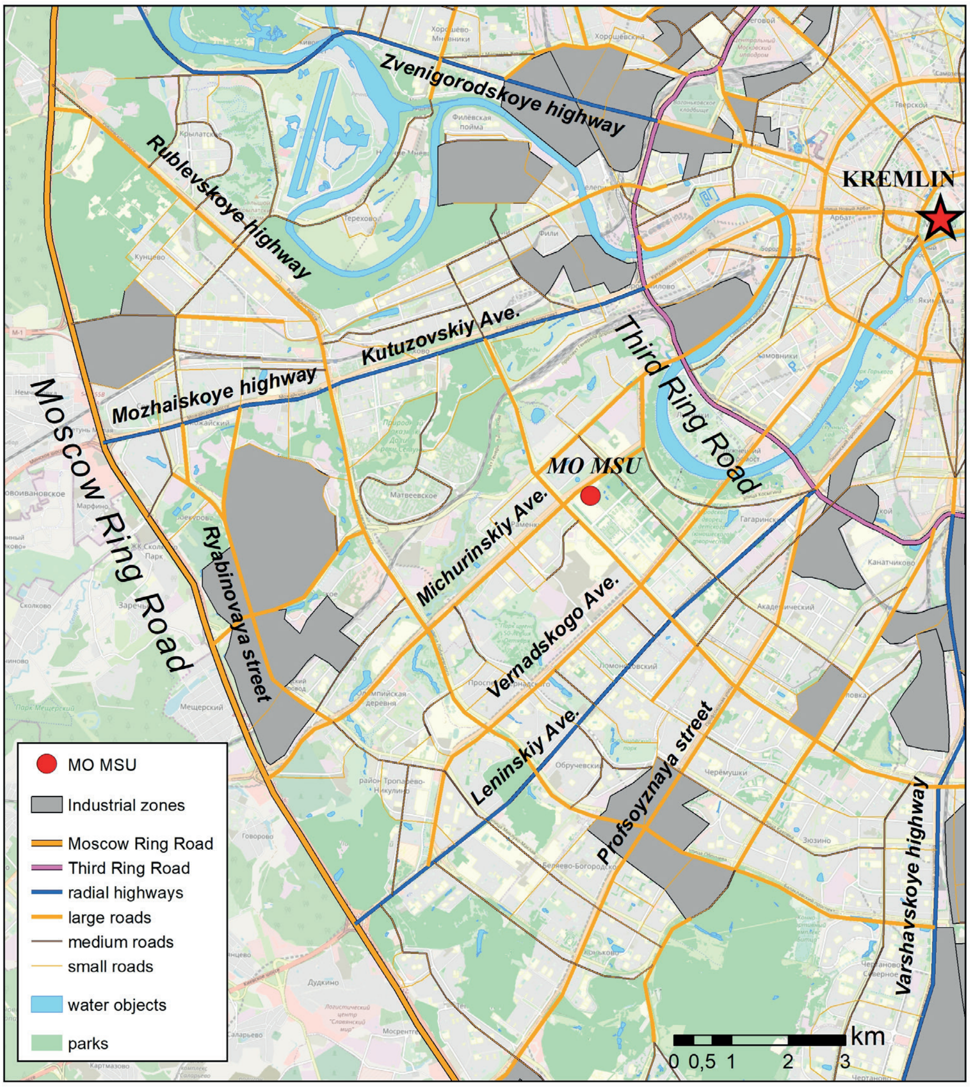

Fig. 1. Rains sampling site (MO MSU) in the southwestern part of Moscow

All-Russian Scientific-research Institute of Mineral Resources named after N.M. Fedorovsky according to certified methods (NSAM № 520 2017).

In this study, the term *wet deposition (D)* means the mass of a chemical element fallout from the atmosphere with rainfall per unit area of the Earth's surface for the entire precipitation event (μg/m² per event): $D = C \cdot X$, where *C* is the PTEs content in rainwater, μg/L; *X* is the precipitation amount, mm (which corresponds to L/m²). The term *washout rate (Dh)* means the mass of a chemical element fallout from the atmosphere with rainfall per unit area of the Earth's surface per unit time (μg/m² per hour). The washout rate shows how effectively (quickly) the pollutant is washed out from the atmosphere: $Dh = C \cdot X / t$, where *t* is the duration of precipitation, hours. The *Dh* index allows to compare precipitation events of various duration to determine the effect of rainfall parameters on the intensity of PTEs washout from the atmosphere. The duration of precipitation was calculated as a difference between the end and the beginning times of a particular precipitation event. These data were obtained from the standard meteorological TM-1 tables and have an error in determining the beginning and the end of the precipitation event on the order of 1–2 minutes, which is more accurate than the 10-minute time resolution of measurements obtained with the pluviograph. At the same time, good correspondence was observed between the data on the duration of precipitation and the pluviograph data. The precipitation intensity (*U*, L/m² per hour) was also estimated as $U = X / t$. From the time difference between the end of the precipitation event and the beginning of the next one, the length (in hours) of the dry period *R* between rain events was calculated.

Due to big variation in wet deposition between particular PTEs, for a comprehensive assessment of each separate precipitation event, all data were normalized: $D'_i = (D_i - D_{min}) / (D_{max} - D_{min})$, where D_i and D'_i are the initial and normalized values of PTEs wet deposition in the *i*-th precipitation event, respectively; D_{max} and D_{min} are the maximum and minimum values of PTEs wet deposition for the entire observation period. Then the total normalized wet deposition (*ND*) in the *i*-th precipitation event can be defined as $\Sigma D'_{ij}$, where *j* are all considered PTEs (in our case, *j* = 1, 2, 3, ... , 24, 25, 26). The normalization was done for the wet deposition of PTEs to the Earth's surface (*ND*), as well as for data on the washout rate of PTEs from the atmosphere *(NDh)*.

Statistical processing of the results was performed in the Statistica® 8 software. To assess the correlation between precipitation parameters (*X*, *t*, *U*, *R*) and the physicochemical properties of rainwater (pH, EC, *S*) on one hand, and values of PTEs wet deposition (*D*) and the washout rates of PTEs from the atmosphere (*Dh*) on the other hand, the nonparametric Spearman's rank correlation coefficients r_s were calculated, the significance of which was tested at a level of $p < 0.05$. To determine the PTEs groups with a similar distribution of wet deposition, cluster analysis was performed using the PTEs grouping by the Ward's method with the similarity measure *d* = 1 – Pearson's *r*.

RESULTS AND DISCUSSION

Rain parameters and physicochemical properties of rainwater.

To characterize weather conditions and identify periods with typical synoptic situations in April–May 2018, meteorological data from the MO MSU and a synoptic maps archive were used (Weather maps… 2020). An analysis of the atmospheric circulation features showed that in early and mid-April, during the period of rainfall, the cyclonic type of circulation prevailed with air advection from the western and northern regions. On April 25–26, a low-gradient baric field was observed with a predominance of air advection from the northern regions. In the first decade of May, air masses from the south and southwest prevailed, and from May 17 to May 20, air advection from the west with a cyclonic type of circulation was observed.

In 2018, the average monthly air temperature values were 2–3°C higher than the corresponding values for 1954 to 2013 and amounted to 8.4°C in April and 16.7°C in May, which matches with the general trend of climate warming (Chubarova et al. 2014). The amount of precipitation fell within the normal range: in April it was 38 mm compared to 41 mm, in May – 50 mm compared to 55 mm according to the long-term measurements. The duration of precipitation varied from short-term rains (less than 4 hours) on April 6–7 and 21, May 2, 4 and 5–6 to 17 hours on May 18–19, and even 25 hours on April 17–18, thus, the rain intensity varied from 0.2 L/m² per hour to 2.9 L/m² per hour depending on the event (Fig. 2). With an increase in the

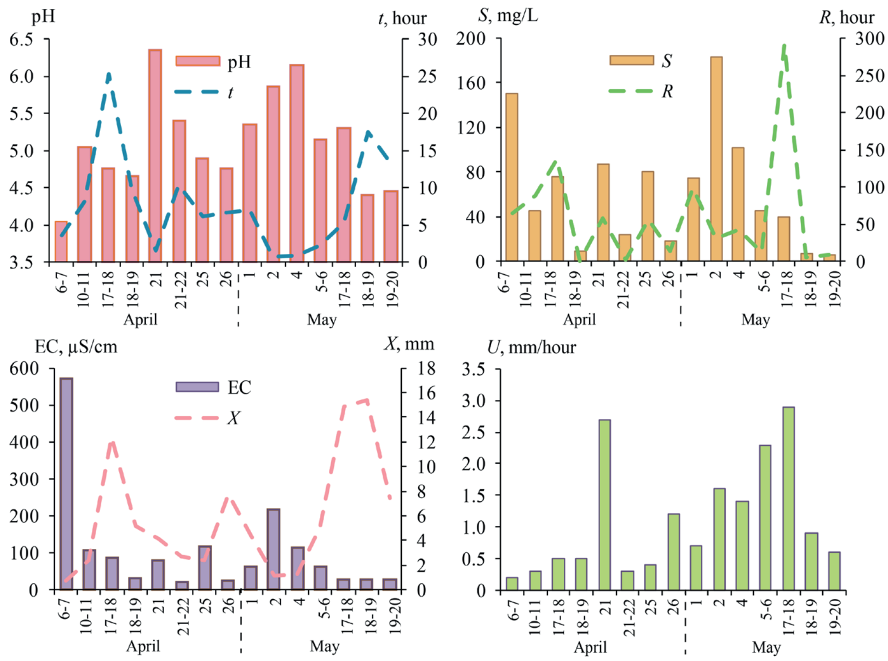

Fig. 2. Physicochemical properties of rainwater and rainfall parameters during the spring experiment. *X* – precipitation amount, *t* – duration of precipitation, *R* – length of the antecedent dry period, *S* – solid particles content in rainwater, *U* – precipitation intensity, EC – electrical conductivity

rain events duration, the precipitation amount also increases (r_s = 0.60; Fig. 3a), whilst the content of solid particles in rainwater decreases (r_s = 0.60; Fig. 3b) due to their intensive washout from the atmosphere at the beginning of precipitation event. As the duration of precipitation increases, the precipitation intensity usually decreases (Fig. 3c).

An excess of the acid precipitation (with pH < 5.0) frequency in April in comparison with the mean values for 35 years at the MO MSU (66% and 17%, respectively) was revealed. At the same time, a lower acid precipitation frequency was found for May (28% and 35%, respectively). All rains were characterized by a slightly acidic to almost neutral reaction with pH variability from 4.05 on April 6–7 to 6.35 on April 21 (Fig. 2). The average pH of rainwater in April and May 2018 was 4.7 (versus the average long-term values for these months of about 5.0 and 4.8, respectively). The highest EC value (572 µS/cm) was also found on April 6–7. In rainwater samples from other days the EC varied from 21 µS/cm to 217 µS/cm (Fig. 2). During the spring experiment, as in the last 13 years, Ca^{2+} was the predominant cation, and Cl^- was the predominant anion in precipitation (Eremina 2019; Eremina and Vasil'chuk 2019). The increase in EC values in rainfall is probably due to the partial dissolution of particulate matter washed out from the atmosphere, as indicated by the strong rank correlation (r_s = 0.85) between EC and the content of solid particles in rainwater (Fig. 3e). The ranking is based on the increase in the values of rainwater properties and precipitation parameters – high ranks correspond to high values of indicators.

The average solid particles content in rainwater during the spring experiment was 63 mg/L, varying from 6.1 mg/L in the last episode of prolonged precipitation in late May to 183 mg/L on May 2 during the public holidays (1–9 May) celebrated in Russia (Fig. 2) which were also characterized by elevated aerosol loading due to predominant air advection from the south and south-western regions (Chubarova et al. 2020). The amount of solid particles washed out with rains depends on the length of the antecedent dry period prior to precipitation event (r_s = 0.53; Fig. 3f), which is associated with the accumulation of coarse aerosol particles in the air during a long dry period and their subsequent washout with precipitation. A significant correlation between the solid particles content in rainwater and precipitation amount (r_s = –0.75; Fig. 3g) was revealed. This is likely due to the dilution effect, namely the mineralization and the content of solid particles in rainwater decrease with increasing precipitation amount (Park et al. 2015). A decrease in EC with an increase in the precipitation amount (r_s = –0.72) is associated with the same phenomenon (Fig. 3h). The decrease in solid particles content in rainwater is influenced by an increase in the duration of precipitation (r_s = –0.70), probably due to the more intensive washout rate of solid particles in the first minutes and hours after the beginning of a rainfall event (Fig. 3b). A decrease in the solid particles content in rainwater with increasing duration of precipitation leads to a decrease in rainwater pH (Fig. 3d) since high pH is associated with the partial dissolution of particulate matter (Singh et al., 2016).

Thus, the most important rain parameters for wet deposition are precipitation amount, duration and intensity as well as the length of the dry period. All of them affect the pH and EC values along with the content of solid particles in rainwater.

Wet deposition and washout rates of PTEs from the atmosphere.

The wet deposition of PTEs in spring varies greatly – on average from 21884 µg/m² per episode for Ca to 0.12 µg/m² per episode for Be (Table 1).

The highest levels of wet deposition (> 100 µg/m² per event) are typical for Ca > S > Na > K > Pb > Fe > Al > Zn > P, while highest washout rates from the atmosphere (> 50 µg/m² per hour) are common for Ca > S > K > Na > Fe > Al > Pb > Zn. For other PTEs, the wet deposition as well as washout rates are much lower and decrease (Table 1). Ca, S, Na, and K are macroelements of atmospheric precipitation and natural waters; the presence of macroelements of the continental crust (Al and Fe) in high concentrations relative to other PTEs in rainwater is associated with crustal and terrigenious sources input; high washout rates of Zn, Pb, Mn, Ba, and Cu are caused by the industrial and vehicular impact, which is typical for most large cities (Galloway et al. 1982; Song and Gao 2009; Kamani et al. 2014; Vlastos et al. 2019).

A comprehensive assessment of the temporal heterogeneity of wet deposition and washout rates of PTEs from the atmosphere was carried out by calculating

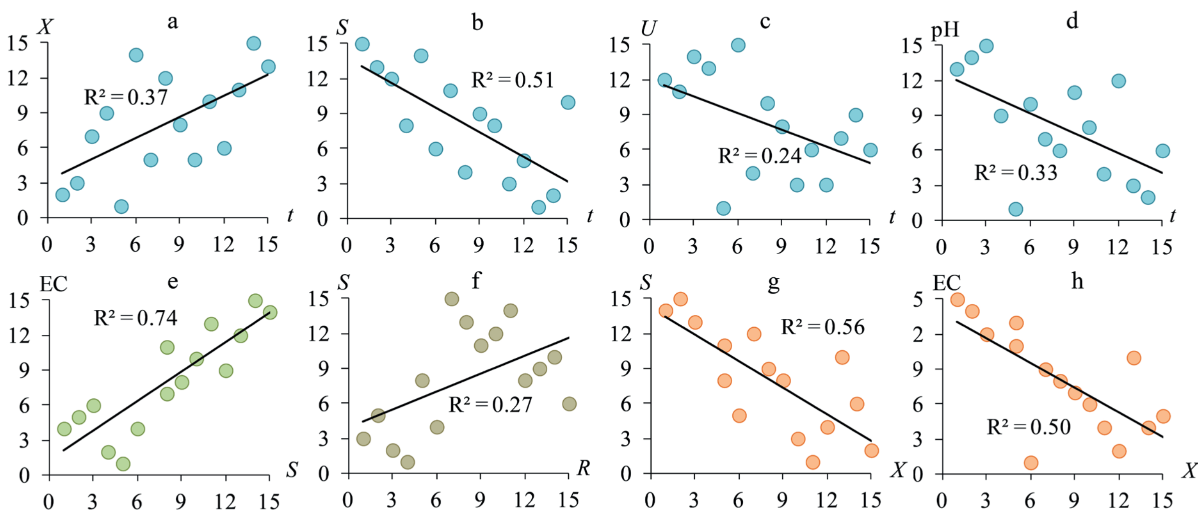

Fig. 3. Rank correlation between the ranks of the physicochemical properties of rainwater and rain parameters: *X* – precipitation amount, *t* – duration of precipitation, *R* – length of the antecedent dry period, *S* – solid particles content in rainwater, *U* – precipitation intensity, EC – electrical conductivity. High ranks correspond to high values of indicators. The color indicates the dependences on the same parameters of rain or the properties of rainwater (horizontal axis): (a)-(d) duration of precipitation, (e) solid particles content in rainwater, (f) length of the antecedent dry period, (g)-(h) precipitation amount

Table 1. PTEs' wet deposition to the Earth's surface and washout rates from the atmosphere at the MO MSU territory

PTEs	Wet deposition, μg/m² per event		Washout rates, μg/m² per hour	
	mean	minimum–maximum	mean	minimum–maximum
Ca	21884	3546–85152	6881	344–31420
S	3519	660–12279	991	64–3496
Na	1979	466–9113	497	35–1608
K	1269	173–3691	546	10–3828
Pb	650	38–3186	79	6.0–190
Fe	592	104–2615	111	10–238
Al	406	39–1860	96	3.8–300
Zn	214	42–922	58	4.0–247
P	123	16–481	42	0.92–278
Ba	95	17–272	24	1.6–82
Mn	76	15–264	28	1.1–165
Cu	51	10–213	10	0.98–35
B	32	3.1–161	7.6	0.31–34
Sb	19	3.1–83	5.4	0.30–23
Ni	2.8	0.51–13	0.78	0.050–4.1
Rb	2.3	0.63–5.8	1.0	0.061–7.4
Cr	1.7	0.43–6.9	0.43	0.042–2.1
Co	1.2	0.20–5.9	0.35	0.020–1.6
Se	0.89	0.18–2.3	0.17	0.039–0.43
As	0.73	0.14–1.7	0.17	0.029–0.74
Mo	0.58	0.070–1.5	0.11	0.020–0.29
Cd	0.55	0.13–1.9	0.14	0.012–0.45
W	0.21	0.038–1.0	0.048	0.004–0.18
Sn	0.2	0.027–0.96	0.057	0.003–0.23
Bi	0.14	0.024–0.73	0.034	0.002–0.11
Be	0.12	0.009–0.53	0.018	0.001–0.058

Note. PTEs are arranged in descending order of their average wet deposition

the total normalized values of wet deposition (*ND*) and total normalized values of washout rates of PTEs (*NDh*) for the entire experiment period. Changes in the *ND* and *NDh* values are shown in Fig. 4.

The highest *ND* values for the majority of PTEs were found for rains on April 17–18, when one of the three rainfall events with the highest precipitation amount (12.4 mm) was observed. These maxima are also associated with the highest aerosol concentration before the beginning of rainfall: from April 11 to April 16, the maximum PM_{10} concentration was observed over the entire period of the experiment and was equal to 43 μg/m³ (Chubarova et

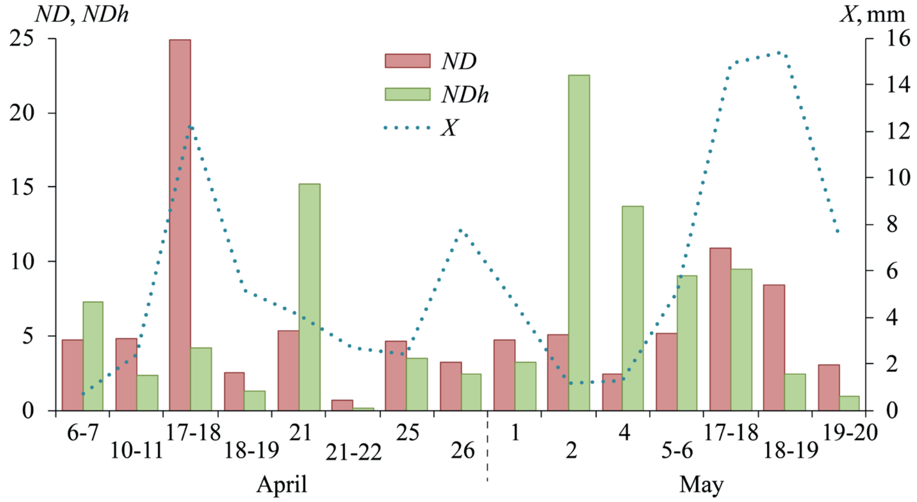

Fig. 4. Total normalized values of wet deposition of PTEs (*ND*, left axis) and washout rates of PTEs from the atmosphere (*NDh*, left axis), as well as precipitation amount (*X*, mm, right axis) on the MO MSU in April–May 2018

al. 2019). Afterwards, from April 17 to April 22, due to the precipitation and washing out of aerosols, a sharp decrease in the PM_{10} content (to 24 μg/m^3) was determined, which in turn caused the high values of total normalized wet deposition on April 17–18 and total normalized washout rates on April 21. Increased levels of total normalized wet deposition of PTEs, relative to other days, were observed on May 17–19, which is also due to a high level of aerosol pollution of the atmospheric surface layer in the previous dry period (Chubarova et al. 2019), large precipitation amount (14.9–15.4 mm) and high rain intensity on May 17–18 (2.9 mm/hour, the most intense rain of the entire experiment period).

The washout rates of PTEs from the atmosphere have a slightly different pattern in temporal changes compared to *ND* (Fig. 4). Very high total normalized washout rates of PTEs (*NDh*) were revealed for May 1–6, when air advection from the south and southwest prevailed. The beginning of this period of public holidays (May 1) is characterized by rather low washout rates of PTEs. However, already on May 2 it increased sharply due to the anthropogenic emission of PTEs to the atmosphere from the biomass burning in suburban areas and the territory of the MSU Botanical Garden, together with the coal burning during picnics near MSU and vehicle emissions due to the large number of traffic jams that occur when residents leave the city. This is confirmed by the increase in the levels of wet deposition of K, Rb, Mn, Sn, Sb, and As these days, which are often used as indicators of controlled biomass and coal combustion or forest fires (Landing et al. 2010; Samsonov et al. 2012; Grivas et al. 2018). Thus, the spring period is characterized by a strong influence of forest fires in the Moscow region and the biomass burning in residential areas on the composition of atmospheric particles in Moscow (Popovicheva et al. 2020a), which is indicated by the high values of the black carbon (BC) to the PM_{10} content ratio in the atmosphere (Popovicheva et al. 2020b), since BC is a marker of biomass burning or fuel combustion.

From April 30 to May 5, a high concentration of PM_{10} of 34 μg/m^3 was observed, which sharply decreased to 23 μg/m^3 in the period from May 6 to May 12 (Chubarova et al. 2019), probably due to short and intense rains on May 2, May 4 and May 5–6, which caused high values of the total normalized washout rates of PTEs. On May 17–18, the PTEs washout rates were also high due to the previous long dry period (11 days), with a large amount of aerosol accumulated in the air on May 13–17, which resulted in high PM_{10} values (Chubarova et al. 2019). During prolonged rains, which lasted several days with only short breaks, wet deposition and PTEs washout rates significantly decreased, which is typical for May 18–19, May 19–20 and April 26, but especially noticeable for April 18–19 and April 21–22 (Fig. 4). These data confirm the hypothesis about the deposition of the main pollutants' masses in the first hours after the onset of rain due to the active washout of aerosols from the atmosphere (Lim et al. 1991).

Thus, the highest *ND* levels for most PTEs were found on April 17–18 and May 17–18 due to a long dry period before these precipitation events (138 hours and 292 hours, respectively) and high aerosol concentrations in the surface atmospheric layer. The maximum *NDh* was observed on April 21, May 2, May 4, May 5–6, and May 17–18 with relatively short and intense (1.4–2.9 mm/hour) precipitation.

Sources of PTEs in rainwater.

In order to estimate the contribution of anthropogenic sources to the content of PTEs in precipitation the enrichment factor (*EF*) could be used: $EF = (D_i/D_{Al})/(K_i/K_{Al})$, where D_i and D_{Al} are wet deposition of the *i*-th and the reference elements, K_i and K_{Al} are the abundances of the *i*-th and the reference elements in the upper continental crust (Rudnick and Gao 2014). Sometimes, when calculating *EF*, the average composition of seawater is used as a reference, and Na is applied as a reference element (Cheng et al. 2011); however, this approach overestimates *EF* values for typically crustal elements that have no significant anthropogenic sources (Si, Al, Ti, Zr, and others). Therefore, for the chemical composition of atmospheric precipitation studies, the content of PTEs in the upper continental crust is used as a reference standard with Al as a reference element (Basha et al. 2010). $EF < 10$ indicates a crustal (or terrigenous) origin of elements, *EF* from 10 to 100 shows probability of anthropogenic PTEs sources, and at $EF \geq 100$ PTEs definitely have an anthropogenic source (Tian et al. 2020).

High *EFs* in the Moscow rains in April–May 2018 certainly indicating the anthropogenic origin of the PTEs, were determined for (the *EF* values are shown in the subscript) Sb_{9392}, Pb_{7680}, Se_{1987}, Cd_{1232}, and S_{1138}. A significant contribution of anthropogenic sources was also observed for Zn_{641}, B_{373}, Cu_{368}, Bi_{175}, Ca_{171}, and Mo_{106}. In many other cities, a substantial enrichment of atmospheric precipitation with these PTEs was also found (Koulousaris et al. 2009; Song and Gao 2009; Özsoy and Örnektekin 2009; Landing et al. 2010; Kamani et al. 2014; Chon et al. 2015), and for Zn, Cd, and Cu it was reported even for the southeastern part of the Atlantic Ocean (Chance et al. 2015). This indicates the significant role of wet deposition processes for the PTEs input into terrestrial landscapes. The main sources of most of these PTEs are vehicle emissions, fuel combustion, tires and brake pads wear, road surface abrasion, roadside soil particles blowing, industrial enterprises emissions, as well as macroregional long-distance transport of pollutants (Demetriades and Birke 2015; Grigoratos and Martini 2015; Grivas et al. 2018; Konstantinova et al. 2020; Liyandeniya et al. 2020; Logiewa et al. 2020; Orlović-Leko et al. 2020; Ramírez et al. 2020; Seleznev et al. 2020; Tian et al. 2020), which is confirmed by the previously identified sources of snow cover pollution in the western part of Moscow (Vlasov et al. 2020). The remaining PTEs on the territory of the MO MSU were apparently of mixed anthropogenic-terrigenous sources (P_{38}, Ba_{31}, As_{30}, W_{22}, Mn_{20}, Sn_{19}, Na_{16}, Co_{14}, Ni_{12}, Be_{11}, K_{11}) and terrigenous origin (Rb_6, Cr_4, Fe_3), which indicates the influence of solid particles blown out from the Earth's surface and included in the atmospheric precipitation.

For a more detailed determination of PTEs sources, a cluster analysis was carried out. Based on its results, four associations of soluble forms of PTEs with similar deposition patterns were identified: (1) Zn–Sb–Ni–Ca–Co–Bi–Sn–Al–W–Cr–Fe–Na–P; (2) Cu–Ba–Pb–Cd–S–B; (3) Se–Mo–As–Be; and (4) K–Rb–Mn (Fig. 5).

The first geochemical association (Zn–Sb–Ni–Ca–Co–Bi–Sn–Al–W–Cr–Fe–Na–P) includes PTEs coming from anthropogenic (Zn, Sb, Bi, Ca), anthropogenic-terrigenous (W, Sn, Co, Ni, Na, P) and terrigenous (Al, Fe, Cr) sources. Sb, Zn, Sn, Bi, W, and Ni indicate the resuspension of road dust and its various grain size particles, since in Moscow and some other cities road dust is highly enriched with these PTEs (Ladonin and Plyaskina 2009; Fedotov et al. 2014; Ermolin et al. 2018; Kasimov et al. 2019a; Ladonin and Mikhaylova 2020; Vlasov et al. 2021b). For example, in the eastern part of Moscow, the fine fraction PM_1 and the coarser PM_{1-10} of road dust are significantly (*EF > 5*) enriched in Sb, W, Sn, Cd, Zn, Cu, Pb, Mo, and Bi, especially on Moscow Ring Road and highways (Vlasov et al. 2015; Kasimov et al. 2020). Al, Fe, and Na are emitted by blowing out particles of contaminated urban soils (Morera-Gómez et al. 2020). This source is somewhat less significant for W, which is presented in the surface horizons of Moscow soils (Kosheleva et al. 2018). Blown-out soil particles are also a source of P in atmospheric aerosols and precipitation (Bencharif-Madani et al. 2019). Deicing agents can supply Na and Ca, since $CaCl_2$ and marble chips $(Ca, Mg)CO_3$ are among the main deicing agents after NaCl in Moscow (Vlasov et al. 2020).

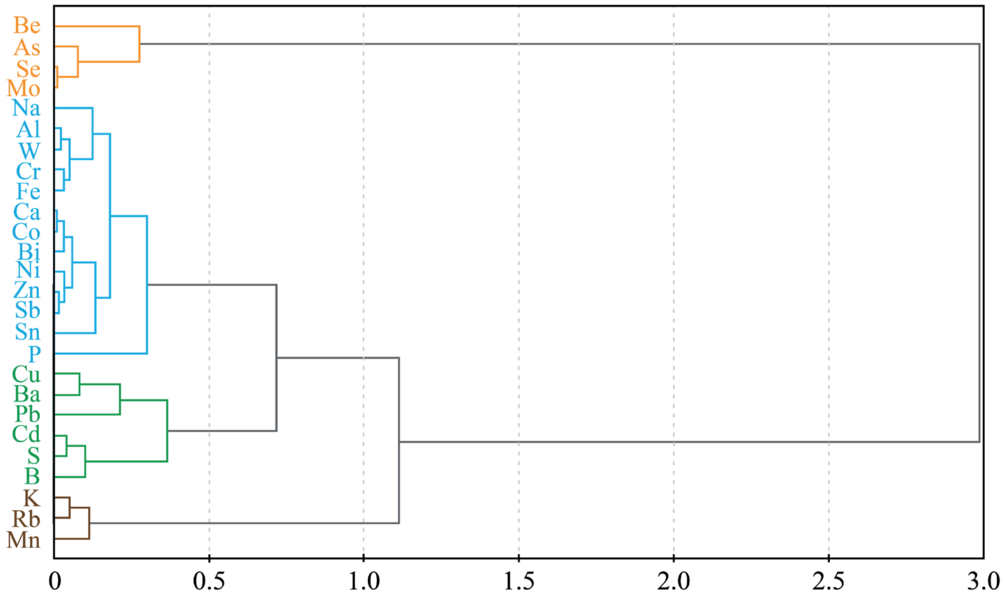

Fig. 5. Dendrogram of wet deposition of PTEs in the MO MSU on April–May 2018 (clustering was done using Ward's method; the similarity measure is *d* = 1 – Pearson's *r*)

Mentioned deicing agents are found in high concentrations in road dust and surface soil horizons in the spring season. Cr, Ni, and Co can come due to abrasion of the asphalt pavement (Song and Gao 2011). Thus, the Zn–Sb–Ni–Ca–Co–Bi–Sn–Al–W–Cr–Fe–Na–P association is mainly formed by the blown out particles of urban soils, road dust and deicing agents, which could be partially dissolved in rainwater. For instance, at the very beginning of the contact of an acidic (pH 4.7) mimicking fog water with atmospheric $PM_{2.5}$, a significant part of K, Cd, Mn, Mo, V, Ba, Al, Fe, Sb, Cu, and Cr are transferred to the soluble form (Di Marco et al. 2020).

The second association Cu–Ba–Pb–Cd–S–B includes elements with high *EFs*, that are coming from anthropogenic sources (Cu, Pb, Cd, S, B), as well as anthropogenic-terrigenous Ba. Copper, as well as Pb and Cd, are used in large quantities in vehicle brake pads and linings (Fabretti et al. 2009; Grigoratos and Martini 2015). Barium sulfates used in the brake pads manufacturing as a friction modifier can supply S and Ba to atmospheric particles and precipitation (Pant and Harrison 2013). Boron also comes from vehicles, since it is used as an additive in the manufacture of polymers, glass and fiberglass, as well as in the production of lubricants, antifreeze and fuel additives (U.S. Borax 2020). Waste incineration can be an additional source of Sb, Cd, and other PTEs (Christian et al. 2010). High S concentrations also often indicate a large contribution of long-distance transport of secondary inorganic aerosols (Cheng et al. 2015).

The third association (Se–Mo–As–Be) is formed by elements with very high (Se, Mo) and high (As, Be) *EFs*, which indicates their predominantly anthropogenic origin in atmospheric precipitation. Likely sources of Mo include metalworking, car repair and painting companies (Demetriades and Birke 2015; Zheng et al. 2018), widespread in Moscow. Arsenic, Se, Be and sometimes Mo can come from waste incineration and diesel fuel combustion (Kumar et al. 2015; Bencharif-Madani et al. 2019), while Se is also used as a coal combustion indicator (Wu et al. 2018). Despite the fact that coal is not used at Moscow thermal power plants, Se accumulated in fine particles (0.25–0.35 μm) could migrate hundreds of kilometers (Gallorini 2000) from those territories where coal is burned (suburbs, summer cottages, even transboundary transfer).

The fourth association (K–Rb–Mn) is probably determined by the biomass burning, since these PTEs, as noted above, are widely used as indicators of this type of impact (Samsonov et al. 2012; Grivas et al. 2018). High *EFs* values are found for Mn and K, while for Rb low *EF* is defined, probably due to its poor solubility in rainwater (Yu et al. 2018) and relatively high abundance in the upper continental crust.

Thus, the Zn–Sb–Ni–Ca–Co–Bi–Sn–Al–W–Cr–Fe–Na–P geochemical association is formed by the PTEs input mainly with blowing out of soil particles and road dust as well as deicing agents' resuspension. The main source of Cu–Ba–Pb–Cd–S–B association is vehicle emissions, while Se–Mo–As–Be association is particularly emitted from industrial sources as well as during waste incineration and long-distance air mass transport. In addition, biomass combustion (including forest fires) and atmospheric migration of plant pollen are responsible for the formation of K–Rb–Mn geochemical association.

Influence of rain parameters on the washout rates of PTEs from the atmosphere.

A nonparametric correlation analysis was carried out to determine the main factors affecting the wet deposition of PTEs to the Earth's surface and the PTEs washout rates from atmospheric air.

The precipitation amount determines the wet deposition values of anthropogenic PTEs with high *EFs* (Table 2, Fig. 6): Se, Mo (r_s = 0.96), As, Pb, Ba, and Cd (r_s 0.83, 0.65, 0.59, and 0.57, respectively). Other researchers also noted a similar positive correlation, for instance, in cities and suburbs of Northern China for Cu, Zn, Cd, As, and Se (Pan and Wang 2015), and Izmir, Turkey for Cr, Cd, Pb, and Ni (Cizmecioglu and Muezzinoglu 2008). Less strong inverse correlation was found between the precipitation amount and the washout rates of soluble PTEs from the atmosphere: r_s values are significant only for anthropogenic-terrigenous Na and P (–0.53); for other elements, except for Se, Mo, and Pb, they are also negative (Table 3, Fig. 7). A decrease in the PTEs washout rates is associated, as noted earlier, with the dilution effect, which reduces the PTEs concentrations and, as a consequence, the mass of pollutants' washout per unit time.

The duration of precipitation has a significant positive correlation with the wet deposition of PTEs of anthropogenic origin including Pb, Mo, Se, and As (r_s 0.63–0.53), and a negative correlation with the washout rate from the atmosphere for all PTEs (Tables 2 and 3, Figs. 6 and 7). Such relations are significant for all PTEs, except for Be and Pb, with r_s values ranging from –0.52 for Mo to –0.90 for Mn. The reason for this is a sharp decrease in PTEs concentrations in atmospheric air by the end of the precipitation event in comparison with its beginning, when the highest PTEs levels are usually found, due to the removal of pollutants from the atmosphere during prolonged precipitation (Ouyang et al. 2015).

The length of the antecedent dry period is one of the most important factors contributing to an increase in wet deposition and the washout rates of PTEs from the atmosphere especially in conditions with elevated aerosol content (Tables 2 and 3, Figs. 6 and 7). This is most pronounced for the wet deposition of PTEs of anthropogenic (Bi, S, Zn, Cu, B, Ca), anthropogenic-terrigenous (Co, K, Mn, Na, Ni, W) and terrigenous (Al, Rb) origin. For the washout rates of most PTEs, such relations are less pronounced, while the correlation coefficients are positive for all PTEs and are significant for W, Ni, B, Be, Rb, and Cu (0.65–0.51). That is, with an increase in the dry period, the washout rate of PTEs increases. The first rain after a long dry period is enriched with PTEs due to in-cloud and below-cloud scavenging processes. During a short dry period, due to frequent precipitation, the below-cloud scavenging processes weaken with the gradual removal of solid particles from the atmosphere (Bayramoğlu Karşı et al. 2018). During prolonged precipitation, an increased amount of aerosols is removed from the atmosphere within the first days. On the subsequent days, due to low concentrations of atmospheric aerosols, the rains wash out smaller amounts of pollutants. An increase in the pollutant concentrations in precipitation after a long dry period and a large load of contaminants in the early stages of river runoff are often referred to as the «first flush effect» that was investigated in detail on urban territories (Schiff et al. 2016; Shen et al. 2016; Liu et al. 2019; Mamoon et al. 2019).

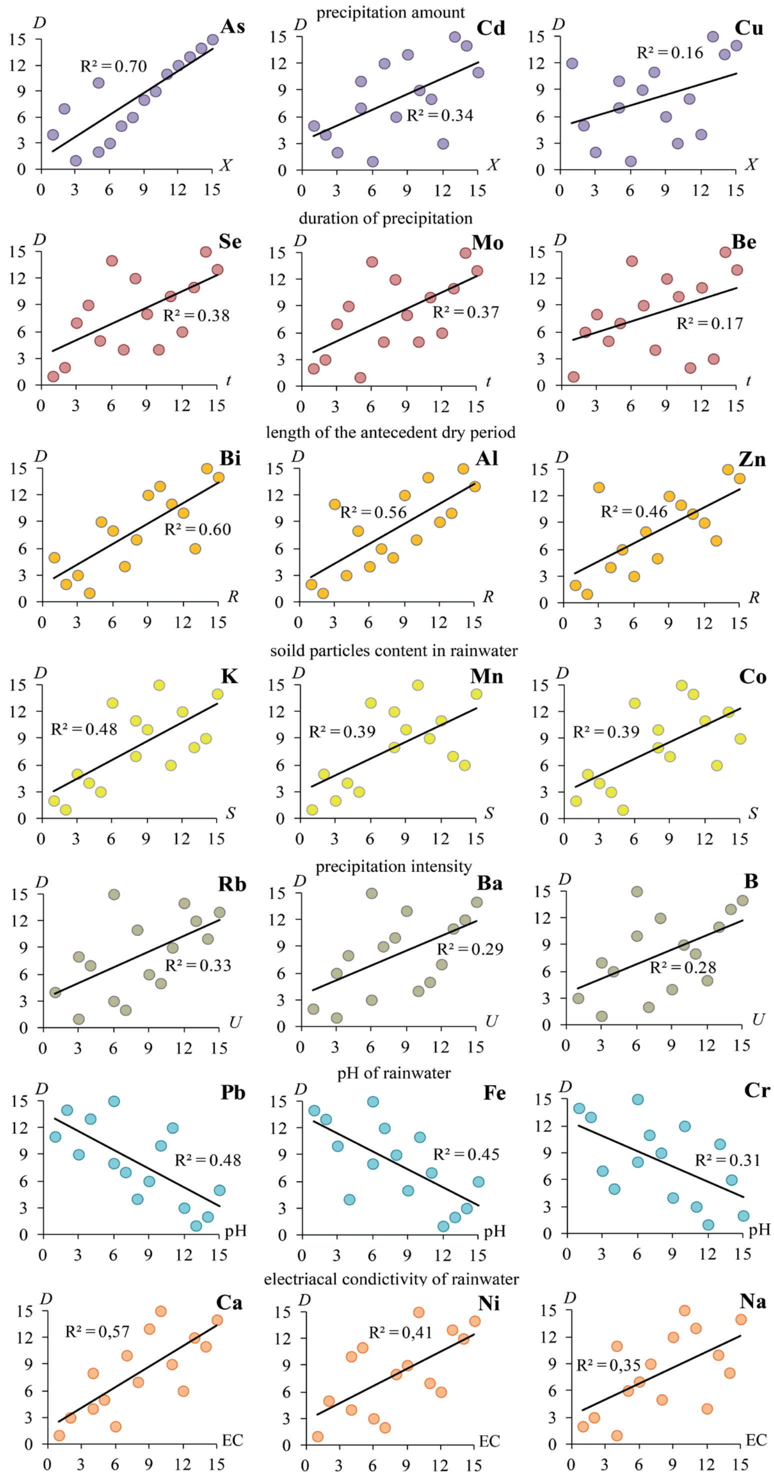

Fig. 6. Examples of rank correlation of wet deposition of PTEs (vertical axis) with the physicochemical properties of rainwater or rain parameters (horizontal axis; designations are shown in caption of Fig. 2). High ranks correspond to high values of indicators. The color shows the correlation with the same rain parameters or properties of rainwater

Table 2. The Spearman's correlation coefficient (r_s) values between wet deposition of PTEs on the Earth's surface, physicochemical properties of rainwater, and rain parameters on the MO MSU territory

PTEs	Physicochemical properties of rainwater			Rain parameters			
	pH	EC	Solid particles content	Precipitation amount	Duration of precipitation	Precipitation intensity	Length of the antecedent dry period
Be	–0.01	–0.17	–0.10	0.38	0.42	–0.11	0.47
B	0.29	–0.02	0.14	0.39	–0.13	**0.51**	**0.56**
Na	–0.07	**0.57**	**0.52**	–0.15	–0.16	–0.09	**0.66**
Al	–0.25	0.45	0.38	0.09	0.02	–0.06	**0.75**
K	0.46	0.46	**0.68**	–0.17	–0.49	0.39	**0.70**
P	0.10	0.31	0.36	–0.12	–0.21	0.08	0.25
S	0.06	0.27	0.28	0.21	–0.05	0.25	**0.72**
Ca	0.07	**0.74**	**0.74**	–0.31	–0.35	0.03	**0.68**
Cr	**–0.57**	0.36	0.15	0.15	0.17	–0.19	0.39
Mn	0.46	0.42	**0.61**	–0.05	–0.40	0.43	**0.69**
Fe	**–0.68**	0.15	–0.07	0.36	0.41	–0.27	0.47
Co	0.06	**0.62**	**0.63**	–0.15	–0.26	0.04	**0.79**
Ni	–0.18	**0.63**	**0.56**	–0.10	–0.08	–0.09	**0.63**
Cu	–0.39	0.18	0.06	0.39	0.28	–0.00	**0.60**
Zn	–0.10	0.38	0.33	0.19	0.01	0.14	**0.68**
As	–0.47	–0.47	**–0.60**	**0.83**	**0.53**	0.24	0.05
Se	–0.48	**–0.69**	**–0.72**	**0.96**	**0.60**	0.22	–0.05
Rb	0.45	0.36	**0.51**	0.06	–0.37	**0.55**	**0.65**
Mo	–0.35	**–0.72**	**–0.75**	**0.96**	**0.60**	0.31	–0.08
Cd	–0.18	–0.06	–0.18	**0.57**	0.24	0.30	0.35
Sn	0.06	**0.59**	0.48	–0.14	–0.11	0.00	0.48
Sb	0.00	0.27	0.18	0.29	0.01	0.30	0.49
Ba	0.06	–0.06	–0.06	0.59	0.14	**0.53**	0.44
W	–0.42	**0.52**	0.30	–0.03	0.19	–0.37	**0.64**
Pb	**–0.70**	–0.20	–0.40	**0.65**	**0.63**	–0.19	0.13
Bi	0.09	0.35	0.46	0.01	–0.24	0.12	**0.77**

Note. The r_s values significant at $p < 0.05$ are shown in **bold**

Table 3. The Spearman's correlation coefficients (r_s) values between washout rates of PTEs from the atmosphere, physicochemical properties of rainwater, and rain parameters on the MO MSU territory

PTEs	Physicochemical properties of rainwater			Rain parameters			
	pH	EC	Solid particles content	Precipitation amount	Duration of precipitation	Precipitation intensity	Length of the antecedent dry period
Be	0.43	0.28	0.48	–0.06	–0.50	**0.54**	**0.52**
B	**0.66**	0.28	**0.54**	–0.05	**–0.68**	**0.77**	**0.54**
Na	0.45	**0.69**	**0.82**	**–0.53**	**–0.81**	0.38	0.45
Al	0.43	**0.72**	**0.87**	–0.49	**–0.82**	0.42	0.50
P	0.45	**0.64**	**0.78**	**–0.53**	**–0.78**	0.34	0.31
S	**0.58**	**0.61**	**0.77**	–0.43	**–0.83**	**0.56**	0.48
K	**0.65**	**0.56**	**0.82**	–0.47	**–0.87**	**0.54**	0.50
Ca	0.50	**0.67**	**0.82**	–0.47	**–0.85**	**0.51**	0.47
Cr	0.34	**0.63**	**0.78**	–0.42	**–0.82**	0.45	0.46
Mn	**0.65**	**0.59**	**0.83**	–0.50	**–0.90**	**0.53**	0.47
Fe	0.30	**0.68**	**0.82**	–0.49	**–0.82**	0.38	0.48

Co	**0.51**	**0.68**	**0.84**	–0.49	**–0.87**	0.49	0.46
Ni	0.45	**0.69**	**0.86**	–0.46	**–0.80**	0.44	**0.55**
Cu	0.43	**0.52**	**0.70**	–0.23	**–0.71**	**0.61**	**0.51**
Zn	**0.51**	**0.66**	**0.83**	–0.43	**–0.83**	**0.53**	0.49
As	0.41	0.19	0.37	–0.13	**–0.77**	**0.78**	0.26
Se	0.34	0.01	0.21	0.13	**–0.67**	**0.90**	0.16
Rb	**0.63**	**0.57**	**0.76**	–0.43	**–0.85**	**0.59**	**0.51**
Mo	0.49	–0.19	0.03	0.31	**–0.52**	**0.96**	0.09
Cd	**0.54**	**0.63**	**0.80**	–0.43	**–0.84**	**0.54**	0.49
Sn	0.44	**0.76**	**0.81**	–0.50	**–0.66**	0.28	0.50
Sb	**0.53**	**0.62**	**0.78**	–0.35	**–0.76**	**0.56**	0.50
Ba	**0.53**	0.39	**0.57**	–0.07	**–0.65**	**0.76**	0.38
W	0.34	**0.74**	**0.85**	–0.46	**–0.68**	0.29	**0.65**
Pb	–0.38	0.11	0.09	0.35	–0.09	0.09	0.43
Bi	**0.56**	**0.61**	**0.83**	–0.48	**–0.85**	0.47	0.45

Note. The r_s values significant at $p < 0.05$ are shown in **bold**

Solid particles content in rainwater contributes to an increase in the wet deposition and washout rates of PTEs from the atmosphere due to the intensification of the gradual dissolution of particles, which in turn leads to an increase in the concentration of soluble forms of PTEs (Table 3, Fig. 7).

The rain intensity proved to have a positive correlation with the wet deposition of most PTEs. High significant r_s were found for terrigenous Rb (0.55), anthropogenic-terrigenous Ba (0.53), and anthropogenic B (0.51) (Table 2, Fig. 6). The washout rate is characterized by stronger correlation (Table 3, Fig. 7) with rain intensity for a large number of PTEs: high r_s values were found for Ca, Mn, Zn, Be, K, Cd, S, Sb, and Rb (0.51–0.59), Cu (0.61), Ba, B, As (0.76–0.78), and Se (0.90). For other PTEs, except for Pb, r_s is also positive and amounts to 0.37 and even higher. A positive correlation between the amount of PTEs washed out from the atmosphere and rain intensity is typical for precipitation in Kyoto and regions of Japan (Sakata et al. 2006), as well as for southwestern Taiwan, when during the typhoon, the amount of washed-out pollutants sharply increased compared to the usual precipitation levels (Cheng and You 2010).

Long dry periods before the onset of precipitation event lead to an increase in the solid particles' content in rainwater, which in turn contributes to an increase in the rainwater pH as a result of the partial dissolution of the suspended matter (Yeremina et al. 2014; Singh et al. 2016). Such partial dissolution of road dust particles can contribute to an increase in precipitation pH since its values for the water extract of road dust in Moscow is 6.4–8.1 (Kasimov et al. 2019b). Therefore, with an increase in the length of the dry period, as well as the amount of solid particles in rainwater and pH value, the intensity of PTEs washout by rain from the atmosphere also increases (Table 3, Fig. 7). The largest r_s values are typical for B, K, Mn, and Rb (r_s 0.66–0.63), as well as Co, Ba, Bi, Cd, Sb, S, and Zn (0.58–0.51). Due to the acidifying effect of industrial and thermal power plants emissions (e.g., on account of sulfate-ion formation as a result of a chemical reaction of emitted sulfur dioxide and water in the atmosphere), vehicle emissions (e.g., nitrate-ion formation as a result of chemical reactions of emitted nitrogen oxides and water), and also deicing chloride reagents (Eremina et al. 2015), a decrease in the rainwater pH is accompanied by an increase in the wet deposition of Pb (r_s = –0.70), Fe (–0.68), and Cr (–0.57), as well as Be, Na, Al, Ni, Cu, Zn, As, Se, Mo, Cd, and W (Table 2, Fig. 6). At the same time, a decrease in the rainwater pH in this case is not the reason for the growth of wet deposition of PTEs, but an indicator of the anthropogenic sources' impact on supplying these PTEs to the urban environment.

Electrical conductivity indirectly shows the amount of ions in the solution (rainwater). Therefore, EC has positive a correlation with the level of wet deposition of many PTEs, and especially Ca, Ni, Co, Sn, Na, and W (r_s 0.74–0.52). For some PTEs, this correlation is negative. This is possible because, due to the predominantly low levels of deposition of these PTEs (first of all, Be, Se, As, Mo, Cd, and Ba), their contribution to EC is insignificant. Therefore, the pattern of EC change is determined precisely by the behavior of elements with high concentrations in rainwater and, accordingly, high levels of wet deposition, e.g. Ca, Na, Fe, Mn, Al, S, etc. (Tables 2 and 3, Figs. 6 and 7). This is confirmed by the fact that positive significant r_s values were found between the washout rates of the majority of PTEs and the EC value.

CONCLUSIONS

In urban conditions, rain is an important factor in the atmosphere purification from PTEs. The contaminated particles of road dust and urban soils input into the atmosphere during wind-blowing, the impact of transport and industrial facilities, waste incineration and biomass burning lead to a strong enrichment of rainwater with soluble forms of Sb, Pb, Se, Cd, and S, as well as P, Ba, As, W, Mn, Sn, Na, Co, Ni, and Be. High levels of PTEs wet deposition were revealed for the public holidays (May 1–6), which is due to the anthropogenic supply of PTEs to the atmosphere during the combustion of organic residues and coal in suburbs, the strong impact of transport and the elevated aerosol content due to predominant air advection from southern and south-western regions. During prolonged rains, the wet deposition of PTEs sharply decreases on the second and subsequent days due to the active below-cloud scavenging of aerosols during the initial moments of precipitation.

In Moscow, one of the most significant rainfall parameters affecting the level of PTEs wet deposition from the atmosphere is the length of the dry period before the

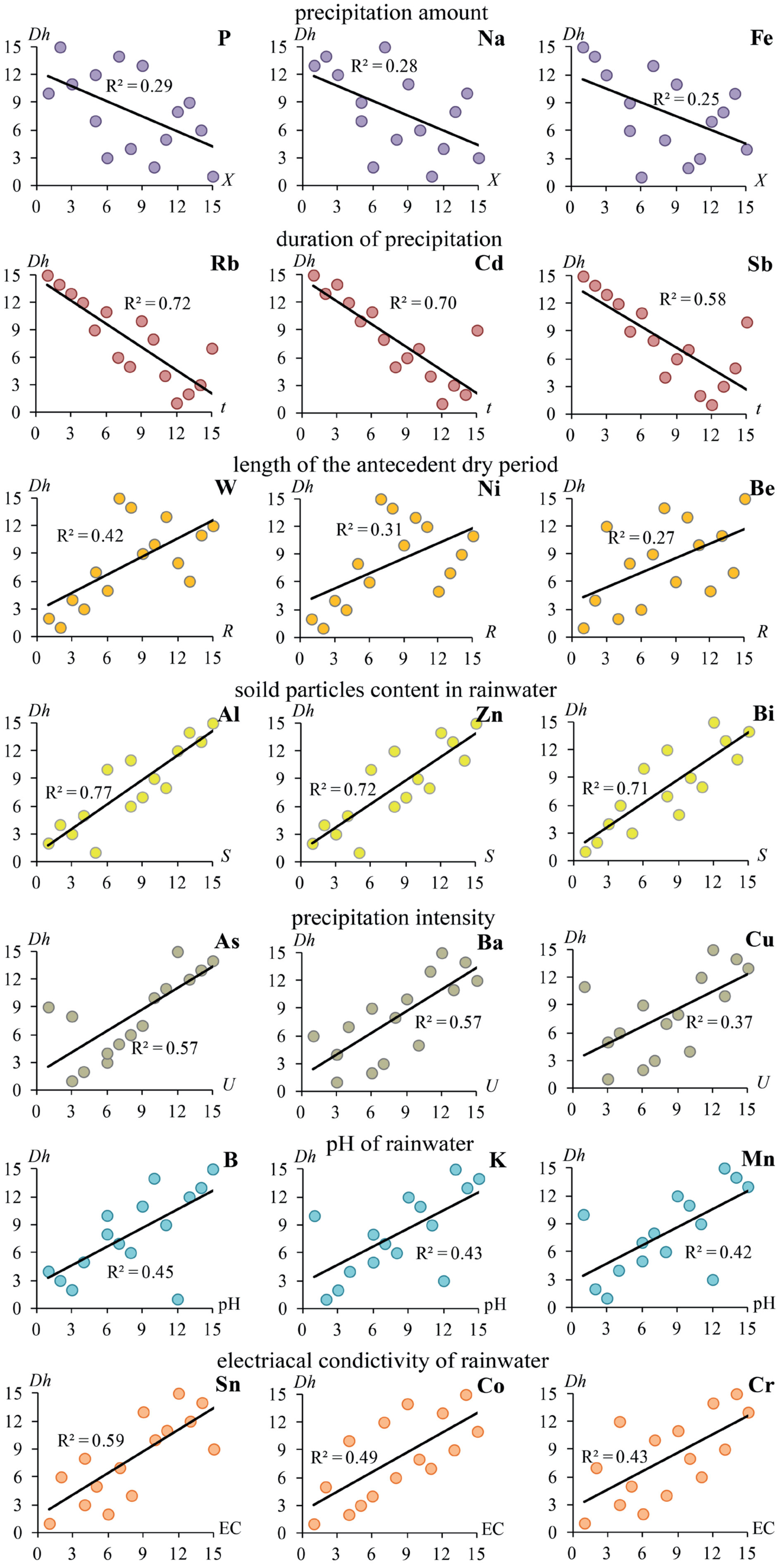

Fig. 7. Examples of rank correlation of washout rates of PTEs (vertical axis) with the physicochemical properties of rainwater or rain parameters (horizontal axis; designations are shown in caption of Fig. 2). High ranks correspond to high values of indicators. The color shows the dependences on the same rain parameters or properties of rainwater

beginning of atmospheric precipitation when aerosol particles accumulate in the air, which leads to an increase in rainwater pH. This factor has a particularly strong effect on the deposition and washout of PTEs of mainly anthropogenic origin (W, Zn, Bi, Cd, Sb, Ni, B, S, K, and Cu). Another important factor in atmosphere purification from PTEs is the rain intensity, which depends on the amount and duration of precipitation. An increase in these parameters leads to an increase in wet deposition and washout rates of most PTEs, especially of anthropogenic Se, As, B, Cu, Sb, S, and Cd, anthropogenic-terrigenous Ba and K, and terrigenous Rb.

The first data obtained for Moscow on the rain parameters affecting the levels of wet deposition and washout rates of PTEs from the atmosphere in April–May are preliminary. However, these results can be useful for urban environmental quality assessment in Moscow and can provide a better understanding of atmospheric deposition processes in urban areas.

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RESEARCH PAPER

ANALYSIS OF YOUTH ACTIVITIES IN THE DIGITAL AGE: TIME-GEOGRAPHICAL APPROACH

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ABSTRACT. The study analyses daily activities of youth in the virtual and actual environment within the framework of theoretical and applied achievements of time geography. The role of mobile devices in youth life, transformation of traditional activity and changes in the daily organization of actions due to digitalization are discussed. Empirical data for the research were obtained via a diary method (the respondents were 18–22-year-old students). Features of individual daily foreground and background activities, digital devices used, activities relation and localization are evaluated by geovisualization performed within the time-geographical concepts. Regardless of the smartphonization, individuals reserve time spans not associated with virtual activities; their online activities are localized within places of residence, study and traffic routes, while public spaces serve as "live communication" platforms (but a complete rejection of virtual activity does not occur here). An attempt to compare youth daily activity under ordinary conditions and during the period of forced isolation during the COVID-19 pandemic is being made.

KEY WORDS: digitalization, smartphonization, time geography, diary method, youth, everyday life, COVID-19

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INTRODUCTION

In the 21st century, it is hard to find a sphere of life not affected by digitalization. Entire systems of various levels are created based on digital processes—from Smart City and Smart State to Smart Body and Internet of Things (Demidova 2018). However, digitalization is not just a technological process. It starts to reformat many socioeconomic systems, affects and often drastically changes traditional models of society functioning. Time-space activity patterns of people also change due to modern information and communication technologies (ICT) (Shaw 2009) as they go to a "temporally and spatially fragmented lifestyle" (Ben-Elia et al. 2018). These technologies determine more and more how we work, study, buy goods and services, travel, and finally how we communicate with each other. For example, the expansion of smartphones has provoked people to restructure their everyday life in terms of time and space use (Ling 2012), while modern transport means saturated with additional functions (like access to the Internet) imposed virtual environment on individuals (Ben-Elia et al. 2018), etc.

These processes have become especially important during the COVID-19 pandemic. The public environment was dramatically affected by COVID-19. Under the quarantine, citizens' physical movement and personal communication were minimized. Throughout the world, including Russia, forced isolation has led to the significant growth in the use of digital devices and services as well as obvious changes in the digital behaviour of users. Internet connection has become an essential condition for maintaining the usual life activities for millions of people. The consequences of the sudden "forced" digitalization we have yet to evaluate. And the main question has to do with what 'digital behaviour' models we will inherit from the COVID-19 era.

In the digitalization process (including smartphonization) the established connections between such fundamental concepts in human life as "activity," "place," and "time" are changing completely, which was pointed out by multiple researchers including geographers (Couclelis 2009, Ellegård 2018). The environment where physical and virtual features are mixed is called cyberspace (Kwan 2001). Cyberspace inhabitants are provided with a special capability—human extensibility, which allows them by means of transport and communication not only to overcome the problem of long distances but also to be situated simultaneously at various points on the timeline. The human extensibility concept was introduced almost fifty years ago (Janelle 1973), but its relevance is only growing: people maintain the opportunity to work, study, do not give up leisure and social contact, etc. (especially in the context of the COVID-19 pandemic).

The population category that is the most susceptible to the digital era trends and ICT achievements is the youth. This specific age group comes in contact with such phenomena as increasingly larger role of new work statuses[1], expansion of sharing economy (such services as BlaBlaCar, et al.), crowdfunding platforms, etc. (Markova 2019). Digitalization also affects youth's social life (Aralina and Ben'ko 2015). Today large parts of their social contacts and interaction with friends have moved to virtual space, and now (compared with the early 2000s) social relations are more independent from fixed places and times (Thulin et al. 2019). According to some studies, young people (this means Millennials here) check their phone 150 times per day, browsing text messages, social media posts and e-mails (Brandon 2017). It is not surprising that during the COVID-19 pandemic the youth (16–24-year-olds) demonstrate the highest social contact virtualization rates (up to 60%) (Digital 2020: April… 2020).

Digitalization and smartphonization are under constant observation by scientists including representatives of socioeconomic geography. Among Russian scientists, attention is paid mainly to the digital economy (Blanutsa 2019, Markova 2019, etc.), while researches dedicated to the Internet, fixed-line and mobile communications' development in the country as a whole and on the regional level are less common (Nagirnaya 2018). Digitalization and its geo-visual aspects in terms of human everyday life and activity in the hybrid physical–virtual space are generally not covered in the Russian works.

In this study, the geographical analysis of youth daily activities in virtual and physical space is done based on the theoretical and applied research in the field of time geography. It deals with issues of correlation between foreground and background activities and application of various mobile gadgets during those activities. An attempt is being made to compare the youth daily activity in real and virtual space under ordinary conditions and during the forced isolation period.

MATERIALS AND METHODS

A study of new socioeconomic phenomena, including smartphonization, requires approaches capable of reflecting the intensive penetration of digitalization in various areas of life. In our opinion, one of the most effective approaches among the existing ones is a time-geographical approach, which, as part of social geography, is primarily aimed at personal behaviour analysis (Ellegård 1999, Lenntorp 1999). However, it is not locked on this level and may be used for the whole process of public interaction (groups of people, households) and activities (the full range requiring direct human participation) within a certain territory (Pred 1977). Time geography objects include people and any objects or phenomena represented in the space-time domain (Carlstein et al. 1978, Lenntorp 1999). The subject of time-geographic research is life dynamics, or, more specifically, the human and social functioning.

Studies of human activity in time geography are based on several basic concepts introduced by the famous Swedish geographer Torsten Hägerstrand fifty years ago (Ellegård, 2019). The central concept is the *path*—a motion pattern of an individual in space-time (within the framework of daily, weekly, annual and other cycles up to whole life). Each path consists of *elementary events* (move, arrive, stay, leave, etc.). It reflects individuals' movement patterns and allows to analyse their actions and interaction with each other (Lenntorp 1999). The main events on the path take place when the trajectories of different people intersect on the way or in the same place (i.e., at *stations*), forming activity bundles together with individuals' belongings, equipment and other resources (Hägerstrand 1970). When an intersection occurs in order to achieve a specific goal (for example, production of industrial or agricultural outputs), a *project* (an activity with a certain sequence of tasks, involving the unification of people, resources, premises or territories in space-time) arises (Hägerstrand 1985).

Initially, the method of graphical analysis was recognized as one of the strong points of time geography that was stressed by its followers and opponents and always specified even by the critics when speaking about its representative potential (Hallin 1991). Analysis of spatiotemporal data on living and activities of people with the help of Hägerstrand's models combines spatial coordinates (position on a two-dimensional map) with the timeline. To a great extent, it facilitates problem-definition and problem-solving in research. Hägerstrand's *space-time prism* is considered to be one of the most successful examples of time integration into geographical analysis.

The development of the time geography concept experienced a rapid rise, decline and a new rise that occurred at the 20th–21st centuries' cusp (Starikova and Treivish 2017). The "revival" of this approach is associated not only with the development of ICTs and expansion of access to new data types[2] but also with the emergence and development of new time geography. In contrast to the classic time geography that originated in the 1970s in the studies of the Lund School, the new time geography puts the stress on exploring digital aspects of human life when physical movement is accompanied by a simultaneous perception of audio-visual data and mobility in a virtual world (so-called hyper-mobility) (Gillespie and Richardson 2000). Specifically, in the new time geography framework the foreign researchers actively address the issues related to the geographic presentation of virtual-actual environment. The Hägerstrand's patterns of space-time paths have been brought up to date in the framework of the new time geography. Now individuals' space-time behavior and their paths and interactions are modeled in a multidimensional space (in classical time geography space-time path is constructed in three-dimensional space) (Couclelis 2009). Geovisualization of daily human activities based on new space-time schemes allows to analyse individual and group activities both in geospace and virtual space with the focus put both on space and time. The latter is viewed as a resource equal in importance or sometimes even more important than financial and material resources (Kramer 2004).

The geovisualization in this work is based on the space-time schemes suggested by geographers who studied the interrelation between foreground and background activities in the life of Swedish youth (it is related primarily to "life" in a virtual environment) (Thulin and Vilhelmson 2019). The main elements of the schemes are space-time path within a framework of circadian cycle of activities[3] and two connected bar charts reflecting time spent on different foreground activities (offline and online) and background online social contacts with friends. In our research we consider not only social contacts: our schemes show different types of foreground and background activities (divided into categories) both in physical and virtual spaces.

[1]Freelance, remote working, i.e., forms of labour that due to the Internet are not rigidly fixed to time and location.
[2]For example, the mobile operators' data on subscribers' movement, which means an increase in the ability to analyse the activities of people.
[3]It is important to note that individuals have to return home in the evening for repose, meal, rest and comfort after a day spent somewhere else (Lenntorp 1976).

The materials for youth daily life analysis were collected by applying a diary method. The diaries of 18–22-year-old respondents (17 respondents, all of them the students of faculty of geography in the Lomonosov Moscow State University) obtained in 2018–2019 served as the quality data source. The application of the diary method allowed forming a clear view on how youth daily activities are organized within 24 hours on workdays and holidays. The respondents noted in chronological order what activities they conducted at what time and where, were they alone or doing something with other people, and also whether they used any digital gadgets during this activity, including personal computers (PCs), smartphones, iPads, etc. (and if so, with what purpose) (Table 1).

Each respondent filled out a diary for two workdays and one holiday, which revealed youth behavior in physical–virtual space for different schemes of daily life organization. On workdays, a respondent is obliged to act according to a certain timetable, while on holidays a day can be planned following individual preferences. Observation of two workdays helps to catch how the main foreground activity (study) combines with other (non-daily or irregular) activity types (a side job, etc.) in actual and virtual space. The capability of the time-geographical approach to visualize life in hybrid physical–virtual space was demonstrated on the example of two most detailed diaries[1].

Data geovisualization we practiced allows: to analyse activity in virtual space (the study of this activity by other methods is associated with a number of problems); to single out the foreground and background activities; to rate interrelation of foreground and background activities within 24 hours as well as the difference in activity types on workdays and holidays; to geo-reference of various activity types.

RESULTS AND DISCUSSION

According to the studies of the International Telecommunication Union (ITU)[2], the Pew Research Center[3] and We Are Social Agency, only approximately 17% of the world population used the Internet in 2005. Between 2005 and 2020, the number of Internet users was growing by 10% a year on average and by 2020 it has reached almost 60% of the population (over 4.5 bln people) (Measuring… 2019, Digital 2020: April… 2020, Digital 2020: Global… 2020). In Russia, the number of Internet users has also significantly increased since the beginning of the 21st century. Now about three-quarters of the Russian population use the Internet (in 2000 it amounted to 3 mln people and has reached 110 mln people by the beginning of 2018) (Nagirnaya 2018). Compared to April 2019, in April 2020, the global Internet audience has increased by more than 7% (over 300 mln people), and the number of active social media users increased by almost 9% (Digital 2020: April… 2020).

Not so long ago it has been widely accepted that technological progress and development of global computer networks results in a decrease in individuals' physical activity (Kramer 2004). This conviction was based on an assurance that people will spend more time at stationary PCs. However, it became clear that mobile gadgets expansion removes restrictions on spatial movement and allows to maintain online activity at any location of the world (provided an individual has certain technical tools and gadgets). Thus, in 2018 about 72% of Russia's adult population used mobile devices to access the Internet from home or workplaces; over 80% of these devices were mobile phones and smartphones (Abdrakhmanova et al. 2019).

The first pocket PC (the name of the first smartphone) was produced by the US IBM company in 1992, while the "smartphone" concept was introduced by Swedish company Ericsson in 2000. However, a true revolution in this field was made by Apple company when they released a gadget in a form of a monoblock unit in 2007. A smartphone became the most

Table 1. Fragment of a respondent's workday diary

Time	What am I doing?	Where I am?	Who is nearby? Who am I interacting with now?	Do I use electronic devices (PC, laptop, smartphone, etc.)?	For what purpose do I use electronic devices?	Comments
09:00 a.m.	I wake up	At home	With family	No	–	–
09:05 a.m.	I wash my face, make my bed, exercise, take a shower	At home	With family	No	–	–
09:30 a.m.	Making breakfast	At home	With family	Smartphone	Listing to music, watching videos	–
10:05 a.m.	I am combing my hair, getting dressed, etc.	At home	With family	Smartphone	Checking social media notifications	–
10:20 a.m.	I am leaving home, going to university	In public transport	Alone	Smartphone	Listing to podcasts/music	–
10:50 a.m.	I am listening to a lecture/ participate in a seminar	In the university	With classmates	Smartphone	Taking pictures of slides	–

[1]It does not pretend to be an illustration of a general Russian youth daily life organization. Such a generalization is possible only using a large sample of respondents. It may be one of the tasks in continuation of authors' studies.
[2]ITU is a specialized agency of the United Nations that is responsible for issues that concern information and communication technologies.
[3]Pew Research Center is an American research institute (think tank), which provides information on social issues, public opinion and demographic trends shaping the United States and the world.

multifunctional gadget among many other items surrounding a man. A present-day smartphone, besides telephony that was its main function, serves as a PC, a camera, a day planner, an alarm clock, a navigator, a music player, a tool for ordering goods and services, etc. According to the study (Smartphone… 2019), in 2018 60% of the world population used smartphones in daily life. In Russia the number of smartphone users accounts for 59% of adult citizens (Fig. 1) and, as expected, the most active group is the youth.

The answers of the respondents from our research also indicate that students use smartphones in their daily life more often than PCs, favouring a gadget that is capable of serving an exceedingly wide sphere of functions. PC plays a role of an instrument for doing training assignments (especially if this cannot be done by a smartphone, for example, when special software can be installed on a PC only) or is used at a workstation in the office.

In April 2020 over three-quarters of respondents reported an increased impact of mobile devices (primarily smartphones) in their lives and their usage time during the isolation in quarantine (Digital 2020: April… 2020). The full range of leisure activities has expectedly moved to the virtual environment compared to the same period in 2019: 57% of respondents noted an increase in the time for watching shows and films on streaming platforms; 40% for listening to music; 35% for computer and video games. A larger part of social contacts underwent virtualization. Almost half of respondents (46–47%) acknowledged a significant growth of communication by social media and instant messenger services[1]. The highest rates (up to 60%) were demonstrated by young people (16–24-year-olds). Besides, for solving different impromptu problems produced by the pandemic, the number of users of previously not so typical applications for videoconferencing (Zoom, Microsoft Teams, etc.) has sharply risen. A new digitalization wave has also transformed those areas that were traditionally kept in the real-world environment: labour activity, education, medical industry, social services and assistance, etc. Every fifth online user plans to stay active in the virtual environment even after the restrictions will be lifted. Because of that, it is important to trace the changes in the digital behaviour of high-tech devices users during the pandemic and after it. For example, today we can assume the difference between a sequence and a set of activities on a student standard workday and its transformation during the forced isolation period: time spent in virtual space is growing, activities related to it are coming to the fore, replacing communication and entertainment outside the home (Fig. 2).

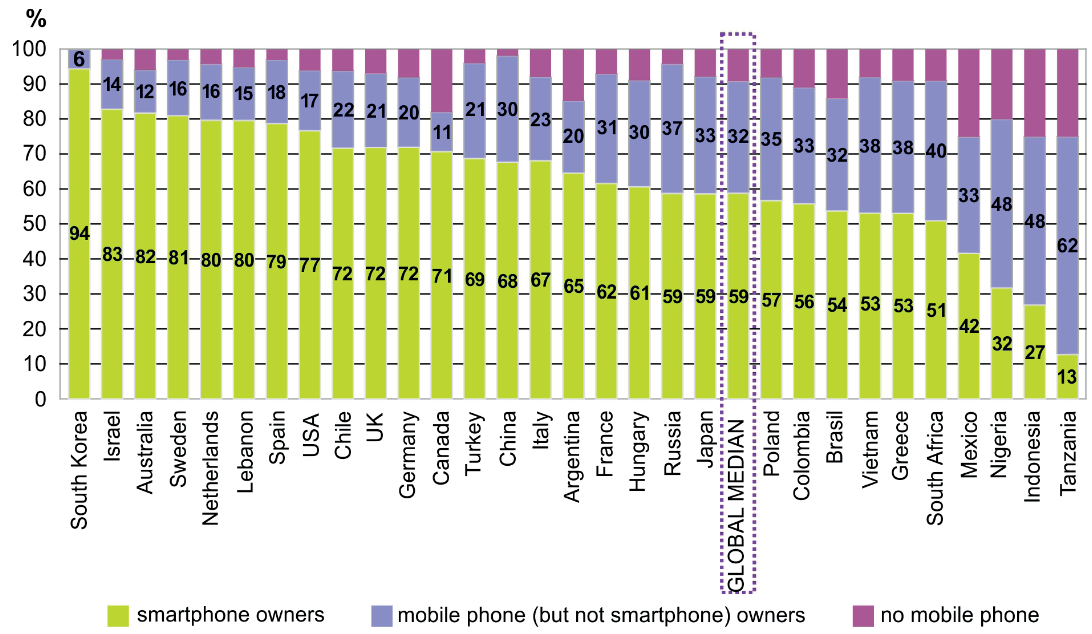

Fig. 1. Adult population owning smartphones and mobile phones (cellphones) in some developed and developing countries, %, 2018. Compiled from (Smartphone… 2019)

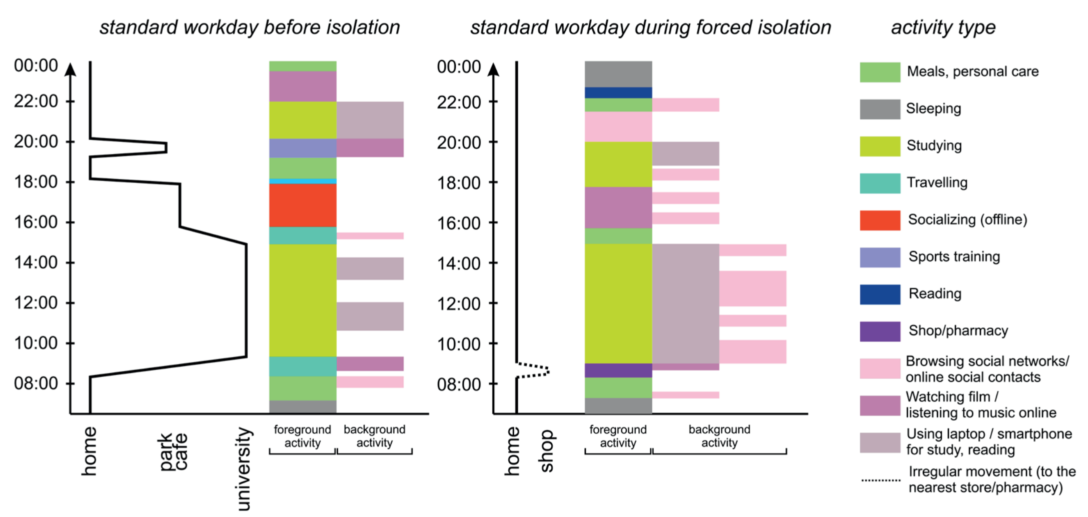

Fig. 2. Activities of a student on a standard workday and on a workday during forced isolation in COVID-19 quarantine

[1]Facebook, WhatsApp, Instagram, TikTok, etc.; in Russia one should add to this list VKontakte and OK.ru social networks.

The study of activity in the virtual environment is associated with a number of problems, such as complication in surveillance and its measurement parameters (Thulin and Vilhelmson 2019). Geovisualization of individual daily life in the time geography framework to a great extent facilitates solving of this problem. In our research, respondents' activity in the virtual environment was divided into the following categories: activities in social networks (interaction, news screening, posting, commenting, etc.); audio-visual content consumption (viewing various types of content, listening to music, etc.); web surfing associated with online searching, including those for the study and work purposes.

According to the analysis of respondents' diaries, we can note that during the normal time youth activity in a virtual space (regardless of active use of mobile gadgets) remains mostly a background activity. "Life" in the virtual world so far rarely comes to the foreground even among this age group. We can consider the organization of Russian students' daily life to be exemplified by two time-geographical visualizations of respondents' dairies: a 19-year-old woman and a man of 22 years. Thus, Fig. 3 demonstrates that on workdays the female respondent allocates approximately an hour just once a day for purposeful social networks screening; however, on weekend online communication and virtual events acquire more value for her, summing up to more than two and a half hours divided into several slots of different length.

Nowadays an average Internet user spends online 6 h 43 min daily (almost a third of the waking hours!) (Digital 2020: Global… 2020). It is fair to assume that a major amount of that time is formed by the contribution of background activity in a virtual environment. The following trait of this activity directly connected to the society smartphonization process should be noted—its principal implementation in parallel with "real" activities (that are replete with new contents for individuals). Geovisualization allows to distinguish different combinations of foreground and background activity types:

- travel by the means of transport or by foot in physical space in parallel with different actions in a virtual one (in this case "real" activities acquire new contents that prompt individuals to view such combination as an activity with a high "added value"[8]);
- study and activities in a virtual environment (it is demonstrated in the daily activity cycle in Fig. 4), when background activity may appear be both the former and the latter; for example, top-priority online communication during a lecture is a telling illustration of bringing activity in virtual space to the forefront;

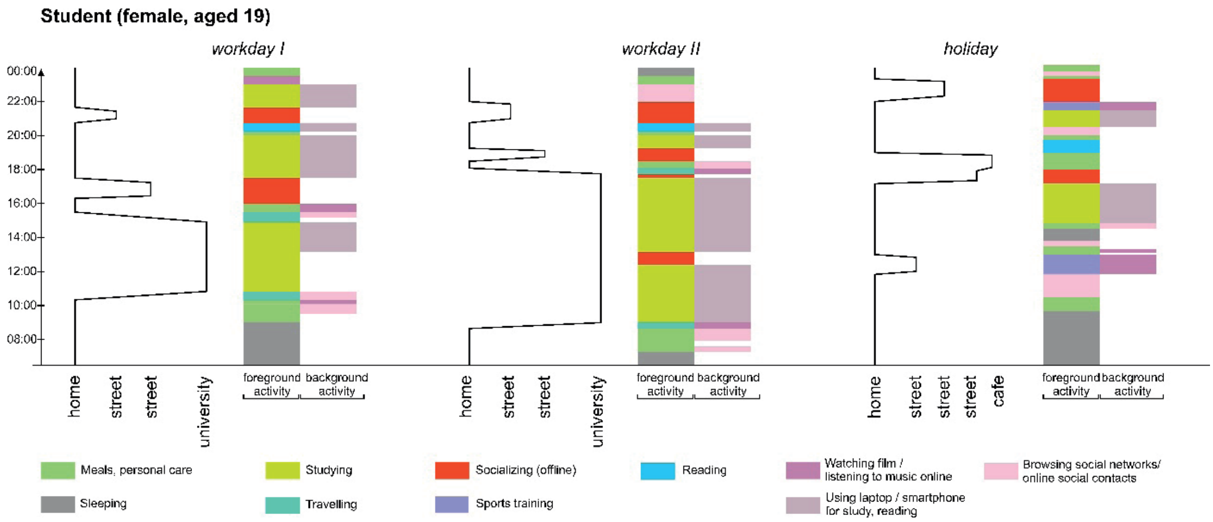

Fig. 3. Daily cycle of foreground and background activities of the respondent (a female student aged 19). Based on materials from the respondent's dairy

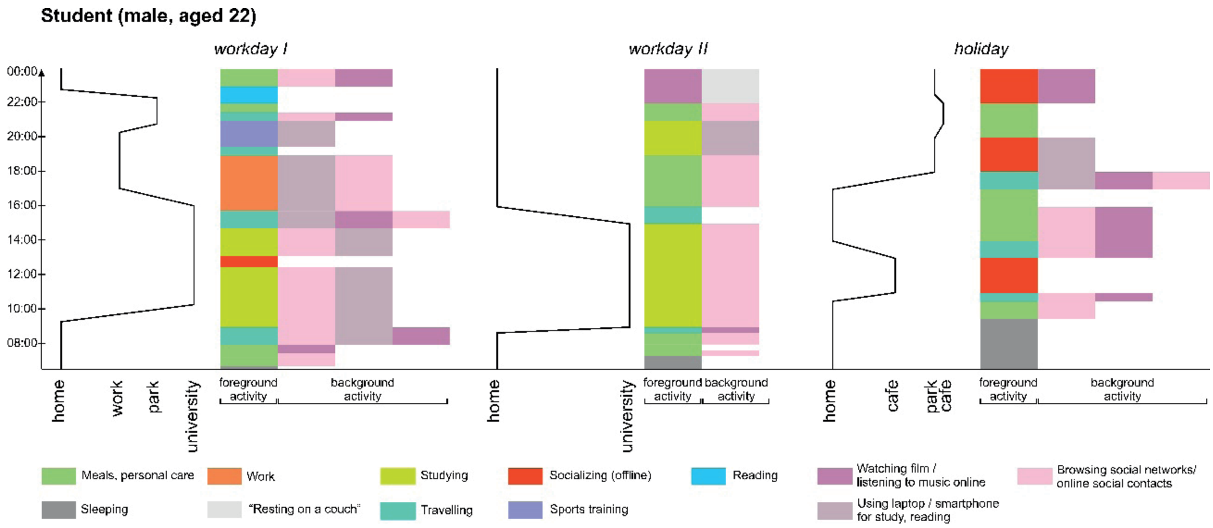

Fig. 4. Daily cycle of foreground and background activities of the respondent (a male student aged 22). Based on materials from the respondent's dairy

[1]There are two ways of judging the time spent on the way: (1) time spent on the way from location A to destination B as 'sacrifice' to transcend this distance; (2) adding a value to this time due to multitasking capability (to cover a distance doing something else at the same time). In the future increase in travel time can become a positive process because of mobile technologies, which will make it more useful and productive (Ben-Elia et al. 2018).

- work and online communication in social networks (Fig. 4, workday I);
- sports activities together with listening to music or watching online instructional video clips (Fig. 3, holiday);
- activities in virtual space during meals or "resting on a couch" (Fig. 4, workday II).

Therefore, an important feature for human existence in cyberspace becomes the dynamic interstructuring of virtual and actual environments. Depending on personal perception of current developments' importance, the virtual environment may be considered as a foreground activity and actual activity—as a background one (for example, top-priority online communication during the lecture and, obviously, on the background of it).

Nonetheless, daily life of the respondents still had time intervals when activity was exercised outside of virtual space and was not related to mobile gadgets usage. Besides sleep and time for personal hygiene, among a few such youth activity types is offline interactions with friends (though smartphonization gradually advances upon actual space, leaving a trace in a form of mutual listening to music etc.). This fact points to an important trend that looms globally[1]: when digital technologies reach out to more and more people and become intermediaries in their communication, live interaction obtains more social value. No matter how paradoxically but namely anti-digitalization of social contacts is viewed as the new upscale trend in the field of social interrelationship, especially in the countries with many years of experience in digital sphere development (United States, Great Britain, Nordic countries). The period during which a person refrains from using any electronic devices was named "digital detox." This is a way to reduce stress and focus again on social interactions in real life, to maintain health and working efficiency (Welledits et al. 2020).

Georeferencing of activity types demonstrated that individual online-activity is localized in the following places: the place of residence, educational institutions and transport routes. At public spaces (cafes, parks, etc.) the respondents still keep "live" interaction with friends as a priority, regardless of the wireless network advancement and active Wi-Fi coverage of the urban environment (Zaporozhets 2016). However, the complete rejection of the virtual environment does not take place even here (respondents search for information related to the topic under consideration in parallel to a conversation, etc.).

CONCLUSIONS

Smartphone has a special place in the life of a modern human. Being a product of technological progress, it is becoming a guide to high-tech solutions for the population. Smartphonization of daily life opens the widest array of opportunities, while an unlimited number of goods and services is located at arm's length from a potential consumer. A smartphone is becoming not only and not so much an instrument of obtaining entertaining content (music, movies, computer games) which it was initially. Entertainment is pushed out by service applications, and even work tasks are solved with the help of mobile gadgets and not PCs or laptops.

The social environment is changing in a fundamental way. If previously communication between people was obstructed by a spatial disengagement, now this connection can be maintained permanently by social networks and instant messenger services. Moreover, social contacts can be maintained above not only spatial but language, cultural and other barriers. The usage of digital devices and virtual social interaction is growing during the crisis situations like the COVID-19 pandemic: it provides the user with the opportunity to work and study, do shopping, obtain entertaining content, interact with friends while staying in isolation. On the other hand, it leads to significant users' digital behavior changes (not always positive), the consequences of which humanity has yet to evaluate.

In the course of digitalization, a transformation of traditional types of activities is taking place. It generates new forms and gives rise to changes in the organization of human daily actions, including their subsequence, intermittency and execution frequency. Deep immersion into cyberspace starts up from parallel processing (overlapping) of actions executed in the actual and virtual world. In this case, background activity in the latter one usually steps forward, i.e., "life" in online-space becomes more important that "physical" existence (the reverse side of this process is a tendency towards the growth of importance and stature of the physical environment as a healthy lifestyle as opposed to digital addictions).

A geographical analysis of phenomena discussed above is bound with bringing in approaches and methods adequately reflecting deep penetration of digital technologies in daily life. Concurrently, one of the most important questions is the one about the possibilities of their geovisualization. The use of theoretical and applied achievements of new time geography (in combination with other geographical and sociological methods) allows examining individual foreground and background activities, specifying localization of different types of such activities, their relation, etc.

Despite the smartphonization, even youth—the most active user of digital devices, the Internet and online social networks—retain time intervals that are not related to actions in virtual space. Online activity of youth is localized in places of residence, study and on transport routes. Public spaces act as platforms for "live" communication (but a complete rejection of virtual activity is not happening there).

[1]For instance, as reported by the New York Times News Analyses. Available at: https://www.nytimes.com/2019/03/23/sunday-review/human-contact-luxury-screens.html [Accessed 23 May 2020].

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RESEARCH PAPER

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THE DISTRIBUTION AND TYPOLOGICAL CLASSIFICATION OF INCIDENCE/MORTALITY RATES AND DYNAMICS OF TUBERCULOSIS IN RUSSIA, 2006–2017

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ABSTRACT. Despite the achieved success in the fight against tuberculosis, the disease remains an immediate problem for a number of countries including Russia. To a large extent, the reasons for the high incidence and mortality of the population are not only medical but also social in nature, which leads to the emergence of geographical patterns in the spread of the disease. The purpose of the study is to identify the spatio-temporal conditions that shape the epidemiological situation of tuberculosis in Russia at both the national and regional levels. Using GIS technologies, an analysis of the current spread of the infection in the Russian Federation was carried out based on data for the period from 2006 through 2017. Typological classification of regions according to the dynamics and magnitude of the incidence rate has been developed. Based on the cartographic analysis that was carried out, regions with the most unfavorable tuberculosis situation in the Russian Federation were identified for a more detailed study at the municipal level.

KEY WORDS: tuberculosis, Russia, mapping, spatial analysis, typological classification, dynamics of incidence and mortality

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INTRODUCTION

Tuberculosis is one of the most pressing and challenging health issues in the world as well as a socio-medical problem for many countries. Tuberculosis affects 1/3 of the world population (Shelkova, Romanenko 2013). According to the World Health Organization (WHO), 7.1 million people were diagnosed with TB for the first time in 2019 and up to 7.0 million – in 2018, which is a large increase from 6.4 million in 2017 and 5.7–5.8 million annually in the period 2009–2012 (Global tuberculosis report 2020). The infection returns to industrialized countries in a more severe and life-threatening form (Vasilieva et al. 2017). People are generally susceptible to tuberculosis, as only 1–3% of people have a genetically determined resistance to the pathogen (Shelkova, Romanenko 2013).

The goal set by the World Health Organization for the world community is to constantly reduce mortality and incidence among the population. It is planned to reduce mortality by 2025 by 75% compared to 2015 and incidence by 50% (The WHO End TB ... 2014; Krasnov et al. 2016). In that context, a significant number of recent studies have been devoted to the diagnosis, prevention and treatment of tuberculosis including latent forms, as well as the study of the body's reactions to the pathogen (Berry et al. 2013; Alsultan, Peloquin 2014; Lee et al. 2015; Lyon, Rossman 2017; Manina et al. 2017).

Among other things, there is a severe problem of the combination of HIV infection and tuberculosis. According to WHO, most of the countries with significant HIV/TB coinfection are located in Africa, the Republic of South Africa being one of the most affected countries (Global tuberculosis report 2020). A particular danger in this case is the difficulty of diagnosing tuberculosis in patients with HIV which, as a result, leads to a high mortality rate (Hosseinipour et al. 2016; Mbu et al. 2018). The problem of coinfection of these two diseases is also associated with the currently topical issue of drug resistance of the causative agent of tuberculosis and the need to create new drugs.

The Russian Federation is among the countries most severely affected by tuberculosis as every third patient in the WHO European Region is from Russia (Vasilieva et al. 2017). On average, more than 100 new cases of the disease appear and about 20 people die of tuberculosis daily in Russia (Nechaeva

2018). In 2017, 70.9 thousand people with active tuberculosis were registered on the territory of the Russian Federation (the diagnosis was established for the first time in their lives) i.e. 48.3 cases per 100,000 people (Healthcare in Russia 2019). Young children are most susceptible to the disease, especially in the first months of their lives. The main source of infection for them are adults suffering from tuberculosis in active phases (Shelkova, Romanenko 2013).

Russia is a country with a high incidence of both common tuberculosis (TB) and multidrug-resistant tuberculosis (MDR-TB) (Global tuberculosis report 2020). In subsequent years, the detection and control of multidrug-resistant tuberculosis will be the main focus of research both in Russia and abroad (Chung-Delago et al. 2015; Barkanova et al. 2018; Girum et al. 2018).

The importance of studying the spatial patterns of the infection spread is closely connected to the impact that the external environment has on the human body. The strategy for solving the priority tasks in the spheres of social policy and healthcare should be based on knowledge of the geography of various indicators of the epidemiological situation.

There is an obvious need to fill the existing gap in the study of spatially differentiated levels in the Russian Federation, both national and regional. Without the compilation of modern maps representing incidence and mortality in Russia as a whole and in individual regions, in particular, it is impossible to provide information support for high-quality monitoring of the epidemiological situation.

World Health Organization has assigned itself a task to ensure a wide exchange of experience in studying the level of health of the world population and introducing the best examples of health care organizations based on science-based preventive measures (The End TB Strategy 2014). The experience of South Africa, a country also struggling with the control and prevention of tuberculosis, will contribute to similar programmes in the Russian Federation. The methods of spatial medical-geographical analysis developed and applied in the Russian Federation can in turn inform geographically differentiated tuberculosis prevention measures in South Africa and elsewhere.

The purpose of this study is to identify the spatio-temporal features of the current epidemiological situation of tuberculosis in the Russian Federation in order to develop targeted preventive measures in the fight against the most lethal global infectious organism (World Health Organization 2020)

MATERIALS AND METHODS

The territory of Russia is divided into 85 federal subjects (hereinafter territorial units -TU): oblasts, republics, krais, autonomous oblasts, autonomous okrugs and federal cities (Fig. 1). The study used primary statistical information on incidence and mortality due to tuberculosis in the Russian Federation for the period from 2006 through 2017. Data were collected at the national level for each of the 85 regions of the Russian Federation from various sources, including publicly available statistical digests, information materials and articles by the Federal State Statistics Service (Rosstat), the Ministry of Health of the Russian Federation, Federal Research Institute for Health Organization and Informatics of Ministry of Health of the Russian Federation, The Moscow Research and Clinical Center for Tuberculosis Control of the Moscow Government Department of Health and Research Institute of Physiopulmonology at Sechenov University.

Federal Subjects of the Russian Federation:

1. Altay Krai
2. Amur Oblast
3. Arkhangelsk Oblast
4. Astrakhan Oblast
5. Belgorod Oblast
6. Bryansk Oblast
7. Vladimir Oblast
8. Volgograd Oblast
9. Vologda Oblast
10. Voronezh Oblast
11. Jewish Autonomous Oblast
12. Zabaikalsky Krai
13. Ivanovo Oblast
14. Irkutsk Oblast
15. Kaliningrad Oblast
16. Kaluga Oblast
17. Kamchatka Krai
18. Kemerovo Oblast
19. Kirov Oblast
20. Kostroma Oblast
21. Krasnodar Krai
22. Krasnoyarsk Krai
23. Kurgan Oblast
24. Kursk Oblast
25. Leningrad Oblast
26. St. Petersburg
27. Lipetsk Oblast
28. Magadan Oblast
29. Moscow Oblast
30. Moscow
31. Murmansk Oblast
32. Nenets Autonomous Okrug
33. Nizhny Novgorod Oblast
34. Novgorod Oblast
35. Novosibirsk Oblast
36. Omsk Oblast
37. Orenburg Oblast
38. Oryol Oblast
39. Penza Oblast
40. Perm Krai
41. Primorsky Krai
42. Pskov Oblast
43. Republic of Adygeya
44. Republic of Altai
45. Republic of Bashkortostan
46. Republic of Buryatia
47. Republic of Dagestan
48. Republic of Ingushetia
49. Republic of Kabardino-Balkaria
50. Republic of Kalmykia
51. Republic of Karachay-Cherkessia
52. Republic of Karelia
53. Republic of Komi
54. Republic of Crimea
55. Sevastopol
56. Republic of Mari El
57. Republic of Mordovia
58. Republic of Sakha (Yakutia)
59. Republic of North Ossetia - Alania
60. Republic of Tatarstan
61. Republic of Tyva
62. Republic of Udmurtia
63. Republic of Khakassia
64. Chechen Republic
65. Republic of Chuvashia
66. Rostov Oblast
67. Ryazan Oblast
68. Samara Oblast
69. Saratov Oblast
70. Sakhalin Oblast
71. Sverdlovsk Oblast
72. Smolensk Oblast
73. Stavropol Krai
74. Tambov Oblast
75. Tver Oblast
76. Tomsk Oblast
77. Tula Oblast
78. Tyumen Oblast
79. Ulyanovsk Oblast
80. Khabarovsk Krai
81. Khanty-Mansi Autonomous Okrug - Yugra
82. Chelyabinsk Oblast
83. Chukotka Autonomous Okrug
84. Yamal-Nenets Autonomous Okrug
85. Yaroslavl Oblast

Fig. 1. Federal subjects of the Russian Federation

Authors selected the following indicators, expressed in absolute values and per 100,000 population, that reflect the current situation of tuberculosis in Russia to the fullest extent: the incidence of all forms of tuberculosis, incidence of pulmonary tuberculosis, incidence of tuberculosis in children and mortality from tuberculosis and other consequences.

The calculation of standardized mortality rates (Everitt, Skrondal 2010) was carried out according to a direct standardization method based on the information on the absolute number of deaths from tuberculosis in the regions of the Russian Federation. This was implemented to eliminate the influence of the age and sex structure of the population. All the collected statistical materials were combined into one database in the form of attribute tables in the QGIS software. The resulting database became the basis for creating GIS layers (QGIS), which were then used to produce a series of analytical and typological maps for the period from 2006 to 2017.

This was followed by a more detailed dynamic typological classification for all of the regions of the Russian Federation for each of the analyzed indicators, which was made using the original classification algorithm with several sequential operations: normalization, weighting and dimensionality reduction for the data, all carried out by variances and mathematical expectations (Tikunov 1997). This made it possible to clarify the spatio-temporal pattern of the distribution of the incidence and mortality rates. The principal component analysis was applied to correct the original space of features distorted by cross-correlations as well as to identify latent variables that reflect the essence of a process or phenomenon.

In the applied typological algorithm, the entire set of parameters for any territorial unit (TU) is denoted by X={x1,…,xN}, where xi- i -th TU, N- the number of TUs. The initial TUs are represented in the form of a TU-sign matrix, which reflects the measurement of signs on TU and contains rows and columns:

$$X = \begin{pmatrix} x_1 \\ x_N \end{pmatrix} = \left(x^{(1)},\dots,x^{(M)}\right) = \begin{pmatrix} x_1^{(1)} & \cdots & x_1^{(j)} & \cdots & x_1^{(M)} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ x_{N-1}^{(1)} & \cdots & x_{N-1}^{(j)} & \cdots & x_{N-1}^{(M)} \\ x_N^{(1)} & \cdots & x_N^{(j)} & \cdots & x_N^{(M)} \end{pmatrix}$$

where

$xi = (x_i^{(1)},\dots, x_i^{(M)})$- i -th TU in M- dimensional space of parameters

$x^{(j)}$ - j -th parameter, $x^{(j)}=(x_1^{(j)},\dots,x_N^{(j)})$,

$x_i^{(j)}$ - the value of j -th parameter of i -th TU,

i∈{1,...,N}, j∈{1,...,M}.

The next stage of the TUs' classification is their pretreatment, which includes normalization, weighing and dimensionality reduction. The normalization was carried out according to the variance and mathematical expectation. The purpose of this normalization is to bring each indicator to a standard form (as a result, the mathematical expectation of any indicator becomes equal to zero, and the variance to unity). Assuming $\overline{x}^{(j)} = \frac{1}{N}\sum_{i=1}^{N} x_j^{(j)}$ is the estimate of mathematical expectation and $var\left(x^{(j)}\right) = \frac{1}{N}\sum_{i=1}^{N}\left(x_j^{(j)} - \overline{x}^{(j)}\right)$ is the estimate of variance of j -th parameter, the normalization means the following recalculation:

$$x_i^{(j)} = \frac{x_i^{(j)} - \overline{x}^{(j)}}{\sqrt{\operatorname{var} x^{(j)}}} \; \forall j \in \{1,\dots,M\}, i \in \{1,\dots,N\}, \text{ т.е } \Delta_1 = \overline{x}^{(j)},\ \Delta_2 = \sqrt{var(x^{(j)})}$$

The next step includes the application of the principal component method. This method solves the problem of analyzing the existing system of attributes that describe TU. The method of principal components is used to correct the original feature space distorted by mutual correlations, reduce the amount of stored data without losing a significant part of information about TU, visualize TU in the feature space (which is achieved, for example, by displaying TU in the form of points on a plane) and reveal hidden indicators that reflect the essence of the process or phenomenon.

The simplest interpretation of the principal component method is geometric. In a multidimensional parameters' space, TU are considered as points, whose cloud's geometrical arrangement, in the case of the normal distribution, resembles an M-dimensional ellipsoid. The main axes of the imaginary ellipsoid are treated as the new parameters, sorted in the descending order of the TUs' dispersions along the axes.

The most general relation is used to calculate the distance for M quantitative parameters:

$$d_e(x_i, x_j) = \sqrt{\sum_{x=1}^{M}\left(x_i^{(x)} - x_j^{(x)}\right)^2}$$

Our classifications aimed to obtain homogeneous TU groups in M-dimensional attribute space, i.e., possible "types" of TU. For this, the largest distance is selected from the obtained Euclidean distances and the two territorial units that it connects become the nuclei of the homogeneous clusters. Clusters are formed by the distribution of the remaining territories between the two cores according to the minimum Euclidean distances. In the case of a larger number of clusters, to determine the third and all subsequent cores, each of all remaining territorial units is substituted in the form of a core, and the rest is distributed between the three cores according to the minimum distance. The procedure for determining the 4-th core and formation of a typology with 4 types is similar to that described above. The maximum possible number of groups t_{max} is specified in advance, similarly to the minimum value t_{min}.The resulting number of groups can be analyzed using the absolute and relative heterogeneity coefficients and, thus, the optimal number of clusters can be chosen:

$$A_k = \frac{100\left\{\sum_{k=1}^{K}\sum_{j=1}^{n}\sum_{i=1}^{n}\left[\sum_{p=1}^{P}\left(x_{ip} - x_{jp}\right)^2\right]^{1/2} I_{ik}I_{jk}\right\}}{\sum_{i=1}^{t_{\max}}\left[\sum_{p=1}^{P}\left(x_{ip} - x_{jp}\right)^2\right]^{1/2}},$$

$$k = t_{\min}, t_{\min}+1,\dots,t_{\max};$$

$$O_k = \frac{100\left\{\sum_{k=1}^{K}\sum_{j=1}^{n}\sum_{i=1}^{n}\left[\sum_{p=1}^{P}\left(x_{ip} - x_{jp}\right)^2\right]^{1/2} I_{ik}I_{jk}\right\}}{\sum_{i=1}^{t_{\max}}\sum_{j=1}^{n}\sum_{i=1}^{n}\left[\sum_{p=1}^{P}\left(x_{ip} - x_{jp}\right)^2\right]^{1/2} I_{ik}I_{jk}},$$

$$k = t_{\min}, t_{\min}+1,\dots,t_{\max}-1.$$

where k – the number of identified groups, p – the number of the orthogonalized coefficients to calculate distances, t_{min}, t_{max} – the maximal and the minimal number of groups, I_{ik}- indicator (binary), pointing to the presence (1) or absence (0) of TUi in group *k*.

A sharp increase in A_k or O_k with a decrease in the number of the identifiable clusters indicates an increase in heterogeneity within the identified clusters, while, on the contrary, a smooth increase in the coefficients is a sign of its uniform increase. The threshold followed by a sharp increase in heterogeneity can be optimally taken as the final number of clusters. In our analysis, the isolation of five clusters in all calculations turned out to be optimal (Tikunov 1997).

The «TB hot spots» of the Russian Federation were determined using cluster analysis. Several groups of regions with similar mortality and incidence rates among the adult population were identified. The k-means grouping was used as a clustering method. As a result of the iterations of the cluster analysis, it was recognized that it was optimal to single out three groups characterized by a gradual increase in both the incidence and mortality rates among the entire population, which reflects the unfavourability of the epidemic situation.

RESULTS AND DISCUSSION

Incidence and mortality from tuberculosis and its temporal dynamics in the Russian Federation

Tuberculosis in Russia remains one of the country's main epidemiological problems. At the same time, during the analyzed period, there was a tendency towards a decrease in incidence and mortality from tuberculosis for all considered indicators. The incidence rate was 82.6 per 100,000 population in 2006 but over 10 years it has dropped by almost half to 48.3 per 100,000 population in 2017.

The mortality is also characterized by a rapid decline, from 20 per 100,000 population in 2006 to 6.5 per 100,000 population in 2017. While there is a decrease in mortality from TB, the «all-cause fatality rate of TB» indicator is rising. The fatality rate depends on a number of factors (for example, the clinical form of tuberculosis, patient's age, social status and presence of coexisting pathologies) and thus indirectly reflects the effectiveness of treatment of patients with tuberculosis.

The decrease in the incidence rate among children was less pronounced. It remained at 16.0 per 100,000 population from 2006 through 2012; since 2013 a decrease in the number of cases was constantly observed and the incidence rate in 2017 was registered at 9.7.

It should be noted that the decrease in the incidence of tuberculosis occurred following a wider roll-out of tests for latent TB infection and a decrease both in the number of postmortem diagnostics and one-year mortality. According to the Central Research Institute for Organization and Informatization of Healthcare of the Ministry of Health of the Russian Federation, the periodic screenings for tuberculosis cover about 70% of the population. The best timely detection of tuberculosis is observed in Volga, Ural, Siberian Far Eastern regions and to a lesser extent Central and Southern federal districts. The low detection rate of tuberculosis corresponds to the Northwest region. The quality of detection rate in the North Caucasian Federal District requires clarification.

Spatial heterogeneity of tuberculosis

Considering the territorial heterogeneity in the distribution of the long-term average annual incidence rate of tuberculosis (all forms) for the period from 2006 through 2017, it should be noted that there is a pronounced differentiation between the European part of the Russian Federation and the rest of the country (Fig. 2). The incidence can be defined as «significantly below average» or «below average» in almost all regions of the European part of the Russian Federation except for Kaliningrad Oblast and the border regions of Russia (Pskov, Smolensk and Bryansk oblasts). The most burdened regions (where the incidence rate is «significantly above average») are located beyond the Urals, mainly in the southern border regions of the Russian Federation (Kurgan, Tyumen, Omsk oblasts and other regions). This category also includes almost all of the regions of Eastern Siberia and the Far East except for the Republic of Sakha (Yakutia), Magadan and Sakhalin oblasts, and Kamchatka Krai.

While analyzing the structure of cases, according to the Central Research Institute for Organization and Informatization of Health Care, it should be noted that among the newly registered patients with tuberculosis, 86.4% belong to the permanent residents of Russia. The proportion of foreign nationals from the countries of the former USSR is about 3.5%; the highest proportion of foreign citizens with tuberculosis is observed in Moscow (31.7%) and St. Petersburg (14.5%). The share of tuberculosis cases in the institutions of the Federal Penitentiary Service (FSIN) accounts for 8%.

Among the affected people, about 65% are men (excluding the cases in the institutions of the Federal Penitentiary Service, where there are mainly young men), and about 35% are women. The age structure is as follows: 30% of cases are among the 18-34 age group, about 30% are among the 35-44 age group and 35% correspond to the group of 45 years old and more.

While there are positive trends in the situation with tuberculosis in the Russian Federation as a whole, the problem of multidrug-resistant tuberculosis (MDR-TB) remains relevant as the number of MDR-TB patients is growing. The proportion

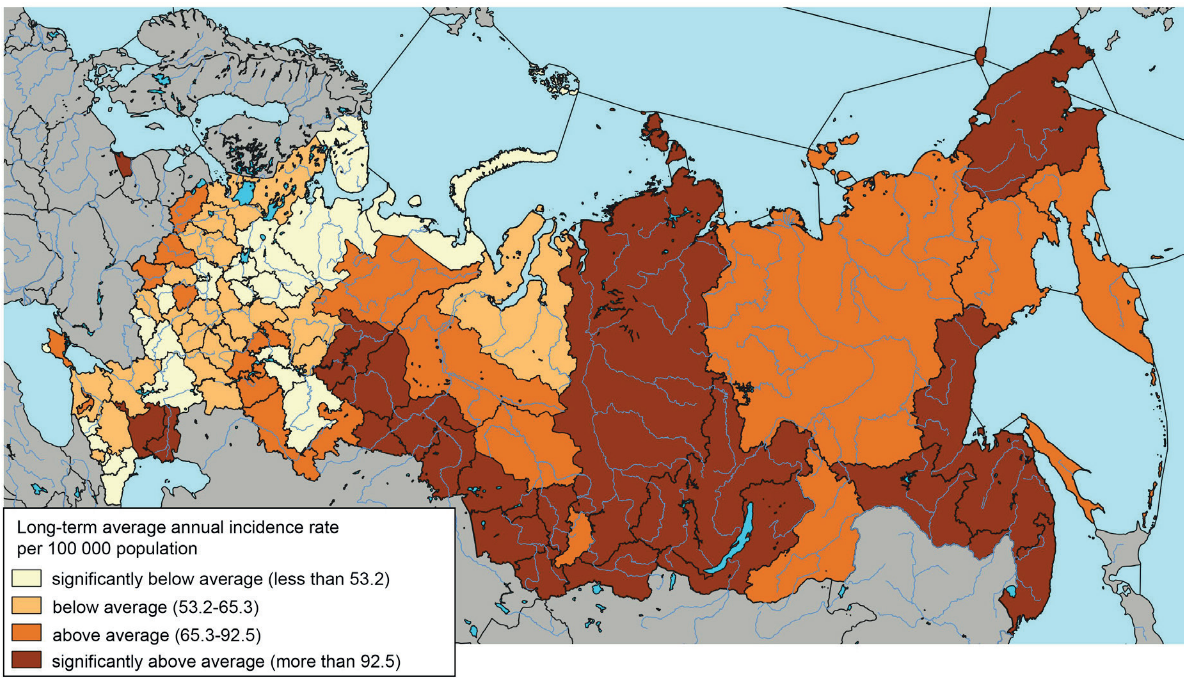

Fig. 2. Long-term average annual incidence rate of TB (all forms) for the period from 2006 to 2017

of patients with MDR-TB among patients with pulmonary tuberculosis was 30% in 2010 and 54% in 2017. Among newly diagnosed TB patients, the proportion of patients with MDR-TB was 14% and 27% in 2010 and 2017, respectively. Among those who were registered and died of tuberculosis in 2017, 44% of patients had MDR-TB; among those who died from other causes, 27.5% had MDR-TB.

The modern paradigm of epidemiological research provides for a joint analysis of the spread of tuberculosis and HIV infection. This is because there has been a drastic increase in the number of tuberculosis cases in patients previously infected with HIV over the past decades.

While there is a stable decrease in the incidence of tuberculosis, at the same time an increase in the incidence of HIV is taking place (Fig. 3). The turning point came in 2014 when the number of people with identified HIV antibodies exceeded the number of cases of tuberculosis (per 100,000 population) (Central Research Institute for Health Organization and Informatization of the Ministry of Health of the Russian Federation 2020). A similar situation in terms of mortality occurred a year later, in 2015. Thus, there is still a risk of additional cases of tuberculosis among HIV-infected people due to a decline in their immune protection. The spread of HIV/TB coinfection is observed primarily in the age groups of 25–44 years, which is typical for all regions of the Russian Federation. Moreover, every second patient registered as having died of HIV infection dies from the progression of tuberculosis at the late stages of HIV infection (Central Research Institute for Health Organization and Informatization of the Ministry of Health of the Russian Federation 2020).

The incidence rate among children by regions overall repeats the picture typical for the entire population of Russia (Fig. 4). The European Russia can be characterized as the most favorable territory (except for Kaliningrad, Bryansk, Yaroslavl oblasts as well as the Republics of Kalmykia and Adygea). A relatively positive situation is observed in the regions of Western Siberia. At the same time, the incidence rate is above average or significantly above average throughout Eastern Siberia and the Far East (except for Sakhalin and Amur oblasts, Khabarovsk and Zabaikalsky Krais).

Considering the age structure of tuberculosis incidence in children of 0–14 years old, it should be noted that approximately 40-50% of cases appear to be in the age group of 7-10 years, about 40% at the age of 3-6 years and about 10% at the age of 1-2 years.

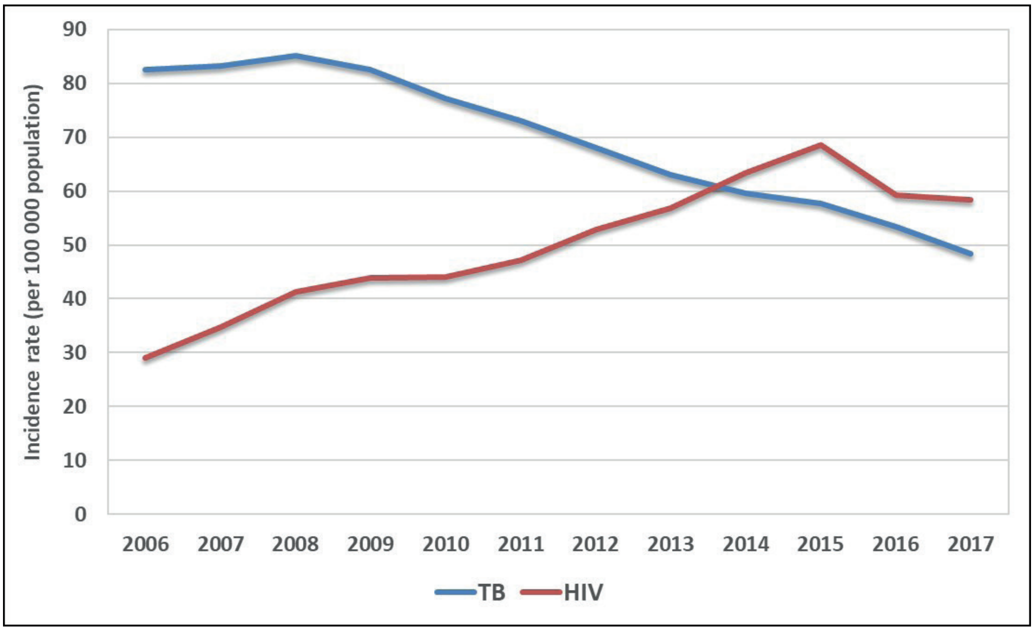

Fig. 3. TB and HIV incidence rate (per 100 000 population) in Russia for the period from 2006 to 2017

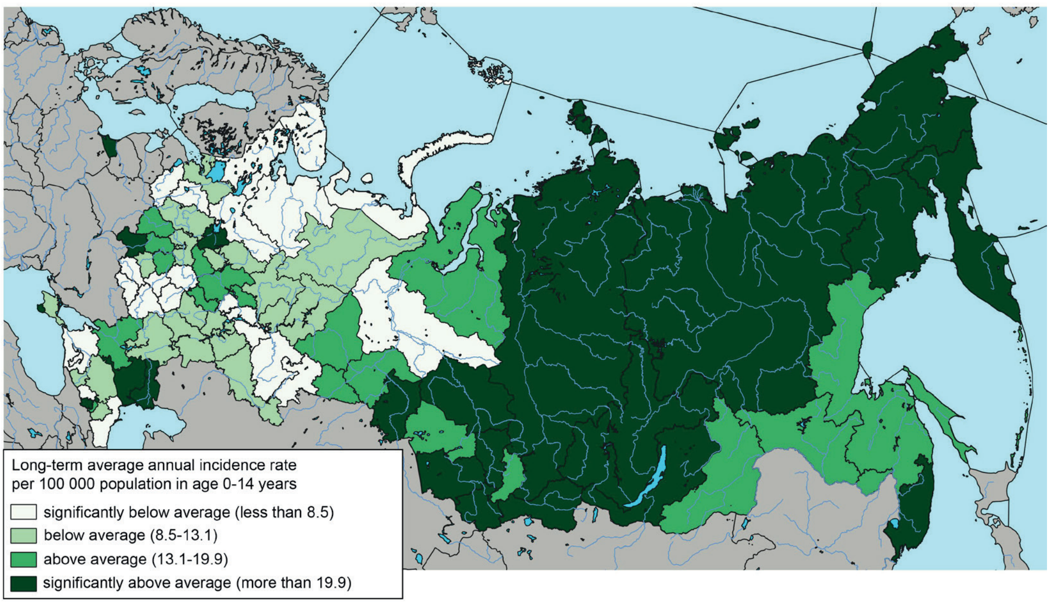

Fig. 4. Long-term average annual incidence rate of TB among children 0-14 years for the period from 2006 to 2017

Although the spatial pattern of mortality from tuberculosis in general repeats the distribution of the incidence, it is far more mosaic and uneven (Fig. 5).

A number of regions that have both high incidence and high mortality rates stand out, for example, Krasnoyarsk and Altai Krais, Omsk and Tyumen oblasts, and some others. The opposite situation is observed in other regions where high incidence correspond to low mortality rates, for example, the Republic of Sakha (Yakutia), Magadan and Tomsk oblasts. The peak of mortality from tuberculosis in the regions of the Russian Federation falls at the age of 35-64 years.

In general, it is possible to conclude based on all the considered indicators, that the unfavorable situation in terms of tuberculosis is confined to the Asian part of Russia.

Typological classification of regions of the Russian Federation according to the level and dynamics of the epidemic indicators of tuberculosis

A typological classification based on dynamic characteristics made it possible to identify regional patterns in the epidemiological situation over the considered time interval as well as some features, representative of the territory of the Russian Federation as a whole.

Analysis of the created typological map on the incidence of tuberculosis in the entire population for the period from 2006 to 2017 showed that all identified types are characterized by a tendency towards a decrease in incidence (Fig. 6). The greatest changes can be detected in the regions, belonging to the following types: type II (high incidence rate accompanied by a pronounced downward trend) represented by the Republic of Tyva, Primorsky Krai, Jewish Autonomous Oblast; type III (decrease in the incidence rate since 2007) represented by only 14 regions located mainly beyond the Urals; and type IV (average incidence rate) represented by 11 regions mainly located along the southern border of the Russian Federation and Kaliningrad region. Types V and VI have an average incidence rate with a gradual downward trend. At the same time, the incidence rate for regions included in type V (mainly the regions of the European Russia and Yamalo-Nenets Autonomous Okrug) is slightly higher than for the regions included in type VI. Type I is characterized by the lowest incidence rate with a similar decreasing trend and includes 18 European regions of the country.

In general, the correspondence of the spatial pattern of the long-term average annual incidence rate (obtained as a result of a cartographic analysis) to the selected typological units taking into account the observed dynamics of the indicator, suggests that the epidemiological situation is reflected objectively and that both methodological techniques were used appropriately.

Considering the typological classification for the incidence rate of pulmonary tuberculosis, the observed spatio-temporal pattern is similar to the incidence rate for all forms of TB with the difference that the selected types are characterized by a smoother decrease and the absence of any peaks (Fig. 7).

The groups identified based on the incidence of tuberculosis in children differ in terms of their dynamics (Fig. 8). Type II (high incidence rate with a zigzag downward trend) links together regions with a severely unfavorable epidemiological situation for tuberculosis in children, particularly Kamchatka Krai and Magadan Oblast. Type VI (high incidence rate with a mild downward trend) also corresponds to a number of disadvantaged regions. This type includes 8 regions located in different parts of the country (Kaliningrad Oblast, Republic of Kalmykia, Astrakhan Oblast, Republics of Altai and Tyva, Kemerovo Oblast, Primorsky Krai and Chukotka Autonomous Okrug). Type III is marked by an average incidence rate with a single spike in 2013. It includes 12 regions, almost all of which are in Siberia and the Far East except for Yaroslavl and Bryansk oblasts (which are located in European Russia). Types IV and V combine regions with an average incidence rate and a mildly pronounced downward trend. These are mostly the European regions of the Russian Federation. Type I characterizes regions with the most favorable situation demonstrating consistently low incidence rates during the entire study period. This type includes 21 regions located exclusively in European Russia.

It should be noted, that the use of a typological classification for the incidence in children demonstrates a more uneven spatial pattern in comparison with the long-term average annual indicator, especially in Siberia and the Far East regions. This could be a result of fairly significant annual fluctuations of incidence in these regions.

The results of the typological classification reveal an even greater differentiation of regions in terms of mortality (Fig. 9). The most unfavorable situation was registered in only one region, i.e., the Republic of Tyva (type II, characterized by high

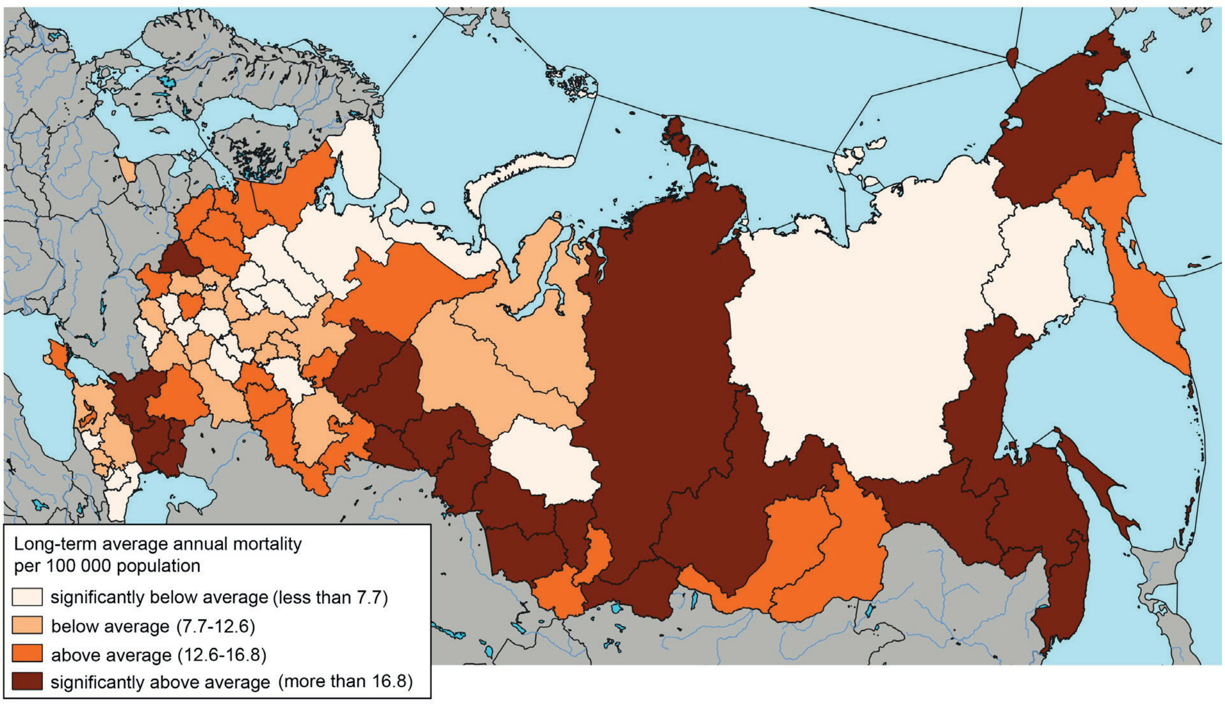

Fig. 5. Long-term average annual mortality from TB for the period from 2006 to 2017

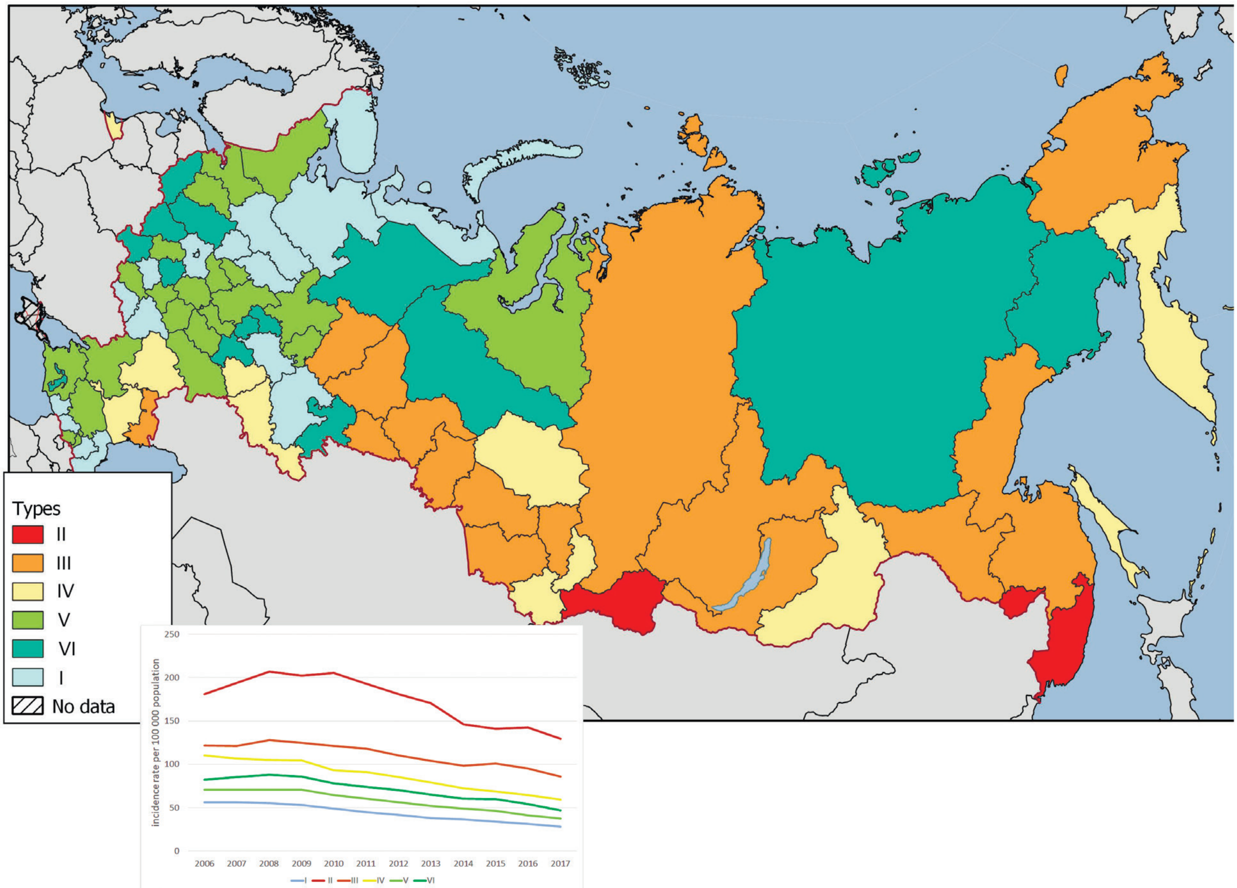

Fig. 6. Types of regions of the Russian Federation by the rate and dynamics of the incidence of TB

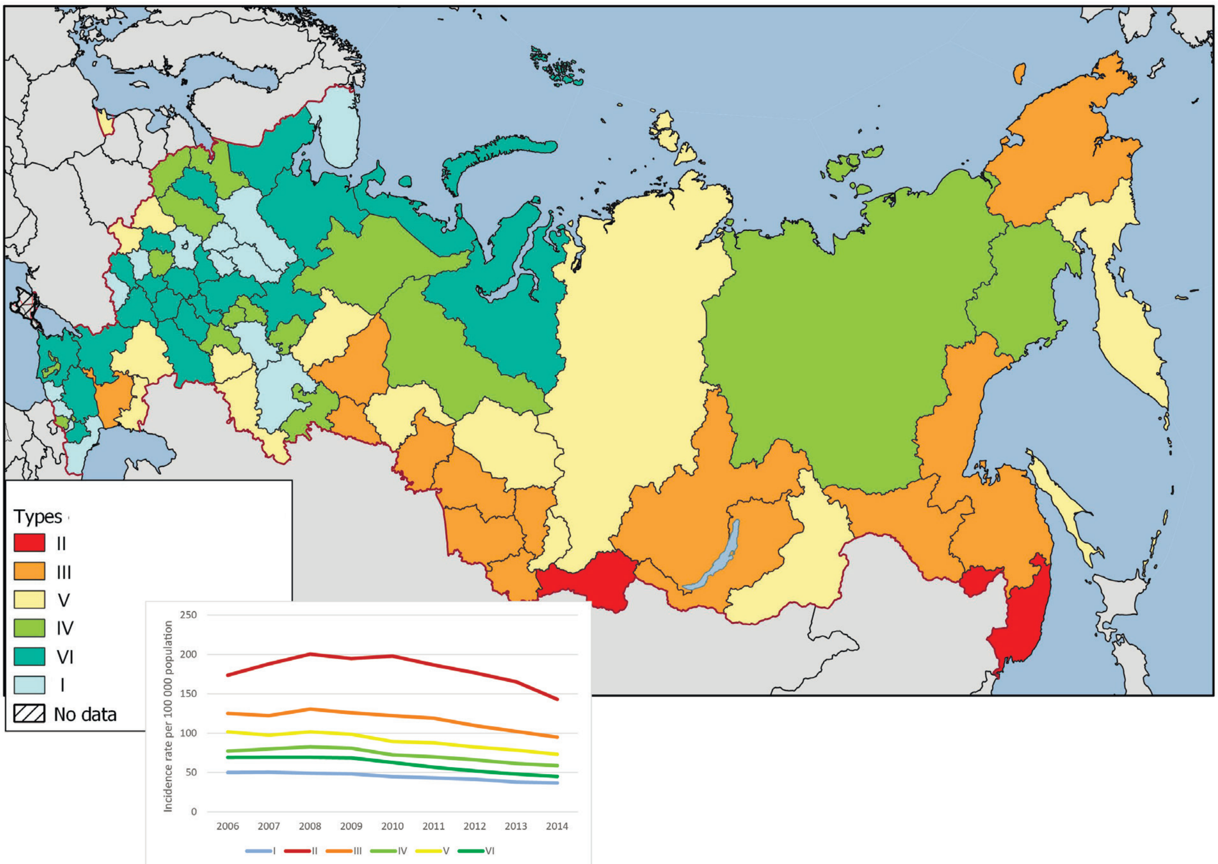

Fig. 7. Types of regions of the Russian Federation by the rate and dynamics of the incidence of pulmonary TB

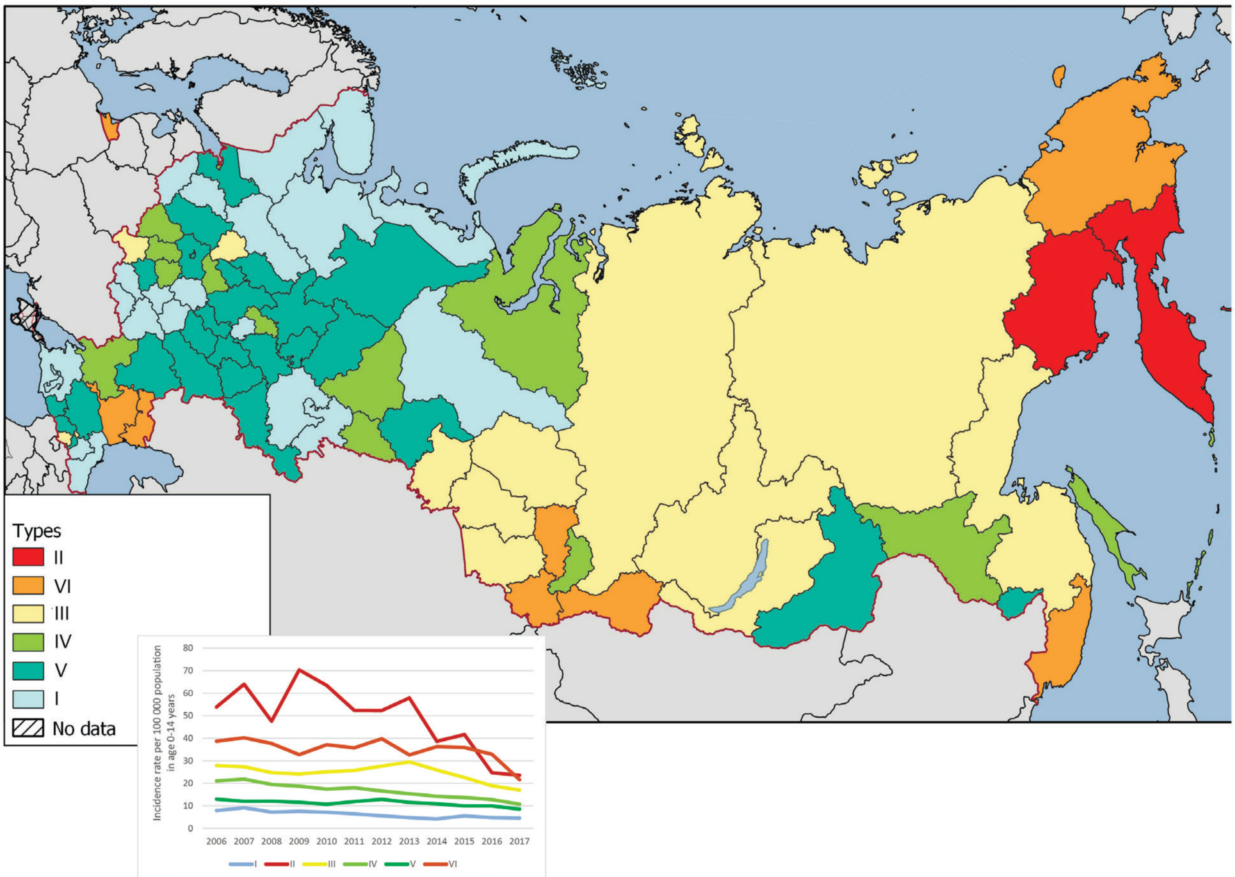

Fig. 8. Types of regions by the rate and dynamics of the incidence of TB among children 0-14 years

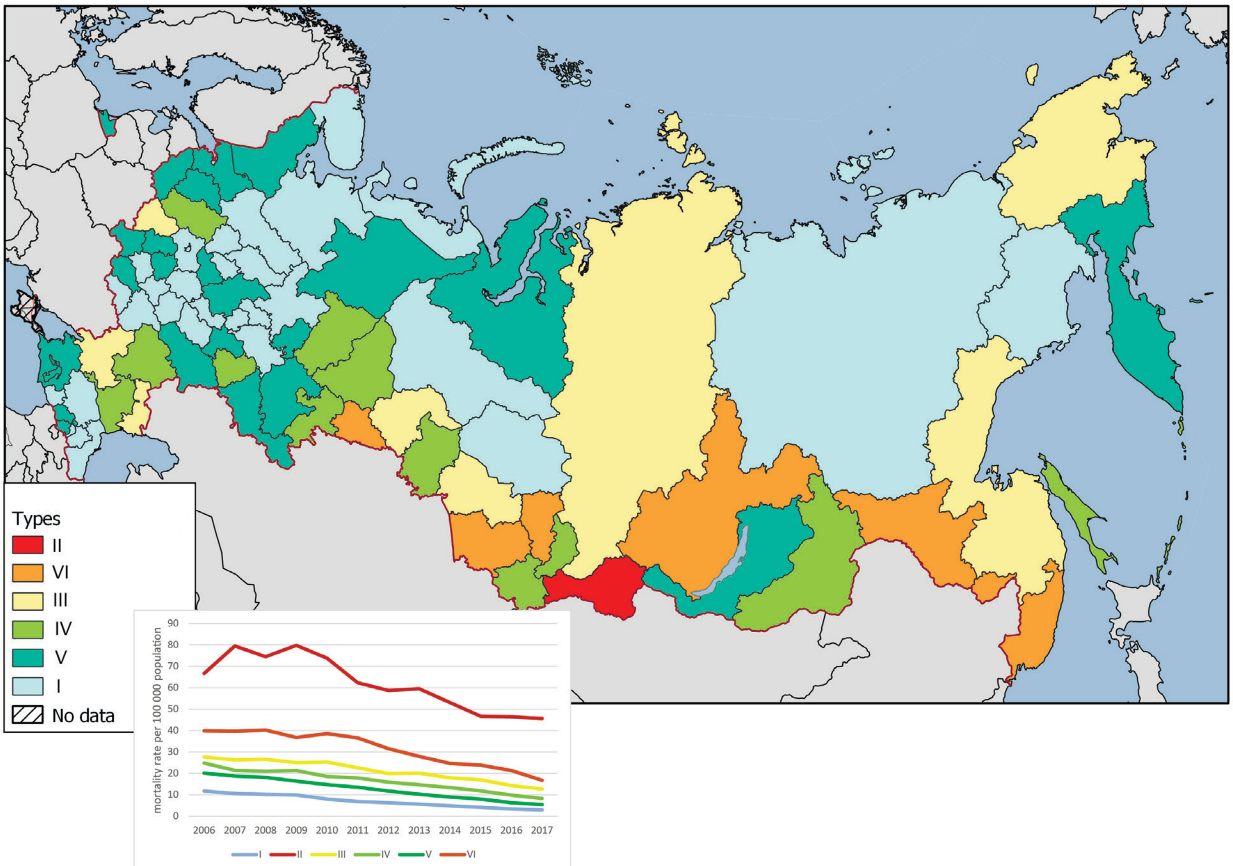

Fig. 9. Types of regions by the rate and dynamics of TB mortality

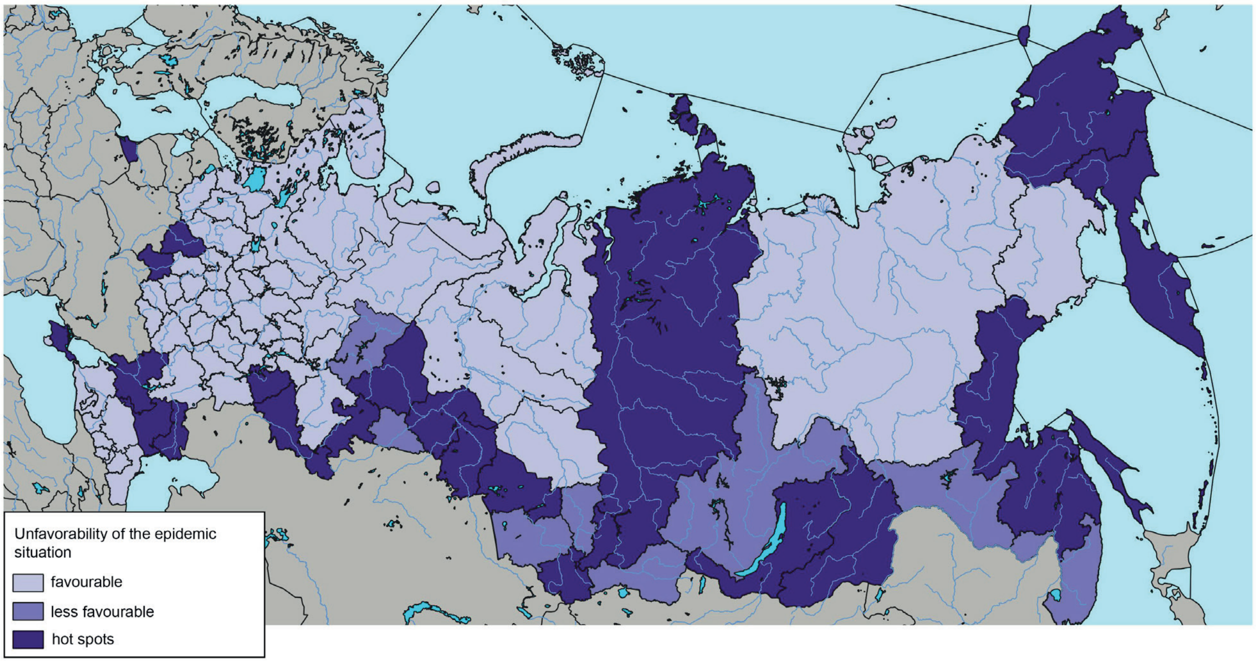

Fig. 10. The unfavourability of the epidemic situation in regions of the Russian Federation based on cluster analysis of the incidence and mortality rates (all forms of TB)

mortality with a pronounced downward trend). Type VI is also marked by a fairly high mortality rate but a less pronounced downward trend. This type includes 7 regions located mainly in the south of Siberia. Types III, IV, V and I differ only in magnitude and have similar tendencies towards a reduction of mortality rates. The vast majority of regions (31) belong to type I which has the lowest mortality rate.

The results of the typological classification show that the identified types differ mostly by the incidence and mortality rates but the dynamics of indicators for all types is characterized by a downward trend.

Hot spot regions of the Russian Federation

Analysis of the cartographic material created using cluster analysis (Fig. 10) made it possible to identify regions with various levels of incidence and mortality from tuberculosis over the analyzed period, i.e., the hot spot regions of Russia and the more favorable regions. The tuberculosis hot spots are found in some regions of European Russia (Kaliningrad, Smolensk, Bryansk oblasts), southern regions (Rostov Oblast, the republics of Kalmykia and Adygea), the Siberian and the Far East regions (Krasnoyarsk Krai, Novosibirsk and Omsk oblasts, Republics of Altai and Buryatia, Zabaikalsky, Khabarovsk and Kamchatka krais, Sakhalin and Magadan oblasts). Less unfavorable, average situation was revealed mainly in the regions of southern Siberia and the Far East (Primorsky Krai, Amur Oblast, Jewish Autonomous Oblast, Irkutsk Oblast, Republic of Tyva and Altai Krai). The rest of the regions of the Russian Federation have a low degree of epidemic tension thus being the safest. The analysis made it possible to differentiate the territory of the Russian Federation and identify epidemically unsafe regions in which more detailed research is required at the municipal level. The obtained results confirm the conclusions of the cartographic analysis presented above.

CONCLUSIONS

An analysis of the current spread of tuberculosis in the Russian Federation was carried out using GIS technologies and epidemic data for the period from 2006 through 2017. As a result of the study, the spatial and temporal features of the epidemic situation in Russia were revealed in terms of the incidence of tuberculosis for the entire population (of all forms of TB), incidence of pulmonary TB, incidence of TB in children and mortality from TB. Typological classification of regions was developed based on the dynamics and magnitude of the incidence rate; it was revealed that there is an overall downward trend in incidence and mortality from TB in recent years. The highest burden regions of the Russian Federation in terms of tuberculosis with consistently high levels of incidence and mortality throughout the analyzed period were identified. The obtained results can be used for a further detailed study of the tuberculosis spread at the municipal level as well as for planning anti-tuberculosis measures in Russia.

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RESEARCH PAPER

LONG-TERM STUDIES OF SURFACE-SEDIMENT DIATOM ASSEMBLAGES IN ASSESSING THE ECOLOGICAL STATE OF LAKE LADOGA, THE LARGEST EUROPEAN LAKE

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ABSTRACT. The study continues a series of observations started in the late 1950s, aimed at inferring changes in the Lake Ladoga ecosystem state recorded in the surface-sediment diatom assemblages. At the pre-anthropogenic stage (prior to the 1960s), the composition of the surface-sediment diatom assemblages indicated an oligotrophic state of Lake Ladoga. With the increased P load to the lake (late 1960s–1980s), the transition to a mesotrophic state was recorded via increased proportions of eutrophic species and decreased abundances of the taxa typical of the pre-anthropogenic stage. In the early 1990s, the composition of the surface-sediment diatom assemblages still indicated a mesotrophic state despite a decreased external P load. At the present de-eutrophication stage of Lake Ladoga (the 2000s), the abundances of eutrophic taxa steadily decrease while some taxa typical of the pre-anthropogenic period return to their dominating position in the surface-sediment diatom assemblages. However, despite the decreased P concentrations, the Lake Ladoga ecosystem has not returned to its pre-anthropogenic state as indicated by the present-day composition of the surface-sediment diatom assemblages. This suggests a delayed ecosystem response to the decreased anthropogenic pressure, and possibly some irreversible changes resulting from the eutrophication. At present, de-eutrophication processes and ecosystem recovery are superimposed upon the recent climatic changes that govern the onset and duration of the vegetative seasons for the phytoplankton communities in Lake Ladoga. The diatom-inferred changes in the ecological state of Lake Ladoga are in agreement with the results of long-term hydrochemical and hydrobiological studies.

KEY WORDS: Lake Ladoga, surface-sediment diatom assemblages, lake ecological state assessment, anthropogenic eutrophication, recovery, climate change

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INTRODUCTION

Being indispensable for all living things on Earth, freshwater is also one of the most limited resources. It only accounts 2,5% of all freely available water in the world, only 0,3% of which is readily accessible in lakes, reservoirs and rivers (Kalff 2001). Population growth and enhanced industrial and agricultural activities have played important role in water pollution and rapid deterioration of aquatic ecosystems starting from the mid-20th century. As a result, in the 21st century, water shortage and/or water quality become one of the major problems for humanity (Ansari and Gill 2014).

Cultural eutrophication, i.e. anthropogenic nutrient (P and N) loading to aquatic ecosystems, is acknowledged as the most widespread form of lake pollution on a global scale (Smol and Stoermer 2010). The lake's ecosystem response to nutrient enrichment results in various ecological problems, such as massive growth of algae or macrophytes, shifts in food web structure, loss of aquatic organisms and depletion of aquatic biodiversity. Furthermore, poor water quality caused by eutrophication restricts its use for drinking, irrigation, industry, transportation, recreation, fisheries, etc. Although major advances in the scientific understanding and management of eutrophication have been made since the late 1960s, eutrophication continues to be ranked as the most common water-quality problem in the world, and remains an active area of scientific research (Schindler 2006; Smol 2008).

In last decades, a series of measures were undertaken in different countries to reduce the nutrient load to the lakes and restore aquatic ecosystems. As a result, many lakes, especially in Europe and North America, have now entered an oligotrophication phase which, however, is a less well-understood and consequently less predictable process (Smol and Stoermer 2010). Basin morphometry, water chemistry, and the nature of the phosphorus sources are among the factors that govern the rate at which lake productivity will revert toward conditions that had existed before cultural eutrophication started (Wetzel 2001).

Besides, recent climate change may fundamentally alter the physical (e.g. stratification, duration of ice cover) and food-web structure of the lake, biogeochemical processes and land-water interactions. This would impact on the pathways and success of lake restoration efforts and may prevent re-establishment of communities typical of the pre-anthropogenic period (Battarbee et al. 2005).

Lake Ladoga in north-western Russia (Fig. 1a), is the largest lake in Europe and ranked among the top fifteen world's freshwater lakes in terms of surface area and water volume. Lake Ladoga represents the only source of potable water for St Petersburg, the second largest city in Russia, as well as for many smaller towns in the Leningrad Region and Republic of Karelia. It also serves as an important transportation route connecting the North-West Region with central and southern regions of the Russian Federation as well as with European countries. Lake Ladoga has rich and diverse biological resources and hosts ca. 400 animal and ca. 600 plant species. Furthermore, it is a unique natural aquatic system for recreation and fishery (Rumyantsev and Kondratyev 2013; Rumyantsev 2015).

Since Lake Ladoga drains a substantial area of north-western European Russia as well as eastern Finland, it also acts as a natural accumulation pool for different kinds of pollutants (Rumyantsev 2015). Nowadays, the state of the Lake Ladoga ecosystem is largely controlled by a complex interplay between natural and anthropogenic processes occurring both within the lake and in its catchment.

Although the lake's shores were inhabited by early humans already in the Early Holocene (e.g. Gerasimov and Subetto 2009), prior to the 1960s human impact on the lake can be considered negligible. Any environment disturbances caused by human activities were apparently leveled due to the Lake Ladoga great size and self-purification capacity. In the early 20th century the state of Lake Ladoga was assessed as clear-water oligotrophic (Balakhontsev 1909), and remained oligotrophic until the late 1960s. Therefore this state of the lake's ecosystem is hereinafter referred to as "pre-anthropogenic", and could be considered as its reference state (Bennion et al. 2011). During the 1960s-1980s, enhanced economic activity in the catchment area of Lake Ladoga resulted in increased nutrients concentration (primarily P) in the lake's tributaries and consequently in the lake itself. The main sources of P enrichment were untreated waters from the aluminium smelter at the lower course of the River Volkhov, waste-waters from pulp and paper industry, sewages from the cattle-farming and surface run-off of artificial fertilizers excessively used in agricultural areas. Lake Ladoga's trophic state shifted from oligotrophic to mesotrophic, as reflected by changes in a series of physico-chemical and hydrobiological parameters. In recent decades, gradual improvement of the ecological situation has taken place facilitated by the economic depression of the early 1990s and the subsequent decline in anthropogenic pressure on the lake ecosystem. However, eutrophication still remains one of the most essential issues for Lake Ladoga (Rumyantsev and Kondratyev 2013).

Diatoms (Bacillariophyta) are one of the most important groups of indicative organisms widely used in assessing ecological conditions of fresh waters. These unicellular algae make up a considerable part of planktonic and benthic microalgal communities in temperate lakes (Davydova 1985; Dixit et al. 1992; Stoermer and Smol 2010). After the diatom cell's death, its siliceous walls settle down, accumulate on the lake bottom and may remain well-preserved in the sediments for hundreds of thousands years. Species-specific morphology enables identification of those sedimentary diatoms to species level, while fairly well-established ecological preferences of many diatom taxa make them useful indicators of past and recent limnological conditions (Cohen 2003; Smol 2010). Diatom assemblages from the surface sediments (0-1 cm) represent an integrated temporal and spatial sample of a lake diatom flora incorporating taxa from different habitats and including both dominating and auxiliary species that have accumulated in the recent 1-5 to 10 years depending on sedimentation rate. Therefore surface-sediment diatom assemblages smoothen and average seasonal changes in diatom species composition and effects of short-term or locally restricted impacts, providing more comprehensive characteristics of the diatom flora of a lake compared to the live algal communities (Davydova 1985; Bennion 1995; Smol 2008). Studying surface-sediment diatom assemblages has proven to be a time- and cost-effective approach in assessing ecological status of lakes all over the world (e.g. Lotter 1989, Yang and Dickman 1993; Smol and Stoermer 2010).

In Lake Ladoga, the surface-sediment diatom studies performed in the early 1960s, late 1970s, and early 1990s (Davydova 1968; Davydova et al. 1997; 1999) revealed that changes in the lake ecosystem resulted from human-induced eutrophication. In the early 2000s, slightly improved ecological conditions in the northern archipelago, one of the most polluted areas in Lake Ladoga, were inferred in response to reduced anthropogenic pressure (Ludikova 2017). The present study continues a series of observations of the environmental changes in Lake Ladoga recorded in the surface-sediment diatom assemblages. It aims to assess the current ecological status of the lake and compare it with the pre-anthropogenic (prior to 1960s) and eutrophication (late 1960s – early 1990s) periods. The study is also intended to demonstrate the value of surface-sediment diatom assemblages for tracking changes in water quality and lake ecological status.

MATERIALS AND METHODS

Study area and previous studies

Lake Ladoga (59°54´ to 61°47´N and 29°47´ to 32°58´E) is the second largest freshwater lake in Russia (water-surface area 17.765 km^2, average depth 48.3 m, maximum depth 230 m, water volume ~848 km^3). Its vast catchment area covering >258.600 km^2 extends through northwestern European Russia and the eastern part of Finland, including such large lakes as Onega, Ilmen and Saimaa. The rivers Svir, Volkhov and Vuoksa (Fig. 1b) draining these lakes are the main tributaries of Lake Ladoga that contribute 86% of the water inflow to the lake. Lake Ladoga drains to the Gulf of Finland via the River Neva. The period of water exchange in the lake is 11 years (Rumyantsev 2015).

Lake Ladoga is characterized with uneven bathymetry. The gently sloping shallow-water zone (to –20 m deep and up to 50 km-wide) extends along the southern shore. In the central basin, the depths gradually increase towards the north from –50 m to –100 m. In contrast to the smoother lake floor of the southern and central parts, the northern basin is characterized with contrasting topography formed by channels and ridge-like structures of various sizes, and greatest depths (>200 m) (Subetto et al. 1998). The very narrow littoral zone sharply transfers to steeply inclined slopes. The shoreline here is incised with a network of bays and coves with numerous islands forming the northern archipelago (Fig. 1b).

Thermal regime and related dynamics of the water masses are the main factors controlling the ecosystem processes in Lake Ladoga. Lake Ladoga is a dimictic lake and mixes from the surface to the bottom twice a year, in spring and autumn. From May until mid July, the thermal bar divides the lake water masses into a warmer shallow-water zone (>4°C) and a colder deep-water zone that includes the central and northern open-water parts of the lake. The nutrients arriving to the lake with the river inflow and spring runoff are concentrated in the shallow-water parts due to the lack of horizontal mixing, which favors spring phytoplankton development.

Planktonic diatom growth in Lake Ladoga can already start in early spring when the solar radiation is able to penetrate through the ice (Petrova 1968). However planktonic diatom blooms follow the ice-out that starts in the shallow-water parts of the lake, i.e. in the south and in the nearshore zone of the northern archipelago, in late April – early May. The low spring water temperatures and intense mixing favor the diatoms of the *Aulacoseira* genus, in particular, *A. islandica* that dominates in the spring phytoplankton (Petrova 1968). As the thermal bar collapses and thermal stratification is established, the summer biological season starts in Lake Ladoga, and *Aulacoseira* spp. are replaced by the planktonic diatom *Asterionella formosa*. In contrast to the spring biological season, when Ladoga phytoplankton is diatom-dominated, blue-green, green and cryptophytic algae are the main components of the planktonic communities in summer (Letanskaya and Protopopova 2012).

The pioneer surface-sediment diatom studies were performed in 1959-1960, and covered > 100 sampling sites all over the lake bottom (Davydova 1961, 1968). In 1978-1979, 19 sampling sites in the central and southern parts of Lake Ladoga were investigated. During the 1991-1994 field campaign, a total of 60 sited were sampled with the particular interest to the northern archipelago part (Davydova et al. 1997; 1999). All sampling campaigns took place during the open-water seasons. Up to 1 cm of the surface sediments were sampled using short gravity-type corers. The sampling sites of the different periods of surveys were quite dispersed and unevenly distributed, which induced distinguishing spatially representative sample sets for each period as summarized in (Davydova et al. 1999). Despite of the spatial heterogeneity of the sampling sites, short ordination gradients suggested fairly homogeneous composition of the diatom assemblages in the open-water part of the lake due to effective water mixing (Davydova et al. 1999, 2000).

Sampling and analytics

Surface sediments sampling was conducted in September 2001 at 9 regular monitoring sampling sites of the Institute of Limnology in the open-water part of Lake Ladoga, and in late October 2004 in the northern archipelago (7 sampling sites). In September 2016, 18 regular monitoring sampling sites (mainly in the open-water part) were sampled (Fig. 1b). Thus 9 sampling sites were visited during both 2001/2004 and 2016 sampling campaigns (Fig. 1b). The samples were collected with the Ekman-Berge sediment sampler. The retrieved sampler was fixed in vertical position, and the water above the sediment surface was allowed to drain. The uppermost ca. 0,2-0,5 cm of the sediments, depending on their composition (i.e. fine sands or silts) were carefully scraped from the sediment surface and used for diatom analysis.

The data from 2001 and 2004 were further treated as belonging to the same sampling period. The rationale for this merging was provided by the short time-span between the sampling campaigns and low sediment accumulation rates in Lake Ladoga (≤0,5 mm per year in average). The surface-sediment diatom assemblages of 2001 and 2004 are therefore believed to represent more or less the same state of Lake Ladoga ecosystem as compared to the previous and subsequent sampling periods (in early 1990s and 2016, respectively).

The laboratory treatment followed the standard procedure using 30% H_2O_2 to destroy organic matter (Davydova 1985). Diatom identification follows Krammer and Lange-Bertalot (1986-1991). Diatom data were expressed as % relative abundance. To estimate the contribution of individual diatom taxa to the diatom assemblages, they were classified as "dominating" (>10% of the diatom counts in a sample), "sub-dominating" (5-10%), "regular" (1-5%) and "rare" (<1%) species, according to Davydova (1985). Given the morphological variability of the planktonic diatom *Aulacoseira subarctica*, its "squat" form (i.e. short and wide, see Gibson et al. 2003) was counted separately from longer and narrower valves.

RESULTS AND DISCUSSION

In 2001/2004, planktonic diatoms dominated in 15 out of 16 surface-sediment diatom samples. Generally, their proportion was lower in the northern archipelago part (58-79%) compared to the other sites (75-94%). The most numerous and widespread planktonic species was *Aulacoseira islandica* (10,5–60%) that prevailed at 15 sampling sites (Fig. 2), often co-dominated by planktonic *Aulacoseira subarctica* (4,5–28%). The latter was generally less common in the archipelago sites. Its "squat" form often contributes to ca. ½ of *A. subarctica* totals. *Cyclostephanos dubius* and *Stephanodiscus minutulus*, typical of highly eutrophic waters were found among the regular and subdominating species at 15 sampling sites. *C. dubius* mainly occurred in diatom assemblages in the archipelago part, while *S. minutulus* was observed at the majority of the sampling sites except for the Volkhov Bay in the south. At some sampling sites in the northern

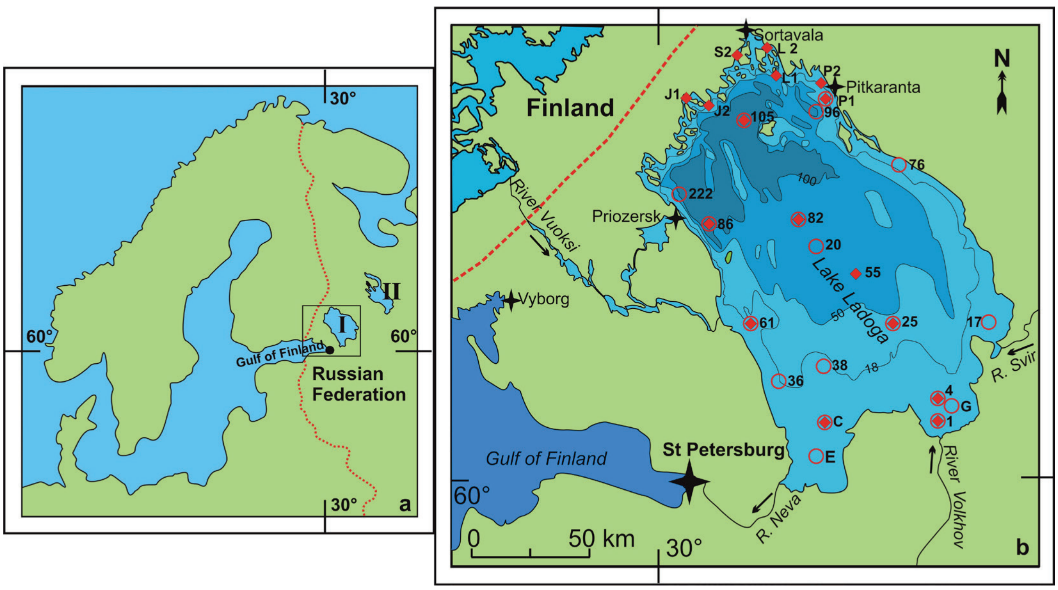

Fig. 1. Lake Ladoga location map (a) and Lake Ladoga bathymetry and location of sampling sites (b). I – Lake Ladoga, II – Lake Onega, diamonds – the sites sampled in 2001/2004, circles – the sites sampled in 2016; diamonds in circles – the sites visited during both sampling periods. 18-m contour shows the outer boundary of the littoral zone.

part of Lake Ladoga, including the archipelago, hypereutrophic *Stephanodiscus hantzschii* was also regular. Other *Stephanodiscus* taxa, mesotrophic or meso-eutrophic *Stephanodiscus medius* and *S neoastraea* reach the abundances of regular or sub-dominating species at 10 and 12 sampling sites, respectively, being less numerous in the archipelago part. Meso-eutrophic *Asterionella formosa* was observed at all sampling sites. Its higher proportions (3-8,5%) were typical of the northern part of Lake Ladoga. Higher abundances of eutrophic *Diatoma tenuis* (up to 10%) were also constrained to this area. Surface-sediment diatom assemblages of many sampling sites also included *Cyclotella radiosa* and *C. schumannii* among the regular and rare species, more common for the open-water part of the lake. Benthic taxa were more abundant in the northern archipelago part (21-59%) as well as at some shallower sites in the western and north-western parts of the lake and in the Volkhov Bay.

In the samples collected in 2016, planktonic diatoms dominated the diatom assemblages of 16 out of 18 sampling sites. Similar to the previous sampling period, *A. islandica* remained the most numerous and widespread taxon, and dominated at 16 sites (16-61%). *A. subarctica* was also observed in all sampling sites (Fig. 3). At 15 sites, it co-dominated and even overdominated *A. islandica*. The contribution of the short and wide morphotype of *A. subarctica* to *A. subarctica* totals is mainly <1/2. The comparison to the 2001/2004 dataset showed that out of the 9 sites sampled during 2001/2004 and 2016, in 4 sites, in the southern and western parts of the lake (Petrokrepost and Volkhov bays, and near the River Vuoksi mouth) the proportions of *A. subarctica* total and *A. subarctica* "squat" decreased.

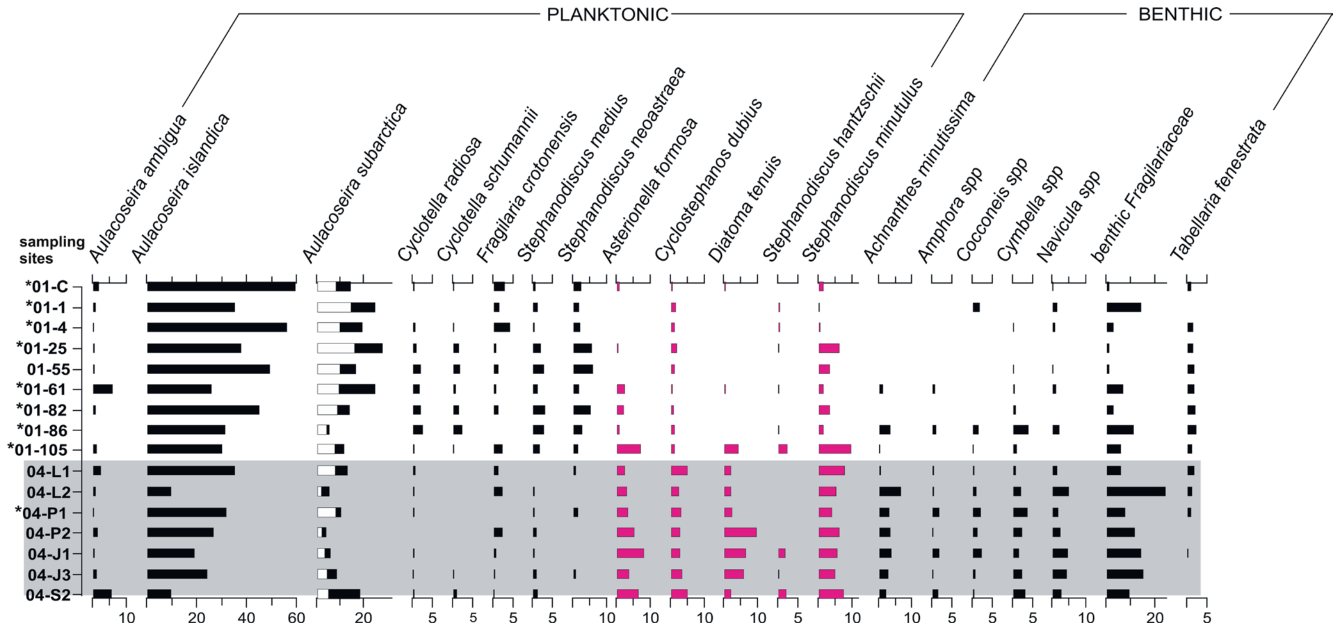

Fig. 2. Relative abundances (%) of the main diatom taxa in the surface-sediment diatom assemblages of 2001 and 2004 (y-axis – sampling sites: year-number). * – the sites sampled during both 2001/2004 and 2016 field campaigns. Shadowed area – the sites in the northern archipelago part. White bars in *Aulacoseira subarctica* – proportions of the "squat" morphotype previously identified as *A. distans* var. *alpigena* (see explanations in the text). Pink bars – species indicative for anthropogenic eutrophication of Lake Ladoga.

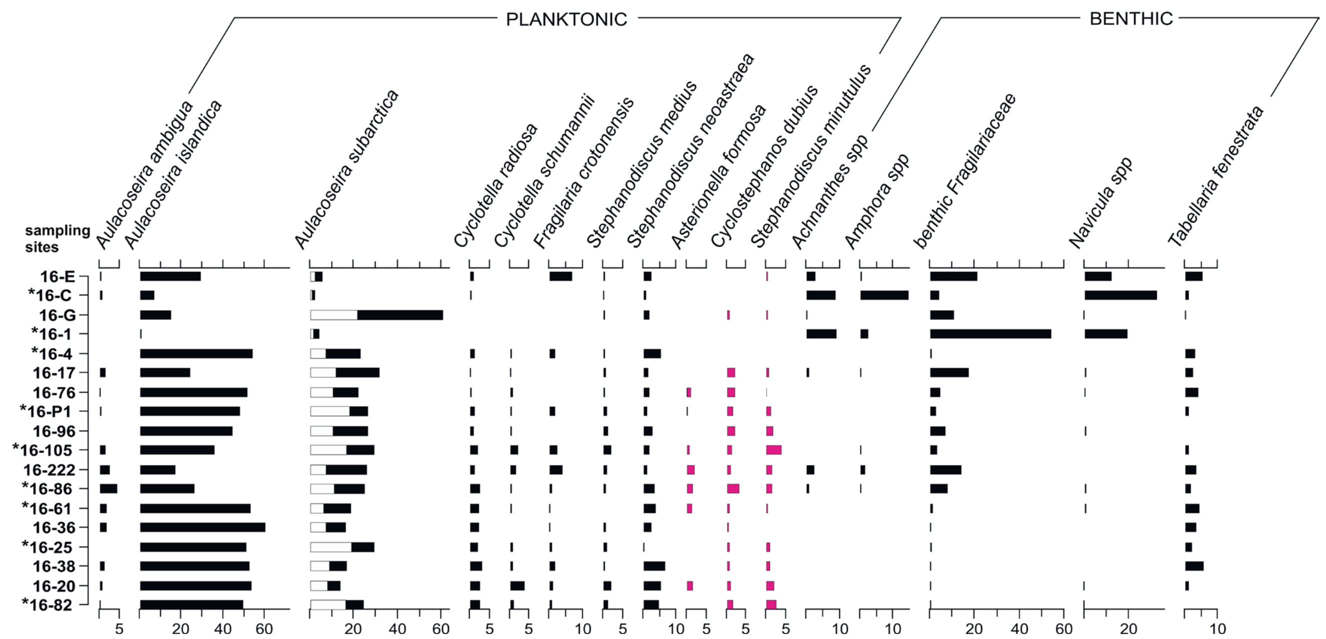

Fig. 3. Relative abundances (%) of the main diatom taxa in the surface-sediment diatom assemblages of 2016 (y-axis – sampling sites: year-number). * – the sites sampled during both 2001/2004 and 2016 field campaigns. White bars in *Aulacoseira subarctica* – proportions of the "squat" morphotype previously identified as *A. distans* var. *alpigena* (see explanations in the text). Pink bars – species indicative for anthropogenic eutrophication of Lake Ladoga.

The other 5 sites demonstrated increased abundances of both *A. subarctica* total and its "squat" form (Fig. 3). The proportions of eutrophic *C. dubius* and hypereutrophic *S. minutulus* slightly decreased compared to the 2001/2004 sampling period, and never exceeded 3,5-4%. Meso-eutrophic *A. formosa*, eutrophic *D. tenuis* and hypereutrophic *S. hantzschii* also decreased in abundance, and were only found among the rare species. Similarly to 2001/2004, other widespread planktonic taxa, included *S. medius* and *S. neoastraea* that were regular or, less commonly, subdominating species in all sampling sites, and *C. radiosa* and *C. schumannii* found at the majority of the sites among the regular and rare taxa. The highest proportions of benthic species were observed at the shallow-water sites in the southern part of the lake.

Comparing our findings with the results of the previous studies we can track the changes that occurred in the Lake Ladoga ecosystem starting from the late 1950s-early 1960s. Prior to this period, the lake was oligotrophic, and species typical of pure waters predominated among its algal population (Balakhontsev 1909). By the early 1960s human impact on its ecosystem remained negligible, as suggested by its hydrochemical and hydrobiological characteristics (Petrova 1968; Raspletina and Susareva 2002). Studies of the long-term diatom records (sediment cores) also indicate that pristine conditions existed in Lake Ladoga till recently. Dramatic eutrophication-related changes only occurred in the diatom assemblages in the topmost few centimeters of the sediments (Davydova et al. 1981; Davydova 1985), i.e. after the 1970s according to ^{210}Pb dates (Kukkonen and Simola 1997).

By the early 1960s, *Aulacoseira islandica* dominated in the diatom assemblages at all sampling sites (Fig. 4a), several times exceeding the abundances of other species (Davydova 1968). *A. islandica* was the most abundant species in the spring and autumn Lake Ladoga phytoplankton communities at this time (Petrova 1968). It has been dominating in Lake Ladoga sedimentary diatom assemblages starting from the Late Glacial when the Scandinavian Ice Sheet retreated from the Ladoga basin (Davydova 1985; Ludikova 2020). *Asterionella formosa* was another common species in the surface-sediment diatom assemblages during the sampling campaign of 1959-1960 (Fig. 4a). As fragile cell walls of *A. formosa* easily break and dissolve during the sedimentation, its abundances in the sedimentary diatom assemblages usually underestimate its contribution to the live communities (Davydova 1968). At the pre-anthropogenic stage *A. formosa* thrived in the late spring, and dominated in the summer phytoplankton of Lake Ladoga (Petrova 1968). At some sampling sites planktonic *Aulacoseira italica, A. (distans var.) alpigena*, some *Cyclotella* spp. and *Stephanodiscus* spp. were also abundant in the surface-sediment diatom samples (Davydova et al. 1997). Thus the predominance of taxa typical of large deepwater, oligotrophic lakes in the surface-sediment diatom assemblages in Lake Ladoga in the late 1950s (Davydova 1968) indicate that human impact on the lake ecosystem was negligible.

The oligotrophic state of Lake Ladoga inferred from the composition of the surface-diatom assemblages (Davydova et al. 1999) was also confirmed by hydrochemical and hydrobiological studies. By the early 1960s, the external P load to the lake was ca. 1,8 tons P year^{-1}. Mean annual inorganic phosphorus (IP) content was 3 μg l^{-1}, while mean total phosphorus (TP) concentration was 10 μg l^{-1} (Raspletina et al. 1967). Phosphorus deficiency and thermal regime of the large cold-water lake, in turn, limited the phytoplankton growth that was dominated by diatoms throughout the vegetative season (Petrova 1968).

The studies performed in 1978-1979 demonstrated significant changes in the composition of the surface-sediment diatom assemblages (Fig. 4b) as mesotrophic *A. italica*, meso-eutrophic *A. formosa* and eutrophic *Diatoma tenuis* became co-dominants of *A. islandica* (Davydova 1968). The growth of *D. tenuis* was previously constrained to the southern part of the lake where it developed in the summer phytoplankton (Petrova 1968). Mass development of the eutrophic co-dominant indicates a shift of the trophic status of Lake Ladoga from oligotrophic to mesotrophic as a result of increased P loading to the lake started in the mid 1960s (Davydova et al. 1997; 1999). Drastically increased proportions of *A. formosa, D. tenuis* and *A. italica* were similarly observed in sediments of the most polluted areas of the neighboring Lake Onega, the second largest lake in the European Russia, where the highest anthropogenic pressure was also recorded in the 1970-1980s (Davydova et al. 1993).

Hydrochemical studies in Lake Ladoga also recorded 4-5 times increase in the mean annual IP concentrations by 1976-1979 as a result of increased influx of phosphates with industrial waste waters and agricultural runoff. External P load rapidly increased and reached 6-7 tons P year^{-1}, nearing the estimated critical values for Lake Ladoga (Raspletina and Susareva 2002). In 1976-1980, mean TP concentration reached 26 μg l^{-1} (Raspletina 1982). Increasing P concentrations, in turn, stimulated phytoplankton development. At the early eutrophication stage, it resulted in the increased abundances of common phytoplankton species such as *A. islandica* in spring and *A. formosa* in summer. As eutrophication proceeded, the proportion of eutrophic diatom species in the phytoplankton communities, phytoplankton biomass and primary productivity increased as well (Petrova 1982).

By the early 1990s, *A. islandica*, *A. formosa* and *D. tenuis* remained the most abundant taxa in the surface-sediment diatom assemblages, while the proportion of *A. italica* decreased (Fig. 4c). At some sampling sites, mainly located in the northern archipelago part of Lake Ladoga, the proportion of *A. islandica* significantly decreased due to increased abundances of the taxa indicative of anthropogenic eutrophication. Apart from the above-mentioned *A. formosa* and *D. tenuis*, they included *Cyclostephanos dubius* and *Stephanodiscus hantzschii* characteristic of highly eutrophic waters (Davydova et al. 1994). This indicated higher trophic status of the archipelago part, and therefore higher anthropogenic pressure resulting from the industrial and municipal waste water discharge from the nearby plants and coastal settlements. The environmental situation was exacerbated by the remoteness of some of the most polluted sites and slow water exchange between the archipelago and the open-water part of Lake Ladoga (Davydova et al. 1994; 1999). Thus, the surface-sediment diatom assemblages of the early 1990s recorded the mesotrophic state of Lake Ladoga, with a more eutrophied archipelago part.

Due to various water protection activities (e.g. introduction of sewage treatment facilities, closing of some pulp and paper mills) of the 1980s and subsequent economic decline of the early 1990s, external P load to the lake decreased to 2,4-3,9 tons P year^{-1} in 1996-2003. However, hydrochemical observations demonstrated that despite the decreasing external P load, mean TP concentrations remained high by the early 1990s (ca. 20 μg l^{-1}) still indicating the mesotrophic state of the lake (Raspletina and Susareva 2002). Furthermore, the phytoplankton composition and biomass studies also showed that Lake Ladoga remained mesotrophic in the early 1990s, with the most eutrophied

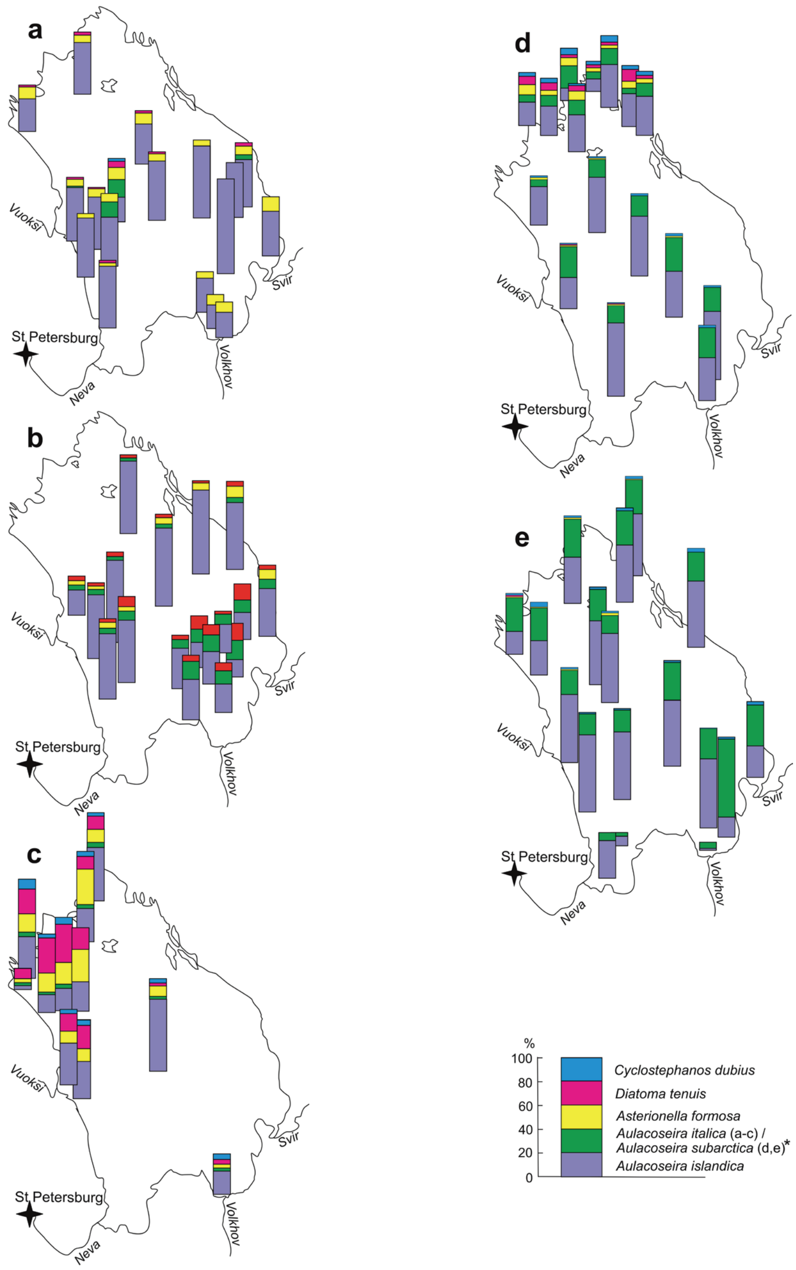

Fig. 4. Proportions of the main diatom species in the surface-sediment diatom assemblages in 1959-1960 (a), 1978-1979 (b), 1994 (c), 2001 and 2004 (d), and 2016 (e). (a-c according to Davydova et al. (1999), d and e – this study; * – see explanations in the text)

areas in the archipelago part and the mouths of the large rivers (Holopainen and Letanskaya 1999).

By the early 2000s, however, the predominance of *A. islandica* typical of the pre-anthropogenic stage, re-established in the surface-sediment diatom assemblages both in the open-water part of Lake Ladoga and in most archipelago sites, as demonstrated by the current study. *A. subarctica* appeared as a co-dominant of *A. islandica* at most of the sampling sites (Fig. 4d). The decline in *A. formosa* and *D. tenuis* that dominated in the surface-sediment diatom assemblages during the eutrophication stage, as well as highly eutrophic *C. dubius*, *S. hantzschii* and *S. minutulus*, indicates an improvement of the ecological state of Lake Ladoga as a result of decreasing anthropogenic pressure, started in the early 1990s. However, the eutrophic species still remained more abundant in the archipelago part, suggesting that the self-purification process in this part of the lake was delayed due to the slow water exchange with the open-water part of Lake Ladoga.

At present, the composition of the dominating species remains similar to the early 2000s, however, in a number of sites sampled in 2016 the abundance of *A. subarctica* is higher than in 2001/2004 (Fig. 4d and 4e). Further decrease in *A. formosa* and *D. tenuis* and the other species indicative of anthropogenic eutrophication (*C. dubius, S. hantzschii, S. minutulus*) reveals the continuous lowering of the lake trophic state. The diatom-inferred de-eutrophication of Lake Ladoga is supported by the hydrochemical studies. They demonstrate that TP concentrations in 2009-2018 were around 11-13 μg l^{-1} while IP content in 2013-2018 did not exceed 3 μg l^{-1} (Petrova 2019), both nearing their pre-anthropogenic levels. Since 2006 the amounts of P from external sources ranges from 2,5 to 3 tons P $year^{-1}$ (Rumyantsev and Kondratyev 2013).

However, comparison of the composition of the dominating species in the present-day diatom assemblages with those of the pre-anthropogenic stage reveals some important discrepancies. In particular, in the late 1950s – early 1960s, *Aulacoseira islandica* was the only dominating species in the surface-sediment diatom assemblages (Fig. 4a), while in most of the samples collected in the 2000s it is co-dominated by *A. subarctica* (Fig. 4d, 4e). *A. islandica* is the most abundant taxon in the sedimentary diatom assemblages of Lake Ladoga throughout the Holocene (Davydova 1985; Ludikova 2020). Besides Lake Ladoga, high abundances of *A. islandica* were also reported both in naturally productive small lakes (Räsänen et al. 2006) and in large turbulent freshwater basins, e.g. Lake Onega, Baikal, Laurentian Great Lakes, large Swedish lakes, etc. (Willén 1990 and references therein). There it similarly co-occurs with its congener, *Aulacoseira subarctica* (Stoermer et al. 1985; Barbiero and Tuchman 2001; Popovskaya et al. 2002; Willén 2002; Ludikova et al. 2020) as their massive growth is favored by seasonal mixing.

The lack of mentioning of *A. subarctica* in the earlier Lake Ladoga datasets (Davydova 1968, Davydova et al. 1997, 1999) is explained by the fact that various morphotypes of *A. subarctica* were previously misidentified as three different taxa, namely *Aulacoseira italica, A. italica* ssp. *subarctica* and *A. (distans* var.) *alpigena* (Genkal 1996). Of these, "*A. italica*" and "*A. italica* ssp. *subarctica"* have more or less elongated valves, while the valves of "*A. alpigena*" are short ("squat") and characterized with low height to diameter ratio. Presently the "squat" form is considered as part of the continuum (Gibson et al. 2003), and the length/width ratio is thought to change with environmental conditions (Tuji and Houki 2004), although the role of particular factors in controlling the morphology of *A. subarctica* remains unclear.

Recent studies of the Holocene Lake Ladoga sediments confirmed this erroneous splitting of *A. subarctica*. They revealed only single finds of *A. alpigena* and no *A. italica* throughout the study period, while *A. subarctica*, in turn, was regularly observed in significant amounts starting from the second half of the Holocene (Kostrova et al. 2019; Ludikova 2018, 2020; Sapelko et al. 2019). Therefore *A. subarctica* significantly contributed to the microalgal communities in Lake Ladoga already in the oligotrophic period, and even long before any human impact on the lake's ecosystem became appreciable. Moreover, between ca. 4000-3500 and 1800 yrs BP, it co-dominated *A. islandica* similarly to present. Both "short and wide" and "longer and narrower" forms were concurrently found during this period, although the "squat" morphotype constantly prevailed (A. Ludikova, unpublished).

By the early 1960s, *Aulacoseira subarctica* "complex" (former *A. italica, A. italica* ssp. *subarctica* and *A. (distans* var.) *alpigena*) was regularly registered in the phytoplankton communities in the late spring biological season (Petrova 1968). All these taxa were also frequently observed in the surface-sediment diatom assemblages in the late 1950s (Davydova 1968). However, a different technique of estimating the species abundances applied in the 1960s complicates a comparison of *A. subarctica* contribution to the surface-sediment diatom assemblages of the pre-anthropogenic stage and at present.

According to Lund (1954), *Aulacoseira subarctica* commonly occurs in moderately oligotrophic to moderately eutrophic lakes in temperate and subarctic regions. In strongly eutrophic conditions, however, *Aulacoseira subarctica* can be replaced by *A. islandica* (Lund 1954, Canter and Haworth 1991; Gibson et al. 2003). *A. islandica*, in turn, is suggested to tolerate wider range of trophic conditions (van Dam et al. 1994). The studies of small lakes in NW Russia and Central Europe revealed its mass development at the early stage of cultural eutrophication (Trifonova 1990; Bennion et al., 1995). However, as eutrophication proceeds its abundances also decline (Stoermer et al., 1981; Trifonova, Genkal, 2001) to eventual displacement by planktonic pennate and / or small centric diatoms (Pienitz et al. 2006; Räsänen et al. 2006). This was also observed in Lake Ladoga, where relative decrease in *Aulacoseira* taxa and simultaneous increase in the pennate *Asterionella formosa, Diatoma tenuis*, and small-sized *Cyclostephanos dubius* and *Stephanodiscus hantzschi*i were recorded with increased trophic state.

Another specific feature of the present surface-sediment diatom assemblages is underrepresentation of planktonic *A. formosa* as compared to the earlier datasets (Davydova 1968; Davydova et al, 1997, 1999). Although the species is known as indicative of moderate nutrient enrichment, it can be also abundant in rather nutrient-poor lakes (Sivarajah and references therein). In large and deep stratified temperate lakes it is typically found in late-spring and summer epilimnetic phytoplankton (Petrova 1990; Willén 2002; Chekryzheva 2015). In Lake Ladoga, *A. formosa* was a common species in the surface-sediment diatom assemblages at the oligotrophic stage (Davydova 1968) alongside with *Aulacoseira* spp. However, the phytoplankton surveys demonstrated that during the vegetative season these taxa occupied different "temporal niches" (Petrova 1990). For instance, *Aulacoseira islandica* in Lake Ladoga already starts blooming under the ice, as was also recorded elsewhere (Stoermer et al. 1981; Bradbury et al. 2004; Nõges 2004), and continues after the ice-out, when there are no other successful competitors in the early spring phytoplankton. As the mixing proceeds and water temperature rises, it is supplemented by *A. subarctica* "complex" that massively develops in late spring, accompanied by *Asterionella formosa* (Petrova 1968, 1990). By the onset of the biological summer season, around mid July, *Aulacoseira* cells submerge to the hypolimnion, while the abundance of *A. formosa* increases. During the oligotrophic stage of Lake Ladoga *A. formosa* dominated in the summer diatom plankton as thermal stratification established (Petrova 1968).

Taken these considerations, the variations in proportions of the main species in the surface-sediment diatom assemblages with progressing eutrophication can be explained as follows. As P concentration in Lake Ladoga steadily increased during the late 1960s – early 1980s, *Aulacoseira islandica* still remained abundant due to its early blooming (Fig. 4a, 4b). Proliferation of *Asterionella formosa* and *Diatoma tenuis* at the expense of *Aulacoseira* taxa is often recorded in eutrophying lakes (Stoermer et al. 1985; Willén 1987; Liukkonen et al. 1993; Hobæk et ak. 2012). However, in Lake Ladoga lower frequencies of *A. islandica* observed in the early 1990s dataset (Davydova et al. 1999) might not indicate its decreased contribution to the microalgal communities but rather results from a relative increase in *A. formosa* and *D. tenuis* (Fig. 4c), accompanied by *Cyclostephanos dubius*, the latter two taxa having been rather uncommon at the oligotrophic stage. Both *A. formosa* and *D. tenuis* used to start growing in Lake Ladoga by the end of the biological spring. However, as eutrophication proceeded, their bloom shifted to the late spring due to intense competition for nutrients with summer-blooming blue-greens (Petrova 1990). Since *A. formosa* and *D. tenuis* are known to outcompete *Aulacoseira* taxa under high TP conditions (Petrova 1990; Reavie at al. 2002) they should have largely displaced the late-spring *A. subarctica* "complex" as reflected by decreased contribution of *A. subarctica* pro parte (*A. italica* and *A. italica* spp *subarctica*) both to the phytoplankton communities (Petrova 1986, 1990) and surface-sediment diatom assemblages (Davydova, 1968; Fig. 4c). It is remarkable, though, that the long-term phytoplankton studies also revealed the opposite trend in abundances of the "squat" form of *A. subarctica*, previously misidentified as *A.* (*distans* var.) *alpigena* that drastically increased in the 1970s-1980s (Petrova 1986). Thus, in Lake Ladoga this morphotype might have benefited from increasing trophic level, although all forms of *A. subarctica* were previously shown to have essentially the same TP optimum (Gibson et al. 2003 and references therein). Besides, this might suggest the competitive advantages of the "squat" morphotype over "longer and narrower" ones, i.e. former *A. italica* and *A. italica* ssp *subarctica* under increased TP levels. Another possible explanation could be in slightly different timing of their blooms, suggesting that the "short" form might start growing earlier when the resources competition is less tense. All these tentative suggestions, however, demand further comprehensive phytoplankton studies to be confirmed.

At the present de-eutrophication stage, the return to the *Aulacoseira*-dominated diatom assemblages is recorded in Lake Ladoga, similar to the other lakes where biological recovery from eutrophication took place (Gibson et al. 2003; Bennion et al. 2012; Fielding et al. 2020). Increased abundances of *A. subarctica* in the surface-sediment diatom assemblages of the 2000s (Fig. 4d, 4e) could result from lowered TP concentrations in the Ladoga waters, which might favored its mass development in the late spring, similar to the oligotrophic stage. The hydrobiological surveys performed in 2005-2009 reported, apart from *Aulacoseira islandica*, high biomass of "*A. italica*", "*A. distans*", and "*A. subarctica*", i.e. the taxa belonging to *A. subarctica* "complex", in spring and autumn phytoplankton (Letanskaya and Protopopova 2012).

Almost complete lacking of eutrophic *Diatoma tenuis* in the recent diatom assemblages is in agreement with decreased TP content in Lake Ladoga, as it was also observed elsewhere in course of de-eutrophication (Willén 1987; Hobæk et al. 2012). One would also expect that *Asterionella formosa*, a common species in Lake Ladoga both in oligotrophic and eutrophication stages, could remain abundant after lowering of P concentrations. However, the present study has documented a decline in its proportions (Fig. 4d, 4e). It is therefore suggested that despite the steady trend towards oligotrophication, the present state of the Lake Ladoga ecosystem is not determined solely by nutrients content, but rather by a complex interplay of various environmental factors that are somewhat different from the pre-anthropogenic stage. Apart from oligotrophication, among the reasons for species replacements and displacements, changing contributions of different functional groups, shifting nutrient requirements, and grazing pressure are often reported (Dokulil and Teubner, 2005). In Lake Ladoga, decreased abundances of *A. formosa* apparently reflect restructuring of the seasonal phytoplankton communities related to eutrophication and subsequent de-eutrophication of Lake Ladoga. With decreasing TP, the late spring blooms of *A. formosa* might be somehow constrained by competition with typical spring *Aulacoseira* species (*A. islandica* and proliferating *A. subarctica*). In summer, in turn, *A. formosa* is mainly replaced by other groups of algae with higher competitive abilities for P, and therefore does not reach its pre-anthropogenic abundances. This corresponds to the total decline of diatoms in the summer phytoplankton assemblages as the contribution of blue-greens and cryptophytic algae increased during de-eutrophication of Lake Ladoga (Holopainen and Letanskaya 1999; Letanskaya and Protopopova 2012). This differentiates the present state of the lake's ecosystem from the pre-anthropogenic period when diatoms dominated in the phytoplankton throughout the vegetative season (Petrova 1968).

However, de-eutrophication process may be not the only factor to determine the present state of the Lake Ladoga ecosystem, as the pathways and success of lake restoration efforts may be also influenced by climate change (Battarbee et al. 2005). In particular, the rise of air temperatures during the last 30 years has affected the ice regime of lakes (Leppäranta 2015), and a great number of studies documented that ice-cover periods have shortened remarkably across the Northern Hemisphere, and the durations of the ice-free and stratified seasons changed accordingly (Gerten and Adrian 2002 and references therein). A growing body of evidences demonstrates the recent climate-driven changes of lake physical and biogeochemical processes, aquatic communities composition and food-web structures (Adrian et al. 2009 and references therein). In particular, the timing of the spring overturn and the onset of stratification strongly affect phytoplankton development. For instance, heavily silicified *Aulacoseira* taxa forming long filamentous colonies require more turbulence to remain suspended in the photic zone (Lund 1954; Wilson et al. 1993), and are therefore widely acknowledged to benefit from long-lasting spring circulation (Kilham et al. 1996; Weyhenmeyer et al. 2008). Often reported as an abundant spring diatom, *Asterionella formosa*, in turn, can also proliferates under prolonged summer stratification due to its ability to form star-shaped colonies to sustain in the epilimnion and utilize available nutrients near the thermocline (Ruhland et al., 2015; Sivarajah et al. 2016). Besides, the displacement of larger and heavier *Aulacoseira* taxa by small-celled *Cyclotella* sensu lato, e.g. *Cyclotella comensis, Discostella pseudostelligera, D. stelligera*, etc.) has been also reported lately as a Hemispheric phenomenon recorded in a number of temperate, subarctic, circumpolar and mountain lakes (Rühland et al. 2015 and references therein; Reavie et al. 2017). Their high light-harvesting and prolific reproduction abilities altogether with lower sinking velocities, make these taxa successful competitors during the prolonged stratification periods (Rühland et al. 2015). Generally, climate changes are reported to have both positive and negative impacts on lake ecosystems, they do not therefore necessary hinder restoration efforts (Carvalho et al. 2012).

In Lake Ladoga, mild winters during the recent ca. 30 years corresponded to less severe ice conditions and frequency of ice occurrence (Karetnikov et al. 2017; Naumenko and Karetnikov 2017). Consequently the spring ice-out and the onset of summer stratification shifted to earlier dates (Naumenko 2021). It could be also hypothesized that the spring mixing period extends accordingly, although it is not clear by far whether the water stability period has also prolonged (M. Naumenko, personal communication). However, the present study of the surface-sediment diatom assemblages has not revealed shifts in their composition in response to the climate-driven changes, similar to those described in many other Northern Hemispheric lakes (Rühland et al. 2015; Sivarajah et al. 2016). Unlike the recent reports (Hadly et al. 2013; Berthon et al. 2014; Sivarajah et al. 2016), the abundances of *A. formosa* steadily decrease in Lake Ladoga during the 2000s possibly reflecting its poorer competitive abilities for resources both in spring and in summer under present conditions. Since *A. formosa* benefits from short circulation periods after long winters (Horn et al. 2011), its recent decline might evidence for changes in the thermal regime of Lake Ladoga, which is consistent with changes in lake ice conditions (Karetnikov et al. 2017). An appearance and proliferation of small *Cyclotella* species is neither a feature of the present state of the Ladoga ecosystem, in contrast to the other observations (Rühland et al. 2015). On the contrary, larger-sized summer-growing species, such as *Cyclotella radiosa* and *C. schumannii*, together with *Stephanodiscus medius* and *S. neoastraea*, are among the regular components of the present surface-sediment diatom assemblages, similar to the oligotrophic stage.

In spring, in turn, earlier ice-out and prolonged circulation period might be inferred from the increasing abundances of a spring diatom *Aulacoseira subarctica* recorded in the 2000s. Given that *A. subarctica* can tolerate relatively low-light conditions and is favored by turbulence, its recent massive growth could be also tentatively assigned, apart from de-eutrophication, to longer mixing periods after short and mild winters, as it has been suggested by recent findings (Horn et al. 2011; Sochuliaková et al. 2018). It can be thereby hypothesized that the above-mentioned co-dominating position of *A. subarctica* in the late Holocene Lake Ladoga sediment records, long before the start of the human impact on the ecosystem, might also reflect climate-related changes in the lake's thermal regime and circulation.

The composition of the present-day surface-sediment diatom assemblages therefore indicates that the Lake Ladoga ecosystem has not completely returned to its pre-anthropogenic state. Although there is a great number of evidences that eutrophication can be managed by reduced P inputs (Schindler et al. 2016 and references therein), a number of studies also report that lake recovery is not simply a process reverse to the degradation (Bennion et al. 2015). Internal nutrients loading, changes in food-web structures and climate changes are among the most common reasons why lake ecosystems response does not adequately track the improvement in water quality, or why ecosystems recovery is delayed (Battarbee et al. 2005 and references therein; Dokulil and Teubner 2005 and references therein; Bennion et al. 2015). Even though the chemical variables may return to their pre-disturbance levels, many lake systems demonstrate complex biological responses, often developing the communities that bear little resemblance to pre-disturbance assemblages (Rühland et al. 2015 and references therein). Therefore achieving reference state of a lake not only depend on the reduction of anthropogenic pressure but also on whether the reference conditions remained a relevant target. For instance, the climate impact in future can potentially modify the lake ecosystem characteristics to a point where the desired reference state is no longer realistic (Battarbee et al. 2005, Bennion et al. 2011).

In Lake Ladoga, one might not only think of somewhat delayed ecosystem response to the decreased anthropogenic pressure, but also of some irreversible changes resulting from eutrophication. Besides, the processes of de-eutrophication and ecosystem recovery are apparently superimposed upon the recent climatic changes that govern the lake's thermal regime and consequently, onset and duration of blooms of phytoplankton taxa in Lake Ladoga. Results of the recent studies of main biological communities of Lake Ladoga (Kurashov et al. 2018) also revealed a series of specific features that clearly indicate a completely new stage in the ecosystem development.

Extending the surface-sediment diatom studies from the late 1950s to present demonstrated that changes in the diatom assemblages composition adequately track the hydrochemical and hydrobiological shifts in Lake Ladoga related to anthropogenic pressure and, lately, to climate changes. The use of surface-sediment diatom assemblages in environmental research has long been proven efficient, and the present study reaffirmed its relevance in monitoring the ecosystem changes in Lake Ladoga. This approach also has certain advantages over the surveying of benthic and planktonic communities. Large sizes of Lake Ladoga provide a large variety of shallow-water habitats in terms of bottom substrate characteristics, macrophyte abundances and composition, wave energy, etc. Therefore benthic communities in Lake Ladoga rather represent local conditions, and do not appropriately reflect the state of the whole basin. The composition of the planktonic diatom communities in Lake Ladoga, in turn, is highly dependent on biological seasons, while intra-seasonal species successions occur as well. Local factors, such as depth, intensity of seasonal circulation, inflow of river waters with different chemical composition (e.g. the River Volkhov), etc. also affect the composition of the planktonic diatoms. Besides, some inter-annual variations may also take place as a result of interplay of temperature, precipitation, lake level fluctuations, etc. Thus sporadic phytoplankton surveys would only catch "snapshots" of specific conditions that may not represent the whole picture. Regular intra- and inter-seasonal phytoplankton studies are therefore required, which recently become increasingly expensive. The studies of the surface-sediment diatom assemblages are well supplemented by phytoplankton surveys, however, they can be also performed alone if regular phytoplankton data are unavailable. Due to low sediment accumulation rate in Lake Ladoga (≤0,5 mm per year in average), repeated surface-sediment diatom sampling can be conducted every 10 years (see also Davydova et al. 2000). Therefore studying surface-sediment diatom assemblages is suggested as an independent time- and cost-effective approach in assessing the ecological state of Lake Ladoga.

CONCLUSIONS

Studies of the surface-sediment diatom assemblages enabled enabled the changes that have occurred in Lake Ladoga ecosystem, starting from the late 1950s as a result of human impact and recent climate changes.

At the pre-anthropogenic stage (until the early 1960s), the predominance of the cold-water oligotrophic taxa in the surface-sediment diatom assemblages indicated the oligotrophic state of Lake Ladoga. As the P load to the lake progressively increased (late 1960s–1980s), increased proportions of eutrophic species and decreased abundances of the taxa typical of the oligotrophic period recorded the transition to a mesotrophic state. In the early 1990s, the species indicative of eutrophication were still abundant in the surface-sediment diatom assemblages suggesting that the lake remained mesotrophic.

At the present de-eutrophication stage of Lake Ladoga (the 2000s), some taxa typical of the pre-anthropogenic period return to their dominating position in the diatom assemblages while the abundances of eutrophic taxa steadily decrease. Declining proportions of the diatom species that previously dominated in the summer Lake Ladoga phytoplankton reflect the restructuring of the live algal communities at a higher taxonomic level, as a consequence of de-eutrophication. Even though P concentrations decreased nearly to their pre-anthropogenic values, the present-day composition of the surface-sediment diatom assemblages indicates that the Ladoga ecosystem has not yet returned to its pre-anthropogenic state. This suggests a delayed ecosystem response to the decreased anthropogenic pressure, and possibly some irreversible changes resulting from eutrophication. The de-eutrophication process as well as recent climate changes are thought to determine the present state of the lake's ecosystem.

The diatom-inferred changes in the ecological state of Lake Ladoga are in agreement with the results of hydrochemical and hydrobiological studies throughout the study period. Therefore studying surface-sediment diatom assemblages can be applied as an independent time- and cost-effective approach in assessing the ecological state of Lake Ladoga.

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