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RESEARCH PAPER

PLANNING STRUCTURE AS A ROAD TRAFFIC POLLUTION DIFFERENTIATION FACTOR: A CASE STUDY OF NUR-SULTAN

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ABSTRACT. The article deals with the problem of spatial differentiation of road transport pollution due to the planning structure changes in the new capital of Kazakhstan. The purpose of the work is to study territorial differences in from vehicles Nur-Sultan from vehicles and to identify the role of embodied planning measures among the main factors of its differentiation. The research methodology included the analysis of 1) the city functions and planning structure transformation as well as the buildings and road network density and concentration; 2) traffic speed and intensity, emissions and their distribution areas for each street.

The analysis showed that since 1997, when Nur-Sultan received the capital status, it has grown 3 times in the area, 3.5 times in population, and 6 times in the level of motorization. However, the volume of traffic emissions in the city increased only 2 times, largely due to the development of the planning structure and configuration of the road network. The development of a second center in the new part of the city along with the decrease in the barrier function of the river and transport transit because of the faster construction of transport infrastructure led to an increase in the density of the road network by more than 2 times while reducing the density of emissions in the city center by 2.25 times. For the rest of the territory, despite different growth rates in the road network density, the density of emissions steadily decreases from the center to the periphery. However, several locations with a high level of pollution are still present in the middle part, while on the outskirts of the city there are blocks of estate-type houses with low-quality roads, which hinder the development of public transport.

KEYWORDS: Urban ecology, road traffic pollution, planning structure, transport network, residential framework, Nur-Sultan

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INTRODUCTION

In the context of globalization, typical market economy processes are taking place in post-Soviet cities. These processes have a significant impact on the transformation of the socio-economic and urban planning conditions for the development of the capital cities in CIS countries (Zubarevich 2017). International brands and standards are being rapidly introduced in the service sector as well as in the design and construction of housing and urban infrastructure facilities. Increasing globalization pushes back the historically established cultural traditions and leads to the unification of the spatial structure of the largest capital cities.

In recent decades, road transport has become the main source of air pollution in cities. For post-Soviet cities, this is complicated by explosive growth in motorization level due to the development of the market economy. However, their architectural and planning structure along with the road network was formed before the car boom and are not able to contend with the sharply increased load, which leads to an increase in emissions of highly toxic pollutants into the atmosphere.

In the research devoted to the impact of road transport, pollution issues are considered from different perspectives (environmental, economic and social). Most studies are based on monitoring data, primarily PM10 and NOx concentration analysis (Deak et al. 2020; Colvile et al. 2004; Kerimray et al. 2020). The volume of emissions is calculated using various impact assessment methods based on traffic intensity, fuel consumption, etc. (Dzhailaubekov 2010; Parsaev et al. 2018; Burón et al. 2004). Several studies are also devoted to the influence of environmental and climatic conditions on emissions (Deak et al. 2020), the impact of pollution on public health (Mueller et al. 2020; Revich 2018), soils (Kosheleva et al. 2018), environmental and social equality (Mitchell 2005), property values (Bityukova et al. 2006).

Another important aspect of research is modeling. The simplest models assess the impact of a single factor and include, for example, model of atmospheric pollutants dispersion under variable wind conditions, Information and forecasting system for private and public transport (VISUM), Transport Emission Model for Line Sources (TREM), Variable Dispersion (VADIS) and others (Borrego et al. 2004; Jacyna et al. 2017; Rafael et al. 2018). For a more comprehensive analysis that considers the influence of several factors, either combination of such models or simulation models are used (Zachariadis 2005).

Several studies analyzed various methods for optimizing the transportation system and the city in general, including traffic regulation (Zhou et al. 2021). In developed urban environments, where a physical change of transport routes is challenging, considerable attention is paid to the redistribution of transport between the existing streets (Wang and Sun 2019).

Many researchers note the necessity to develop public transport (Santos et al. 2010; Chavez-Baeza and Sheinbaum-Pardo 2014) or even return to the Soviet urban planning practice, in which public transport was prioritized (Blinkin and Koncheva 2016). The example of European countries shows the effectiveness of more stringent government regulations for cars and fuel (Burón et al. 2004). Much attention is also paid to indirect (educational, advertising) measures that help the population to make decisions regarding transport (Santos et al. 2010).

Besides the transport system itself, the level and impact of pollution are also affected by the urban environment. For example, traffic can be significantly reduced by providing comfortable conditions to travel on foot or using alternative modes of transport (Chien and Hu 2020; Mueller et al. 2020, Weiss et al. 2015). Greening, which absorbs noise and contributes to the conversion of greenhouse gases to oxygen, also reduces the impact of transport emissions (Morillas et al. 2018; Mueller et al. 2020; Rafael et al. 2018).

Despite a large amount of research in this field, urban planning structure is rarely considered as a separate factor affecting pollution. The analysis of this extremely inertial system, which forms over a long time and is a product of the city's development and previously adopted planning decisions, usually boils down to identifying differences at the micro-level (Bityukova and Mozgunov 2019).

Nur-Sultan[1], the new capital of Kazakhstan, is a rare exception. Over the years since it received the capital status in 1997, the city has not only tripled its area but also radically changed the planning structure. The traffic emissions increased only 2.1 times with almost 6-fold growth in motorization. This is a consequence of the vehicle fleet renewal, improvement of fuel quality, expansion of the road network, increased connectivity, reduction of barriers, and other planning factors that provide the optimal speed of cars.

The observed changes make it relevant to consider the impact of the renewed planning structure on traffic pollution. However, such studies of traffic pollution, which were already conducted for the previous capital city of Almaty (Kerimray et al. 2020), have not been carried out in Nur-Sultan yet. This work, which analyzes the influence of urban planning structure on air pollution from vehicle emissions, is aimed to fill this gap.

MATERIALS AND METHODS

At the first stage, analysis of the Nur-Sultan urban planning structure transformation since 1997 was carried out based on the study of master plans, cartographic data and field research. Field surveys were conducted from 2007 to 2019 in about 50 key districts with different location, specializations, types of development and time of incorporation into the city. Using their example, the changes in the composition and placement of individual functional zones and the transformation of the planning structure of Nur-Sultan were analyzed.

At the second stage, a large-scale assessment of the *density and concentration of buildings and roads* as factors of traffic emissions was carried out. *Built-up and road network density* are traditionally used in urban planning studies to characterize the share of built-up areas and roads within a certain area. Estimates show that there is a 30% reduction in traffic emissions when vehicles are moving without congestion (Bityukova et al. 2011). The increase in building density creates conditions for a change in the urban transport system organization and the development of intermodal transport systems with an emphasis on public transport (Rodrigue 2017).

A distinctive feature of Nur-Sultan, as well as other cities of Kazakhstan, is the high proportion of blocks with individual housing. To reflect the specifics of these areas in the study, the *concentration of buildings and roads* was calculated, which, unlike the first two indicators, shows the total number of buildings and road sections in a certain area. Highly concentrated blocks with individual housing have a low density of road network with high-quality pavement, which reduces the average speed of traffic and affects the increase in emissions from vehicles. Unlike density, which takes into account the length and width of road sections, concentration shows the number of road sections within an area and allows to estimate the number of road crossings. This indicator is taken into account when calculating the volume of emissions into the atmosphere in a certain area (Bityukova, Mozgunov 2019).

The calculation of these indicators was carried out using an automatic QGIS tool based on a vector grid with regular cells of the same area (1 km^2). Square cells of a small area were used for the most optimal assessment of indicators in a city with a predominant regular planning structure. The vector grid, dividing the space into equal sections, contributes to a uniform assessment of unevenly distributed buildings and road traffic systems.

To assess the *spatial structure of traffic pollution*, a technique developed and tested for cities in Russia was used[2]. It includes 5 steps:

[1]Until 1961, the city was called Akmolinsk, then Tselinograd, in 1992 it was renamed Akmola, in 1998 – Astana, and in 2019 – Nur-Sultan.

[2]In particular, this technique is considered in detail in the example of Moscow (Bityukova and Mozgunov 2019).

1. Division of the city's transport network into sections within which traffic intensity does not change and determining their length (in total, 54 thousand sections were allocated in Nur-Sultan).

2. Assessment of traffic intensity in selected sections using operational monitoring by the road congestion services, based on data from Yandex and Google maps and the OSM API service (to determine the number of lanes for traffic in a considered section).

3. Calculation of traffic emissions volume at every section based on the information on Vehicle Kilometers Travelled (VKT) and Emission Factors for Road Transport[1].

4. Calculation of impact areas (with concentrations exceeding a threshold) for each section of the road network according to the methodology approved by the Ministry of Natural Resources of the Russian Federation based on speed, volume, and height of the gas-air mixture emissions.

5. Calculation of emissions density as the ratio of emissions volume in the allocated territory to the area of contamination.

RESULTS AND DISCUSSION

Transformation of functions and planning structure

The decision to move the capital, taken in December 1997, became a key factor for the development of Nur-Sultan, stimulating rapid growth of its socio-economic potential, territory expansion and formation of the planning structure (Fig. 1). The transport network (more precisely, the inability to reconstruct it to meet the new requirements of the capital city) has become one of the leading factors that changed the vector of the city's planning structure development since it quickly became clear that the construction of government buildings and elite housing in the old city center would lead to a transport collapse. In 1998, a group of architects led by Kise Kurokawa began developing a master plan, which was presented to the government in August 2001 (Abilov et al. 2017).

Due to the absence of significant natural and artificial barriers (rivers, railways, airports, etc.), the planning framework of the rapidly growing city developed in different directions at approximately the same pace, only limited by natural and economic development constraints. According to the general plan, the transformation of the city's planning structure was supposed to include:

- a creation of a new administrative center on the left bank of the Esil River;
- preservation of the administrative functions in the old center on the right bank;
- a transformation of the residential framework, increase in the number of storeys and density of;
- development of a new planning axis perpendicular to the river and the railway, between which the city was stretched;
- strengthening of the transport network connectivity, change of its configuration towards the radial-ring type, construction of bypass roads.

As a result, a ***new city center*** with a presidential residence and other representative institutions began to form on the left bank of the Esil river. The historical center

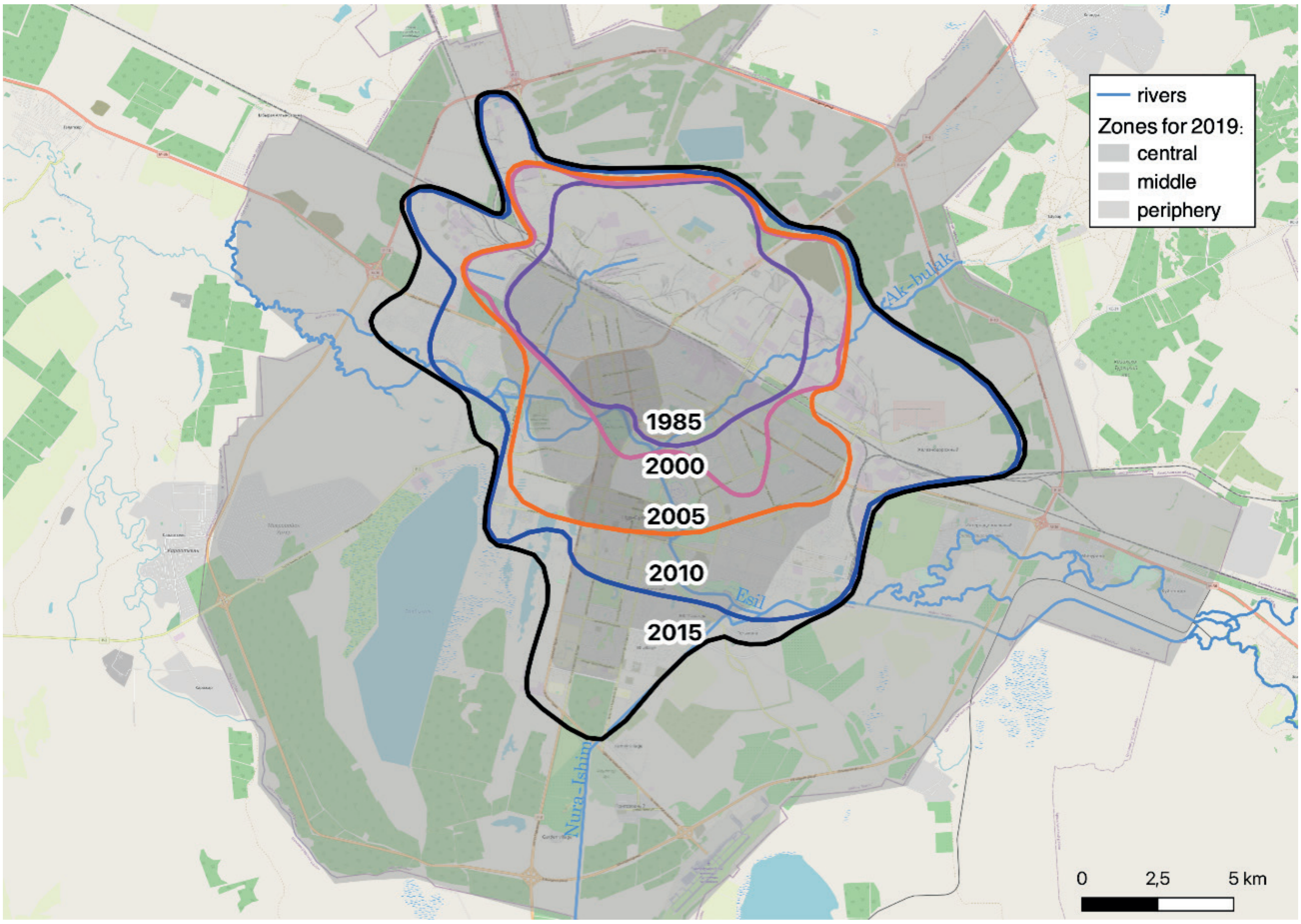

Fig. 1. The spatial extent of Nur-Sultan, 1985–2015

[1]GOST 56162-2014, 2014, Emissions of pollutants into the atmosphere. Method for calculating emissions from motor vehicles when conducting summary calculations for urban settlements. Moscow: Standartinform.

on the right bank also changed as new offices, business, shopping and entertainment centers, high-rise residential complexes appeared as a result of densification. Meanwhile, preservation of old buildings has generally mothballed the existing transport network, limiting the width of central streets and the parking system development.

Currently, public and business buildings occupy 3,5% of the city's territory (2.8 thousand hectares). They are mainly concentrated in the center, mostly in the new part of the city on the left bank. Essentially, both city centers have almost merged, forming one central business district. The concentration of public and business facilities in the center (old and new) led to the adjustment of the general plan. In 2005, it was decided to create seven planning districts with their own sub-centers along the main streets in the middle part of the city to unload the center.

Simultaneously with the creation of the new center begins the ***transformation of the residential framework***. Large-scale compression of suburban areas (the number of allotments decreased 2.7 times) and demolition of poor-condition housing allowed the city to develop in the eastern and western directions. Due to the development of the left bank of the Esil River and absorption of garden plots and nearby villages, the city also grew in the southern, southeastern, and southwestern directions. New residential areas on the left bank stretch in several directions. In the old part of the city, residential development mainly takes place north of the Esil River. Here you can still trace the features of a linear city with parallel recreational, industrial, warehouse, and residential zones (its creation was envisaged in the 1960s when the former Akmolinsk became the center of the wildlands development).

Residential buildings currently occupy one-fifth of the city's territory (9,5 thousand hectares). Apartment buildings and individual housing account for almost the same share of residential buildings. Despite the reduction in their area, there are still 28 low-rise residential districts in the city. Meanwhile, a significant part of residential areas in the middle and peripheral parts of the city can be characterized as so-called commuter districts. The large share of estate-type housing increases the average development level of the periphery and semi-periphery with low infrastructure availability. Currently, the expansion of the city leads to an increase in the road network length, individual transport usage, share of low-capacity buses and travel time, which results in higher emissions.

Reduction of industrial functions. In Soviet times, industry in most cities occupied on average one-fourth to one-third of the total area, which was two to three times more compared to cities in Western Europe (Stanilov 2007). In modern Nur-Sultan, it only accounts for about 8,6% of the city's area. There are no industrial zones in the new part of the city, which was built as a center of a post-industrial service economy. The only industrial and warehouse zone remaining from the Soviet era is located on the periphery and constrains the city's growth in the northeastern direction. It is surrounded by a low-rise residential and suburban area with minimal service facilities and poorly developed transport links.

Development of the transport network. The rapid growth of the population and area of the city, together with the increasing motorization, led to the modernization and expansion of the transport framework. For its development, new roads were cut through residential areas, forming a web-like system that linked remote districts together.

Formally, the main highways and the bypass road form a radial-circular structure of the road network. However, in most of the city, it still has a rectangular configuration, which, although having a higher capacity, poorly connects the peripheral territories. The Esil River is a significant barrier, which divides the city into two parts. The districts located on opposite banks are connected by 17 road and pedestrian bridges, 7 of which connect the new city center with the right bank. However, compared to the cities in Western Europe, where bridges are built every 500 m, their number is still insufficient. In the new part of the city on the left bank, the distance between roads is larger and the role of barriers is played by large green areas, including parks.

The existing planning structure of the city facilitates the transit of transport through the center due to the extremely uneven distribution of residence and employment facilities. In the central part, which has a relatively low population density, the density of workplaces is high. Peripheral sleeping areas, meanwhile, are characterized by an inverse ratio, which causes daily population migration. Despite the creation of seven planning districts, in which the development of large counter-magnet centers was planned to attract the population of peripheral districts, residential functions there still dominate over public and business functions. At the same time, the large area of the city along with the distance between its different parts and the center leads to congestion of the city center, slows down traffic and increases air pollution.

The development of transport infrastructure in a modern city is not only about developing new territories and constructing new roads, bridges and junctions. The world's best practices focus on creating a large number of streets with slow traffic or without traffic at all together with many multi-level overground and underground parking lots (Guidelines 2014). However, in Nur-Sultan, as well as in other capitals of the post-Soviet countries, these practices are still being introduced. People continue to view cars as a convenient means of transportation and not as a source of pollution, which predetermines the continuation of the upward trend in the level of motorization. Public transport is dominated by buses and a taxi network is developing. However, construction of the monorail, which was supposed to connect the airport and the new railway station in opposite parts of the city, was not completed.

Density and concentration of buildings and roads. The highest built-up density is typical for the central and middle zone. Multi-storey Soviet-type buildings and new housing complexes are concentrated in the old center, while the new center is mainly occupied by public and business buildings. In the middle part of the city, industrial, utility and storage areas, as well as districts with multi-story housing have the highest built-up density. Built-up density decreases in residential areas with individual houses in the east and west (Fig. 2). The concentration of buildings is highest in areas with individual housing in the middle zone and periphery, while the old and new centers are characterized by low concentration (Fig. 3).

The right bank is characterized by a higher built-up density, which evolved back in the industrial Tselinograd, the neighborhoods of which spanned between the center on the Esil River and the northeastern industrial zone. The layout of the old city is represented by a regular network of roads, most of which have no more than four lanes. Low road capacity leads to regular traffic jams at intersections. The main streets on the right bank are the most congested as they are highly regulated by traffic lights and stretch across the entire bank, connecting its different parts.

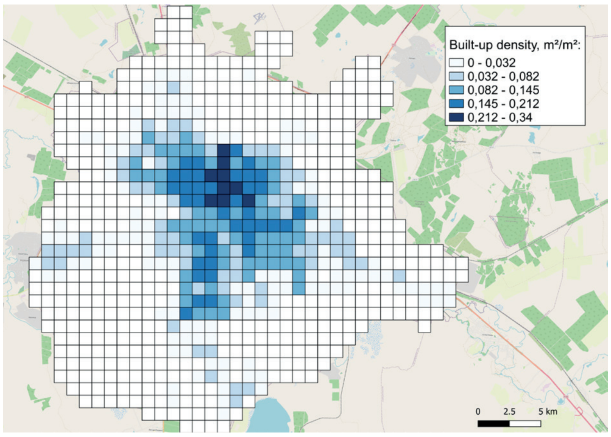

Fig. 2. Built-up density, 2019

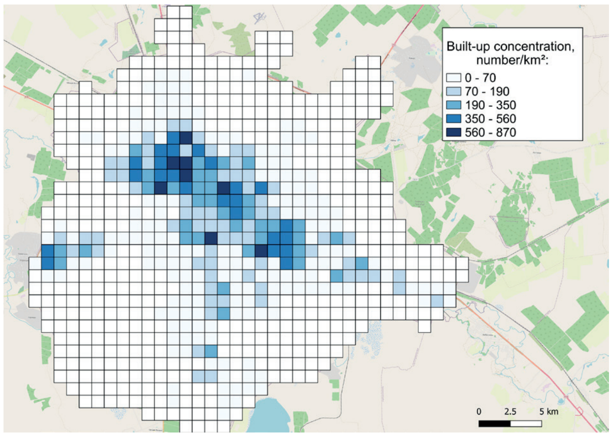

Fig. 3. Built-up concentration, 2019

The left bank, on the other hand, is characterized by a higher road network density, the planning of which was based on new principles that considered growing motorization. In the center of the left bank, roads do not always cross at right angles. However, the attractiveness of the new center also contributed to the emergence of numerous road network connectivity barriers as it includes large administrative and commercial facilities and extensive boulevards. The density of road network in the old and new city centers is equal to 19.6 km/km^2 and 20–25 km/km^2, respectively, and decreases towards the periphery (Fig. 4, 5).

Spatial structure of pollution as a reflection of the planning structure

Traffic emissions in Nur-Sultan in 1998-2019 grew faster than in other cities of Kazakhstan (from 35.5 to 74.8 thousand tons/year) due to the highest growth of the motorization level (from 88.6 to about 500 cars/1000 inhabitants). Meanwhile, the vehicle fleet renewal is slow, the average age of vehicles is 10 years and the average class is Euro-3, which does not correspond to the level of the capital city.

The transport network could not cope with such growth in the level of motorization despite the rate of construction of the new roads, junctions, and bridges that exceeded the plan. This led to the formation of numerous congestions and, consequently, to an increase in toxic traffic emissions. The average density of emissions decreases from the center to the periphery from 250 to 113 t/km^2. A particularly strong reduction is observed in the transition from the middle zone to the periphery, where the density and concentration of buildings and roads decrease 3–5 times, leading to a decrease in the average density of emissions by a factor of 1.5.

The center and some parts of the middle zone, despite the high density and concentration of roads, remain heavily loaded (more than 2000 cars/hour), while the rest of the city is characterized by a higher speed of traffic and relatively low emissions.

The old center is characterized by insufficient road capacity due to the high built-up density. Intersections of regional highways and city streets also lead to congestion of transport hubs due to the complexity of the road network geometry. The presence of large parks, squares and alleys, along with the industrial zone in the northern part of the city leads to a decrease in the road network connectivity, which also contributes to the congestion. The main streets – planning axes – are characterized by a high level of traffic intensity, which leads to the high density of pollution.

The middle zone and the periphery are heterogeneous in terms of density and concentration of buildings and roads, and, consequently, in pollution. For the middle zone, this is due to the presence of public hubs that play the role of subcenters and are characterized by a high density and concentration of roads, which creates congestion within them. The middle zone also includes areas of irregular development, which have a low road network density and high building concentration. This part of the city is on average characterized by a higher speed of movement, which corresponds to relatively lower traffic intensity. Based on the density of emissions, it is divided into 4 subzones:

1) areas between the tributaries of the Esil river and the center zone with an average emissions density of up to 200–250 t/km^2;

2) new development areas: Nazarbayev University, EXPO and «the Pyramid» area (up to 200 t/km^2);

3) residential areas of the northwest with a moderate level of pollution (about 150 t/km^2 on average), low traffic intensity, and a relatively high density of the road network;

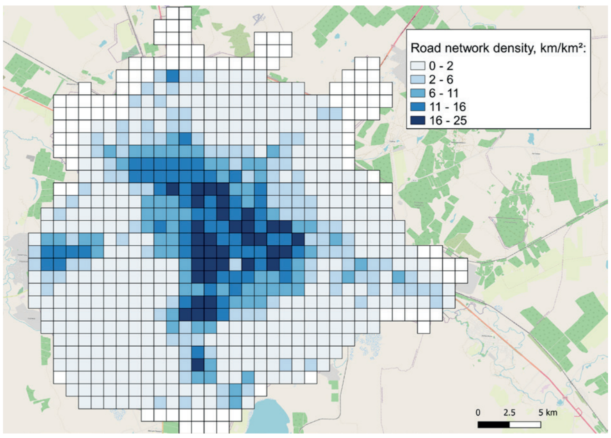

Fig. 4. Road network density, 2019

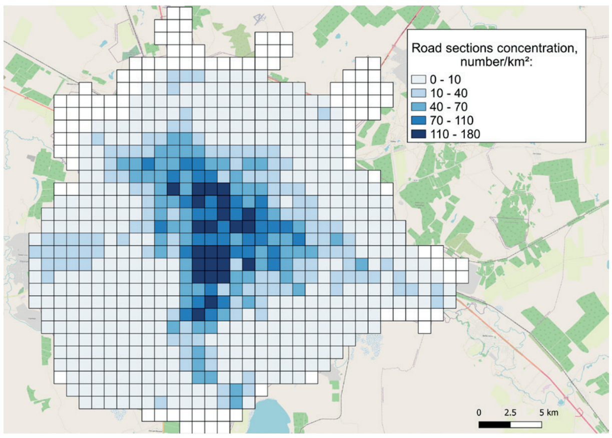

Fig. 5. Road sections concentration, 2019

4) residential areas of the southeast with a low level of pollution (up to 140 t/km^2).

The periphery of the capital is also heterogeneous and includes an industrial zone, residential settlements with low a density of urban development and utility infrastructure, as well as state and interregional highways. Here, high levels of pollution are typical only for the territories near the high-speed highways (Fig. 6).

Thus, in the middle zone with less than a twofold decrease in the density and concentration of roads, there is a decrease in traffic intensity by 16% and in emission density by 30%. The reduction in emission density is due to a 30% reduction in building density and, probably, to a better network structure. Capillary, not heavily loaded streets of the local residential areas are connected to wider streets (the average number of traffic lanes in this zone is 4.5 versus 4 in the center), which results in the average traffic speed increase to 32 km/h (compared to 26 km/h in the city center).

In the periphery zone, the density and concentration of buildings decrease 3 times, the density and concentration of roads – 3.4 and 4.8 times, respectively, which means that roads are getting wider (up to 5 lanes on average). As a result, the average traffic speed increases to 48 km/h and the emission density is reduced by 36%. Thus, despite different rates of reduction in the density and concentration of roads, the emission density steadily decreases from the center to the periphery. This is because a decrease in population density and development, widening of roads, and improving pavement quality, all result in the traffic speed increase, which becomes closer to optimal, reducing the net emissions per kilometer. However, this does not eliminate the congestion of certain highways and local areas with high emission density along them. For example, on the outskirts of the city, the density of emissions increases near the wholesale, food, construction, and other markets due to the underdevelopment of public transport, and near industrial, utility and storage areas – due to the high share (up to 20%) of freight transport in the traffic.

CONCLUSIONS

Due to the long period of development within the USSR, post-Soviet cities have many common features both in terms of urban planning in general and in terms of the planning organization of the territory. However, the trend of their modern development is less predetermined by their common historical heritage and more – by the processes of globalization and the world division of labor as well as political and geopolitical aspects.

Relocation of the capital to Nur-Sultan led not only to rapid population growth, expansion of the territory, intensive housing and office construction but also to the transformation of the spatial and planning structure of the city in accordance with the new challenges. The following effects of changing the planning structure can be considered positive:

- transfer of the administrative center of the city to the left bank. This allowed not only to unload the old center but also to begin the development of its transport network, connecting it by tunnels, overpasses, ramps, and junctions in the conditions of a high building density;
- mitigation of the barrier role of the river due to the faster construction of bridges;
- construction of a bypass road.

At the same time, the historically established functional zoning of the city led to the preservation of the estate-type housing, which is typical for many cities of Kazakhstan and has low infrastructure availability and poorly developed public transport.

The combined influence of the inherited and transformational factors of the planning structure development led to its ambiguous influence on the spatial structure of traffic pollution. In contrast to small-scale studies conducted for individual cities, which revealed an inverse relationship between the density of road network and density of emissions (Bityukova et al. 2011), the analysis of intra-city differences showed a much more complex picture.

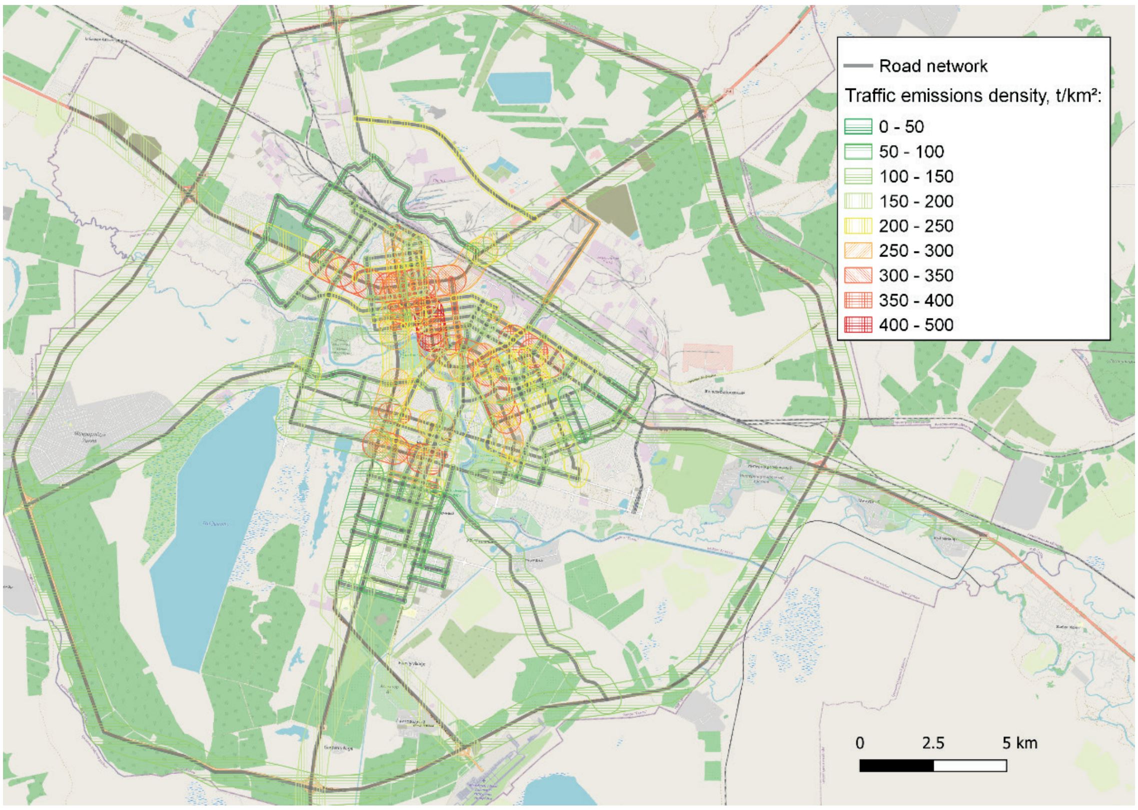

Fig. 6. Traffic emissions density, Nur-Sultan, 2019

Despite different growth rates in the density and concentration of roads, emission density steadily decreases from the center to the periphery. However, the growing concentration of roads and their increased connectivity in the city center cannot yet compensate high traffic flows, although the density of emissions is growing at a slower pace. In the middle zone, compared to the center, both built-up and road network density decreases, but this is compensated by an increase in road capacity and traffic speed, which also decreases the density of traffic emissions. On the periphery, the density and concentration drop 3 times for buildings and 3-5 times for the road network. New roads with higher capacity are being built outside the city center, which increases the average traffic speed and decreases the emission density. Between these highways, large areas of estate-type housing with a high road network density remain, however its quality is poor, which does not contribute to the development of public transport.

The continuing trend towards further extensive growth of the city due to the absorption of low-rise building areas with private plots will lead to higher emissions due to an increase in the road network length, use of individual transport, share of low-capacity buses, etc. This confirms the Downs-Thomson paradox revealed for the European capitals in the 1960s (Ding and Song 2011), with the same level and growth of motorization. Positive changes in the dynamics of road traffic pollution are possible within the framework of post-industrial trends in the development of various multifactorial approaches for different areas of the city. For the center of Nur-Sultan, given the current road network concentration, it will be impossible to adapt to extensive motorization simply by building roads, instead, a clear distinction between the population mobility and mobility of personal vehicles will be required (the first should be developed in every possible way, the second should be limited). For the middle zone, it is necessary to develop public transport, road network, traffic management and systems of parking spaces, as well as improve the structure of the vehicle fleet and fuel. For the periphery, it is also necessary to increase the concentration of roads and develop a capillary network for low-rise areas. These measures should lead not so much to a decrease in the density of pollution, but to its more even distribution. ■

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RESEARCH PAPER

URBAN BIOPHYSICAL QUALITY MODELLING BASED ON REMOTE SENSING DATA IN SEMARANG, INDONESIA

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ABSTRACT. Cities are centres of economic growth with fascinating dynamics, including persistent urbanisation that encroaches adjacent arable lands to build urban physical features and sustain services offered by urban ecosystems. Even though industrial revolution, economic dynamics, and environmental changes affect spatial feasibility for housing, complex urban growth is always followed by the development of environmentally friendly cities. However, with such quality having multiple facets, it is necessary to assess and map liveable areas from a more comprehensive and objective perspective. This study aimed to assess, map and identify the biophysical quality of an urban environment using a straightforward technique that allows rapid assessment for early detection of changes in the quality. It proposed a multi-index approach termed the urban biophysical environmental quality (UBEQ) based on spectral characteristic of remote sensing data for residential areas calculated using various data derived from remote sensing. Statistical analyses were performed to test data reliability and normality. Further, many indices were analysed, then employed as indicators in UBEQ modelling and tested with sensitivity and factor analysis to obtain the best remote sensing index in the study area. Based on PCA Results, it was found that the built-up land index and vegetation index mainly contributed to the UBEQ index. The generated model had 86.5% accuracy. Also, the study area, Semarang City, had varying UBEQ index values, from high to low levels.

KEYWORDS: remote sensing index, urban biophysical environmental quality, principal component analysis

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INTRODUCTION

Urbanisation affects population growth, causes functional shifts in land use and urban climate change and degrades water and air quality (Yuan & Bauer 2007). Within the context of rapid global urbanisation, participatory urban spatial planning plays an essential role in preventing uncontrolled city expansion, dealing with segregation and reducing carbon emission in cities (Psaltoglou & Calle 2018). Sustainable Development Goal (SDG) No. 11.1 states that in 2030, regional governments will guarantee access to housing and basic services that are decent, secure, and affordable for all society members, thus improving the condition of slums. Goal No. 11.7 also mentions that by 2030 regional governments must have provided universal access to green, public open spaces that are safe, inclusive, and easily accessible. To support such planning, it is imperative that actual steps to create a sustainable green environment be taken according to the ecological resilience of an urban biophysical environment to climate change (SDG 13). SDG 13 document deals with increased resilience, adaptive capacity and risks arising as an effect of climate change and disasters in all countries, as well as education improvement, awareness enhancement, human resource capacity, and the role of institutions in the mitigation, adaptation, impact reduction and early warning of climate change.

A large share of urban lives is exposed to conditions that harm human health and well-being and threaten natural resources. With the complex interrelation between urban physical environments, social components, and economic demands, it can be said that most environmental issues like pollution do not originate in urban physical characteristics but rather the behaviour and way of life of the residents that sometimes exacerbate the situation (Li et al. 2016). The liveability of an urban environment depends on three main factors: biophysical features (i.e., built-up land, vegetated areas and water bodies), climate and air quality (Xiao et al. 2018). Therefore, the development of sustainable and liveable cities needs to be supported by effective and efficient planning that also takes into account urban biophysical conditions and ecological resilience (Rezvani et al. 2013). Some examples include building settlements outside hazard-prone areas (e.g., riverbanks), enforcing spatial planning laws and ensuring that new planning simulates mobility and optimises urban structural design so that it does not merely lead to the increasing number of vehicles but also provides new solutions for effective transport (Mao et al. 2014).

Understanding and exploring ecosystems and standards of living (liveability) in various land uses in a city will provide insight into urban planning, governance and management (Fu, Yu, & Zhang 2019). A city is an economic-spatial system that requires biophysical and social approaches in its management. Examples include temperature to characterize urban redevelopment (Pan et al. 2019) and relative humidity generated by fire emissions to model urban air quality (Cuchiara et al. 2017). Some more complex approaches commonly used for spatial ecological analysis in cities are temperature-carbon storage relationship, urban green space calculation and planning and computation of thermal comfort in cities. However, simple urban biophysical factors with remote sensing-derived data have not been widely used for liveability measurement. Therefore, this research proposes the mapping of urban comfort using a simple biophysical approach. Comfort (liveability) is very carefully considered when discussing urban environments, but in general there is no universally acknowledged definition of the parameter because it can be measured from various points of view; the same case applies to quality of life, welfare or development stability. Comfort is also part of urban biophysical environmental quality, which is a function of built-up land and urban vegetation (Hidayati et al. 2019).

Urban Biophysical Environmental Quality (UBEQ) is a term used in scientific studies to assess the quality of the biophysical environment in urban spaces, assuming that a high-quality biophysical environment is a precondition for liveable areas. A biophysical environment comprises biotic components (vegetation) and abiotic components (e.g., built-up land and water) (Hidayati et al. 2019b; Stossel et al. 2017), which in the context of UBEQ shape a city's ecological resistance and sustainable development. UBEQ modelling is a simplified version of the quality of housing environments that determines whether or not and to what extent a residential area provides decent lives for its inhabitants. Urban Environment Quality attempts to address current challenges in urban environmental quality assessment: complicated modelling (Liang & Weng 2011). There is a vast possibility of how many, and which research variables and data can be included to accurately model UBEQ. Multitemporal and multiscale data from many sources can help determine relevant variables and optimise the number of variables used in modelling. The evolution of biophysical parameters starts with Forster (1983), who considered residence quality as an approach to assessing residential biophysical quality. Further development in 1990–2000 defined biophysical quality as a result of surface temperature, building density and socio-economic parameters, namely income per capita and educational attainment (Charreire et al. 2012; Weber et al. 2014). A decade later Deng & Wu (2012) introduced Biophysical Composition Index (BCI) and compared it with several remote sensing indices (NDVI, NDISI, and MNDWI) using Landsat ETM+, IKONOS and MODIS image data. Results prove that BCI can effectively assess impervious surfaces and bare soils. State of the art in biophysical quality assessment techniques is the extraction of vegetation data from high-spatial-resolution images by Aditya et al. (2021) to determine urban greenness.

This research uses remote sensing data with various spatial resolutions (level of mapping scale/detail) and spectral resolutions (the ability to distinguish spectral characteristics of remotely sensed data) in addition to primary spatial data collected through field surveys. Remote sensing is selected because this technology can distinctively provide global coverage data both in pure and mixed pixel relevant to geo-information technology, such as GIS, spatial analysis and dynamic modelling. Further, a combination of remote sensing and GIS data is thereby used extensively for monitoring, synthesising and urban environment modelling that involve internal complexities. Many urban features can be extracted from remote sensing imagery (Silva & Mendes 2012), e.g., built-up land, vegetation and temperature. The data extraction usually involves two main methods, namely digital classification and spectral transformation (index). Based on spectral reflection alone, the red, near-infrared and mid-infrared image bands provide varying spectral responses and can show spectral differences in built-up land (Zha et al. 2003), meaning that remote sensing technology captures the unique appearance and distribution patterns of buildings, vegetation, water and bare land in urban spaces (Xu et al. 2000). The response spectra of developed urban areas increase significantly in near- and mid-infrared bands.

Overall, the city's liveability is indicated by the urban environmental quality that factors in both physical and biophysical factors. The mapping of urban environmental quality uses socio-economic approaches and involves very complex parameters, but this paper attempts to produce the same map using two main parameters, namely vegetation and built-up land, and spatial data derived from remote sensing imagery. Also, it cannot be denied that cities are constantly developing and changing. Therefore, remote sensing products that offer spatial and temporal records are used to help urban communities and decision-makers maintain or improve the liveability of their cities in the future. This approach is beneficial for developing countries like Indonesia, whose big cities are overpopulated and need decent residential spaces. Currently, Semarang is one of the big cities that has problems regarding land availability (Muladica, Murtini & Suprapti 2018). Urban development causes limited land availability. Mijen Semarang area which is in peri urban area also experiences high land conversion. Therefore, it is necessary to analyse the environment quality in Semarang along with the high land conversion. The aims of the research were (1) to select UBEQ parameters based on the spectral characteristics of remote sensing-derived data and spatial data and (2) to analyse the spatial distribution of UBEQ in the Semarang urban areas. This information is expected to provide a straightforward approach for land-use mapping, planning and monitoring in urban areas.

MATERIALS AND METHODS

This study used medium-resolution Landsat 8 OLI images recorded on 13 September 2019, path 120, row 65. To achieve the first goal, it performed various data extractions, i.e., image transformation index: building index, vegetation index, water index, land surface temperature index, and impervious surface index (Table 1). Also, to select the appropriate index, it performed factor analysis on Normalized Difference Built-up Index (NDBI), Normalized Difference Vegetation Index (NDVI), and Soil Adjusted Vegetation Index (SAVI.The transformation index formulas used are presented in detail in Table 1.

Table 1. Formulas of the image transformation indices analysed in the study

Index	Formulas	Sources
NDBI	$\frac{SWIR1 - NIR}{SWIR1 + NIR}$	Zha et al., (2003)
NDVI	$NDVI = \frac{NIR - RED}{NIR + RED}$	Guo et al., (2015)
SAVI	$SAVI = (1+L)\frac{NIR - RED}{NIR + RED + L}; L = 0,5$	Huete (1988)

Landsat 8 image processing involved radiometric and geometric corrections to ensure the quality of the images. In the radiometric correction, pixel values were converted to spectral radiance values, with corrections to the reflectance values made using the formula developed by Chander et al. (2009). Processing of the indices used the normalized difference index formulation.

The research location was the City of Semarang (the Province of Jawa Tengah, Indonesia), which is bordered by the Demak Regency, Semarang Regency, Kendal Regency, and the Java Sea. It has varying topography from lowland to hilly areas. To the south, there is Mount Ungaran, which affects urban environmental quality and vegetation distribution in the city. The research location is shown in Fig. 1.

Selection of the Research Variables

This research stage consisted of four steps: detection of outliers, data normality, sensitivity analysis and factor analysis. The research variables comprised various built-up land and vegetation indices. The best index was chosen to create a composite UBEQ index of urban biophysical environmental quality represented by NDBI, NDVI, and SAVI (Hidayati 2019). Outliers were detected as data that were outside the normalized index range, namely -1 to 1. If an error was found in the image correction process or in the normalized index, the correction process was repeated, starting with radiometric image correction. The next step was to test the data normality using two variables: vegetation and built-up. If one variable fulfils the normality assumption, then all variables are also considered as satisfying data normality. Furthermore, the test between the variables used to determine the perfect relationship between them does not require the two variables to have the same value; to a certain degree values are always accompanied by changes in the value of other variables (Morisson 2012). Statistically, factor analysis was used to complete the index selection, wherein the index was determined whether or not it would be used by considering the return value of Bartlett's test of sphericity or the measure of sampling adequacy (MSA). Analysis of the feasibility of the variables was conducted in stages by performing the sensitivity analysis on the variables one by one to obtain the optimal statistical value. Here, optimal means the correlation value is close to 0, Kaiser-Meyer-Olkin (KMO) and Bartlett's test return values are above 0.5 and an MSA value is > 0.5.

Combining the Research Variables

Principal component analysis (PCA) is a transformation that identifies an equation that is the optimum linear combination of several input bands that can calculate the image variance value (Campbell & Wynne 2011; Danoedoro 2012). It is basically a rotation technique applied to a multiband coordinate system resulting in a new image with fewer bands. PCA can reduce the dimensionality of data; thus, it is often seen as a very efficient data compression technique (Danoedoro 2012). Its role in this study was to combine the research variables derived from remote sensing data with different spatial and temporal

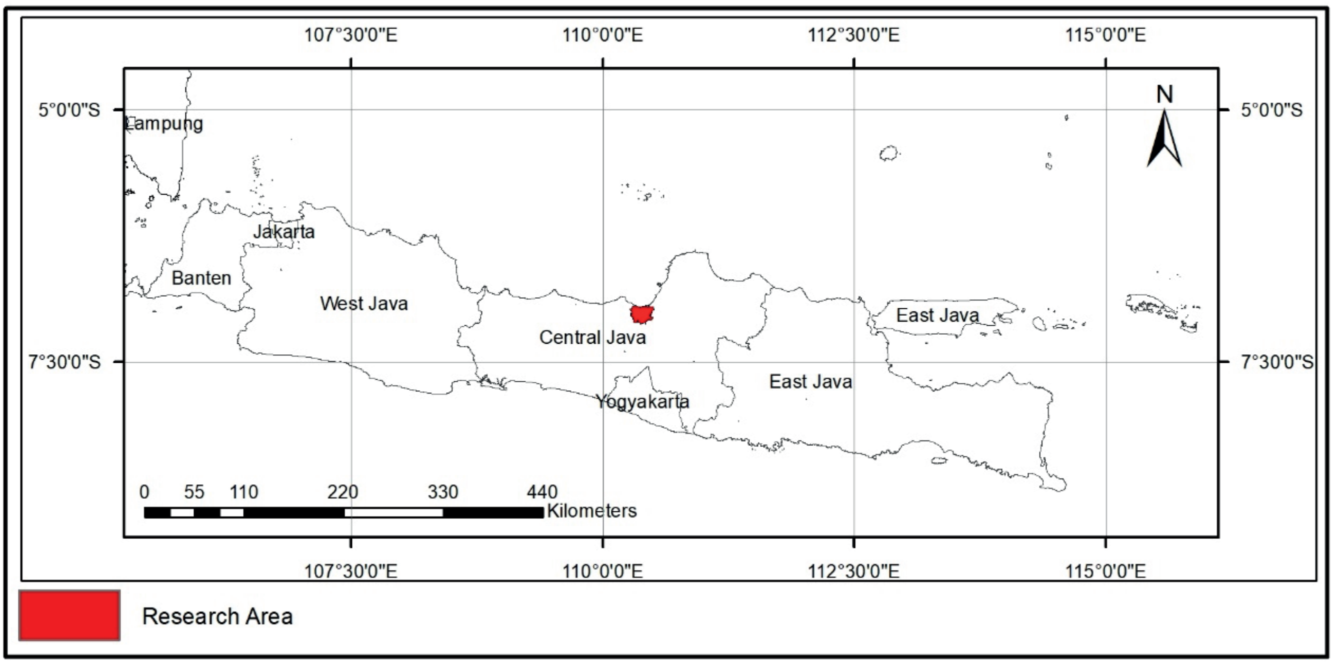

Fig. 1. The location of the research area on Java Island, Indonesia

resolutions. Therefore, because the variables are on different scales, PCA was performed based on a correlation matrix to obtain the desired standard value.

RESULTS

Selected Research Variables

Vegetation data were extracted from the Landsat imagery using several normalized index values. One of these is NDVI (infrared and red bands), which was found to be in the range of -0.185 to 0.752. Soil reflection has a positive correlation with wavelengths; in other words, the greater the wavelength, the higher the electromagnetic energy reflected by the soil, especially at wavelengths between 0.4 μm and 1.0 μm. For example, the normalization used in NDVI is the spectral response between the near-infrared and red band reflections. However, a very typical spectral response such as NDVI is not in the range of soil reflections because soils have widely diverse and complex physical and chemical properties. Therefore, in this study the combination used is adjusted to the spectral reflectance of the soil sample. Soil indexing is directly related to the complexity of soil properties and the spectrum used. Here, indexing aims to calculate the ratio of differences in the indices that had been selected effectively based on the reflection curve used in order to avoid spectral variability in different geographic studies. SAVI was used to observe vegetation reflections by involving near-infrared (NIR) with red reflections. SAVI is an algorithm developed from NDVI that suppresses the influence of soil background on canopy brightness. It uses vegetation isoline equations (vegetation with the same density and different soil backgrounds) derived from canopy reflectance approximation with a first-order photon interaction model between the canopy and the soil layer. The spectral reduction of the red mixture, the darker ground area, causes a significant increase in NDVI values.

The index developed from the unique spectral response of built-up land had higher reflections at SWIR than at NIR wavelengths. Several image transformations were used for the transformation of urban built-up land indices, such as NDBI (Normalized Difference Built-up Index), EBBI (Enhanced Built-up and Bare Land Index), UI (Urban Index) and NDBaI (Normalized Different Built-up and Bare Land Index) (Hidayati 2019). These indices are intended to ascertain which is the most suitable for detecting built-up area because each has its own advantages and disadvantages. The statistical correlations between NDBI and the two vegetation indices (NDVI and SAVI) are presented in Table 2. In general, NDVI is the standard method used to measure and distinguish healthy vegetation and is expressed in the range of -1 to 1. Utilisation of other indices such as infrared/red will produce a simple ratio whose values are always positive, and it gives the possibility that there are also certain unlimited mathematical values. Apart from NDVI, SAVI is also used in the research to produce different variables from NDVI.

NDVI was selected as the most suitable index, or in this case variable, for assessing UBEQ in that the results of the NDVI radiometric correction were high, unlike SAVI. Some vegetation indices incorporate certain numbers that are determined using reflectance data, e.g., spectral bands used in SAVI and NDVI. The vegetation index was adjusted to soil reflection in the SAVI calculation by adding a constant 0.5 and a multiplying factor 1.5 to the formula used. It is assumed that the red and near-infrared spectral reflections are on a scale of 0–1. The spatial distributions of NDVI and NDBI are shown in Fig. 2 and Fig. 3, respectively.

Table 2. Formulas of the image transformation indices analysed in the study

Correlations				
		NDVI	NDBI	SAVI
NDVI	Pearson Correlation	1	0.091**	1.000**
	Sig. (2-tailed)		0.000	0.000
	Sum of Squares and Cross-products	78138.792	1989.265	115401.660
	Covariance	0.087	0.002	0.129
	N	893514	893514	893514
NDBI	Pearson Correlation	0.091**	1	0.088**
	Sig. (2-tailed)	0.000		0.000
	Sum of Squares and Cross-products	1989.265	6091.454	2836.282
	Covariance	0.002	0.007	0.003
	N	893514	893514	893514
SAVI	Pearson Correlation	1.000**	0.088**	1
	Sig. (2-tailed)	0.000	0.000	
	Sum of Squares and Cross-products	115401.660	2836.282	170438.064
	Covariance	0.129	0.003	0.191
	N	893514	893514	893514
** Correlation is significant at 0.01 (2-tailed)				

Sensitivity Analysis and Factor Analysis Results

The factor analyses of three variables, namely NDBI, NDVI and SAVI, were based on KMO, Bartlett's test, and MSA values. The KMO and Bartlett's test return values were 0.500 for NDBI and NDVI (a significance value of 0.000<0.005), meaning that the combination of the three variables is suited for factor analysis (Table 3). As seen in the MSA calculation results in Table 3, one of the factors must be reduced to get an MSA value 0.5, which would indicate that the variable is predictable and further factor analysis can be performed. Because SAVI and NDVI both represent vegetation characteristics, one of which was reduced. Hidayati (2019) has also tested several variables for UBEQ modelling and found that the KMO and Bartlett's test results of the NDBI, NDVI and SAVI were 0.343, meaning that the three indices are statistically not accepted for further modelling.

The factor analysis and sensitivity analysis results showed that the MSA of NDBI and NDVI (0.500).). This indicates NDVI as the most representative vegetation index. After the SAVI was omitted, the MSA of NDBI and NDVI was 0.500 (Table 4). The return value of the KMO and Bartlett's tests for NDBI and NDVI was 0.500 (Table 5). Therefore, NDBI and NDVI can be used for liveable index analysis. The assumption used for the factor analysis was the determinant of the correlation matrix test, which shows that the variables were interrelated. KMO is an index comparing the distance between the partial correlation coefficients and the variable pairs of low values and the number of correlation coefficients.

The combination of NDVI and NDBI indicates that the built-up land has a negative value (-), while the vegetation has a positive value (+) (Table 6). This proves that vegetation and built-up land directly affect UBEQ, although with different effects. NDBI is associated with discomfort: a higher building density results in more uncomfortable living and lower UBEQ (less liveable city). Similarly, when combined with NDVI to create a composite index, NDBI contributes to inconvenience and is inversely proportional to NDVI: the more extensive the built-up land in urban areas, the narrower the vegetated land.

Principal component analysis was used to identify uncorrelated components and to provide wide variance to the original indicator. Based on PCA analysis, eigen values greater than 1 are retained and used in modelling, while eigen values less than 1 are excluded from the model. An eigen value shows the contribution of the factor to the variance of all original variables. In order to obtain optimal PCA results, the varimax method was used to rotate several components to make them consistent. The factors formed were in accordance with the existing theory: UBEQ modelling requires the simplest variables, namely built-up and vegetated land. The more extensive the built-up land, the fewer the vegetated area. Thus, component 1 is termed

Table 3. Formulas of the image transformation indices analysed in the study

Anti-image Matrices				
		NDVI	NDBI	SAVI
Anti-image Covariance	NDVI	1.108E-5	-0.002	-1.108E-5
	NDBI	-0.002	0.521	0.002
	SAVI	-1.108E-5	0.002	1.108E-5
Anti-image Correlation	NDVI	0.406[a]	-0.689	-1.000
	NDBI	-0.689	0.017[a]	0.689
	SAVI	-1.000	0.689	0.406[a]
a. Measures of Sampling Adequacy (MSA)				

Table 4. MSA analysis results of NDBI and NDVI

Anti-image Matrices			
		NDVI	NDBI
Anti-image Covariance	NDVI	0.992	-0.090
	NDBI	-0.090	0.992
Anti-image Correlation	NDVI	0.500[a]	-0.091
	NDBI	-0.091	0.500[a]
a. Measures of Sampling Adequacy (MSA)			

Table 5. KMO and Bartlett's test return values of NDBI and NDVI

KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.500
Bartlett's Test of Sphericity	Approx. Chi-Square	7459.495
	Df	1
	Sig.	0.000

Table 6. Component Matrix result

Component Matrix[a]	
	Component
	1
NDVI	0.739
NDBI	-0.739
Extraction Method: Principal Component Analysis	
a. 1 components extracted	

Table 7. Total variance explained for the principal component analysis of NDVI and NDBI as the Urban Biophysical Environmental Quality (UBEQ) variables

Total Variance Explained						
Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	1.091	54.559	54.559	1.091	54.559	54.559
2	0.909	45.441	100.000			
Extraction Method: Principal Component Analysis						

'the impact of land-use change'; the higher the component's score, the worse the biophysical environmental conditions (UBEQ).

The PCA results of NDVI and NDBI showed that PC1 had a variance value of 54.55%, which means that PC1 constitutes 54.55% of information of the UBEQ index (Table 7). This figure serves as a coefficient in UBEQ index calculation. Meanwhile, PC2 explains 45.45% of UBEQ. The coefficients of PC 1 and PC2 are the values used for UBEQ modelling that describe the spatial distribution of the biophysical environments. The formed factors correspond to the theory that UBEQ modelling needs the simplest variables, namely built-up land and vegetated land—and an increase in built-up land almost means a decrease in vegetation. Based on the communalities, the two variables have a negative correlation value for NDBI (-0.739), which is a reflection of urban built-up land (i.e., asphalt, concrete and paved roads), and has a positive correlation value for NDVI (0.739), which closely represents vegetation characteristics. This urban environment quality component decreases by growing the urban built-up land and impervious area and reducing urban vegetation and green areas. The results of the rotation matrix also illustrate that built-up land and vegetation are components of liveability, which are expressed by component 1: built-up land with a negative value and vegetation with a positive value.

In this research, the index representing built-up land was primarily observed because this object is typical of urban areas. Based on the designed UBEQ model, NDBI tended to have negative effects, making it a degrading factor in UBEQ. In the UBEQ model, the variant value of NDBI and NDVI was multiplied by the result of PCA derived from NDBI and NDVI, NDBI multiplied by -1 and NDVI multiplied by 1. The statistical analysis and factor analysis results showed that the combination of NDBI and NDVI could be a simple parameter in measuring UBEQ.

DISCUSSION

A settlement can be defined as an area with a certain scope dominated by a residential environment and equipped with infrastructure, environmental facilities and a workplace that provides limited services and opportunities. An environment consists of many elements, both in natural and built-up areas. It also comprises physical parameters and social, economic and political forces that control human life and eventually form a separate settlement pattern. In urban residential areas, the symbiosis between physical and social factors is highly visible and intercorrelated. Every day human activities are greatly influenced by and depend on the physical conditions of the area. The liveability concept, which in this case is actualised as urban biophysical environmental quality (UBEQ), refers to people's perception of their residence. Basically, it is determined by three issues, namely water, soil and air. Urban biophysical data were extracted by making use of remote sensing data from Landsat 8 OLI imagery. The variable sensitivity analysis was conducted if the statistical analysis results showed that the variable observed did not fulfil the requirements. Factor analysis combined various research parameters and was intended to ensure that each variable on each parameter did not experience information redundancy both spatially and spectrally.

Spatial Pattern of Liveability in the City of Semarang

Semarang is one of the big cities in Indonesia with rapid urban development that directly impacts changes in built-up land and vegetation in urban areas. The image transformation index NDBI was in the range of -0.82 (lowest) to 0.69 (highest). In this case, negative NDBI indicates non-built-up land, while positive NDBI means built-up land. Most of the built-up land is located at the city centre and close to the sea, for example, the northern part of Semarang. In this part of the city, the level or flat topography attracts the development of offices, settlements, trade and services. Urban development in the north is different from that in the south. The built-up land distribution in the south depends on transportation networks and industrial areas; therefore, more trade and industrial areas are developing in the southern city. Other urban activities in this area are scattered around the Simpang Lima Semarang, the trade

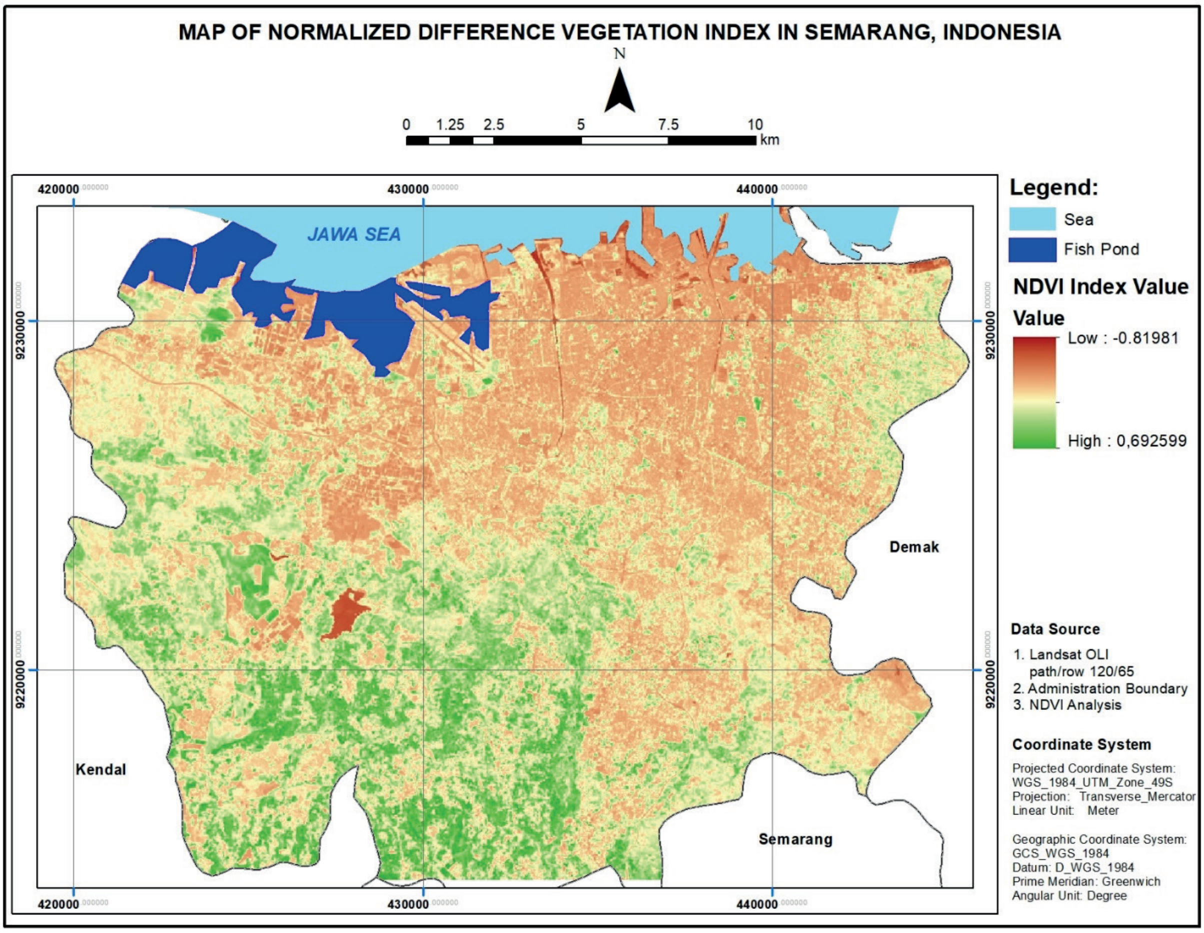

Fig. 2. Spatial distribution map of NDVI in Semarang, Indonesia

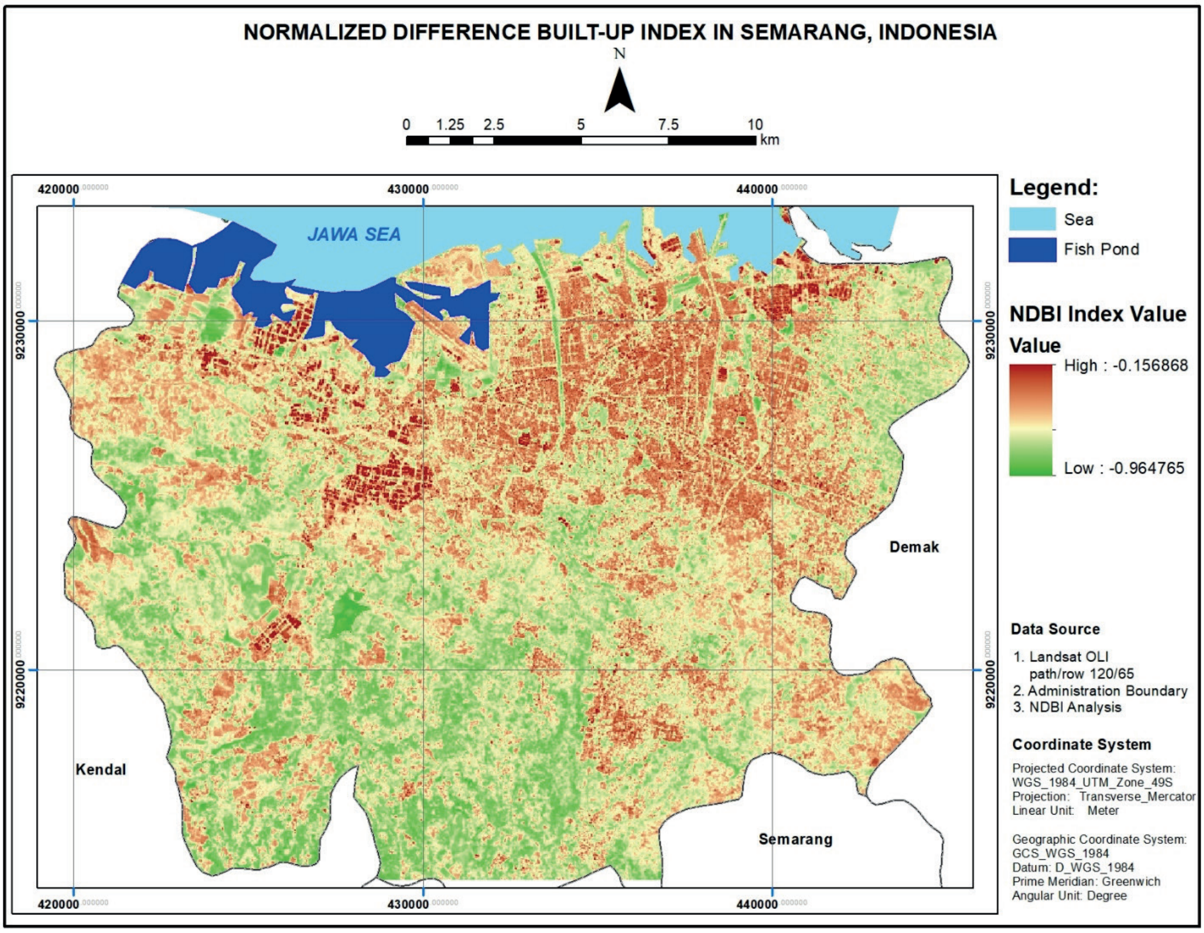

Fig. 3. Spatial distribution map of NDBI in Semarang, Indonesia

and business area along Jalan Pemuda and Jalan Gadjah Mada and the Johar trade and market. The development of the road network in Semarang, especially the ring road network at the city centre, strongly influences the existence of built-up land (Fig. 4). The liveable city modelling for Semarang illustrates that some areas with extensive built-up land inevitably create poor living conditions because of various other physical aspects. In Fig. 3, it is shown that the areas with pooriving conditions are located in Kelurahan in East Semarang, including Tambakrejo Village on the city's outskirts. Some of the residents in these areas are economically disadvantaged (Gultom & Sunarti 2017) and live in normally uninhabitable regions. These conditions result from economic and social limitations of the community and issues in spatial management so that comprehensive cooperation between the community and local officials is needed to overcome the problem. The local government in the PLPBK and NUSP-2 (Neighbourhood Upgrading and Shelter Project-2) programs has planned and arranged the distribution of the settlements in the Tambakrejo Sub-district to provide more liveable space for the residents.

Residential areas with low living conditions are situated around industrial locations. High building density and low indices in this location are influenced by the development of built-up land and urban industries. In general, people have two principles in their lives: residing in a liveable place and fulfilling daily needs. The settlements on the coast of Genuk Sub-district have become very developed after industries sprung up in the area and started to pull a large influx of workers from Genuk (i.e., Muktiharjo Lor, Genuksari and Gebangsari Villages) to live close to their workplaces. The rapid industrial growth, especially coupled with industrial clusters in Terboyo Wetan and Trimulyo, has resulted in greater land development. The growth of built-up land, e.g., boarding houses and rented houses, and the narrowing of urban green space means Genuk has a low index. The settlement development has an enormous impact on UBEQ. Urbanisation and commuting routes sometimes make unfavourable contributions to certain areas. The UBEQ model shown in Fig. 4 also illustrates that Genuk has a low index because it has many industrial buildings, non-residential built-up land, irregular settlements and only a few vegetated areas. An index value below -2 means that the location has a very low UBEQ index. Secondary data also show high PM10 as a consequence of motorised vehicles in the study area.

In addition, the north coast of Semarang has also grown into a centre for trade and services, industry and transportation. The coastal area developed into densely populated settlements, as opposed to a coastal management zone. In a low-lying land like the coast, the residents are at risk of coastal floods – a precondition for a low UBEQ index. The UBEQ index developed from biophysical components (i.e., built-up land and vegetation) has relatively good results.

Other densely populated areas with high NDBI are Ngaliyan and Babankerep Sub-districts. Ngaliyan and Tugu Sub-districts are priorities for the development of industrial and housing areas in the city development zone II. Therefore, the combination of population density and limited green open space yielded a low UBEQ index. Some areas are also priorities for settlement or housing development, which are scattered in Ngaliyan, Tambak Aji, Bringin, Gondoriyo, Podorejo and Tugurejo Villages. Regarding some sub-disricts with a fairly good urban quality index, namely Tembalang, Mranggen and Pedurungan, the Tembalang area has been developed as an education zone,

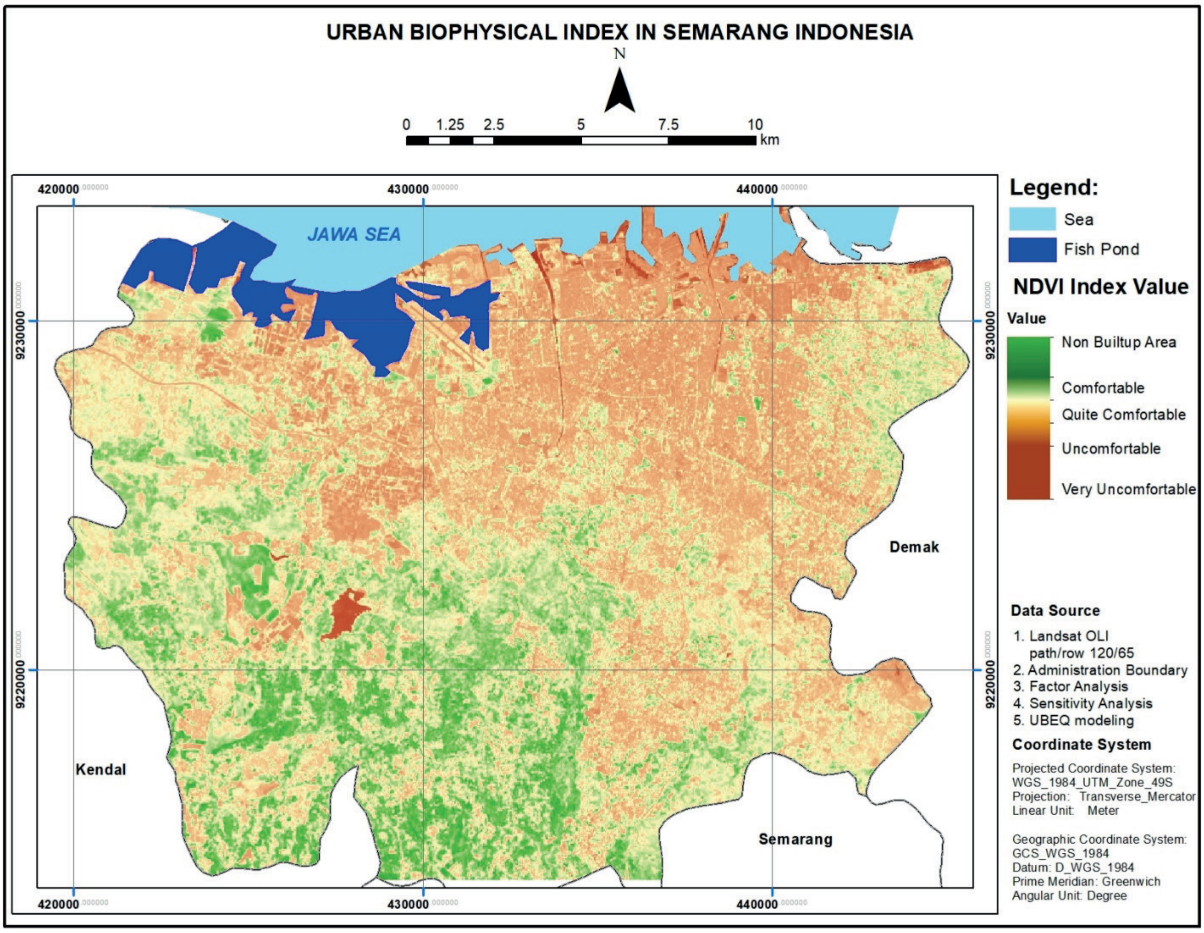

Fig. 4. Spatial distribution map of NDBI in Semarang, Indonesia

because the locations are very comfortable. However, changes in residential areas also often occur because many students come to stay in the area throughout their studies. An example includes the urban area near Diponegoro University that has a moderate built-up land index and an acceptable vegetation index.

Residential areas with a high UBEQ index are located in Gunungpati and Mijen Sub-districts. The results of the remote sensing image analysis illustrate that the area continues to have high vegetation covers. The UBEQ values were 0–2, indicating a comfortable area for living. Haidir & Rudiarto (2019) stated that Gunungpati Sub-district still has 13,727,048 m2 of land potentials for development into settlements. This implies that Gunungpati is still very comfortable for living because it still has a large green open space and adequate vegetated lands; high vegetation density is associated with very good air quality. Gunungpati had three development areas: an urban development area including Gunungpati, Plalangan, and Sekaran Villages, rural development areas and conservation development areas. Protected areas in Gunungpati are also maintained, such as river borders, spring borders, degraded land and disaster-prone areas. Therefore, the balance of the ecosystem in this area is highly maintained for high UBEQ at Semarang.

Unlike the case of Mijen Sub-district in Semarang City – which also has a high UBEQ index, this Mijen suburban area is growing quite rapidly. This area is part of the development of the BSB Satellite City (Bukit Semarang Baru), with the concept of integrated urban development with an environmental perspective (Adiana & Pigawati 2015). The area also has an elite zone equipped with housing support facilities, such as offices and industrial, educational, and service areas. The behaviour of people who live in certain locations strongly determines the conditions of the environment in which they live. The relationship between an environment and its residents is reciprocal and influential (Soemarwoto 1983).

The UBEQ model constructed with biophysical parameters shows that the factors of each parameter are constant. The research variables, i.e., NDBI, NDVI and SAVI, contributed to the first factor with different roles. NDBI always gives the opposite direction to NDVI and SAVI. The formed factors correspond to the theory that says simple UBEQ index modelling is influenced by two factors: built-up land and vegetation. The more extensive the built-up land, the narrower the vegetated areas. Based on the communalities, these three variables (NDBI, NDVI and SAVI) have a negative correlation value for NDBI (-0.739), which is a reflection of urban built-up land, asphalt, concrete and paved roads, and has a positive correlation value for NDVI and SAVI (0.739), which closely represent vegetation characteristics. This component increases by expanding the level of urban built-up, impermeable land, reducing urban vegetation and green areas. The vegetation index is the second variable that must be used in UBEQ modelling. Based on the component matrix, NDVI always contributes to NDBI. Therefore, the NDBI and NDVI indices are the most basic UBEQ indicators that both can be used in the simplest UBEQ modelling.

CONCLUSIONS

The mapping of liveable areas at Semarang City involves two indices. The index selected as the representative of medium-resolution built-up land is NDBI (using SWIR and NIR wavelengths). NDBI is the most suitable index to identify built-up land and assess the UBEQ or liveability at the research location based on the transformation index. The accuracy test shows 86.57%. In addition to the built-up land index, the UBEQ modelling uses two vegetation land indices: NDVI and SAVI, with 87.65 and 85% accuracies, respectively. Also, based on the factor analysis and sensitivity analysis results, it can be concluded that the combination of these three indices (NDVI, SAVI and NDBI) can represent urban biophysical parameters. Increasing the number of indices used to examine UBEQ does not necessarily produce better results. Redundancy of information on the spectral channel gives suboptimal results. In simple terms, the vegetation and built-up land indices can be used for UBEQ research, assuming that the urban areas consisted mostly of vegetation and built-up land. This simple method of mapping is highly applicable for medium-scale UBEQ mapping based on remote sensing imagery as long as the SWIR, NIR and visible wavelengths are used. The liveability aspect highlighted in this research is the urban biophysical environmental quality (UBEQ) instead of socio-economic factors like environmental preservation and exploitation patterns or perceptions about garbage disposal. The UBEQ modelling operates on the concepts that (1) high vegetation density decreases temperatures and increases humidity and (2) high building density induces urban heat island as a result of expanding impervious surfaces.

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RESEARCH PAPER

DYNAMICS OF URBAN GROWTH AND ENVIRONMENTAL CHALLENGES: A CASE OF KOLKATA, INDIA

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ABSTRACT. The history of development of Kolkata as a megacity in India dates back to 300 years. The scenario changed when the administrative headquarter of the British East India Company was established in erstwhile Calcutta, located at the bank of the River Hugli in the lower Gangetic plain. Since its inception, Kolkata has undergone rapid formal and functional change. Both national and international migration has led to the demographic explosion, urban industrial development and an increase in economic opportunities which caused environmental degradation. Until 1793, the urban dynamics of Kolkata followed a linear pattern along the left bank of the Hugli River. A similar trend continued along the right bank from 1793 to 1947 and extended up to its periphery post-independence. In this paper, an attempt was made to explore the influence of river ghats on the urban environment along the selected stretch of the River Hugli. Human activities like garbage disposal (0.089), sewage disposal (0.088) and idol immersion (0.084) have a negative impact on the river water. Secondly, this paper attempts to study the vertical expansion of Kolkata. It has been observed that the average height of buildings in the CBD area is 84.6 meters while along the peri-urban area it is only 10.61 meters proving the distance decay effect (R^2 = 0.405 and R^2 = 0.314). Besides, the mean values of DO (5.179mg/l), BOD (8.5mg/l) and COD (34.5mg/l) in the river water reflect the degrading water quality for the aquatic environment. Geospatial assessment techniques were used to understand the research problems and combat the environmental challenges. Complex functional development and decaying urban quality of life along the Hugli River has led to critical environmental transformation.

KEYWORDS: Urban Morphology, Distance Decay Effect, Sustainable Development, River Water Pollution, River Ghats

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INTRODUCTION

Since its inception Kolkata, or erstwhile Calcutta, has undergone a rapid change in terms of its urban morphology, environmental interaction, ambient air and water quality management (Roy 1982; Kosambi and Brush 1988; Mahadevia 2001; Bardhan et al. 2011; Mukherjee 2012). Due to rapid industrial growth, expansion of trade routes, progress in communication and commerce as well as irrigation in the agricultural sector there has been a swift increase in the urbanization in Kolkata along the river Hugli (Ghosh 1950; Helmer and Hespanhol 1997; Singh et al. 2015). As a result, exodus number of people from the vast hinterland started settling within the urban centres in search of job. The banks of the river Hugli experienced an imbalance in the growth of population because the river acted as a natural barrier that hindered people from settling alongside equally (Dhar 2014). This phenomenon led to the foundation of the crisscross transport network to connect either side of the river by rail and roadways development (Mandal 2000; Chatterjee 2007). Besides, densely settled urban pockets along the river discharge toxic waste which contaminates the water and is then transported further down the stream to reach the Bay of Bengal (Mukherjee 2009; Cengiz 2013). The long stretch of the river Hugli on the western side of Kolkata is characterized by the presence of numerous ghats ('Ghat' means series of broad and flat steps leading down to a river or water body. The term is commonly used in many parts of South Asia), which sprung up during different periods of history. They served for embankment protection apart from the services they rendered for trading, loading of merchandise on barges, boarding passengers on vessels and other religious and household chores (Chakraborty and Nath 1995; Dey 2013). With increasing layers of complex functional attributes, urban centres started flourishing in both vertical and horizontal dimensions at the cost of the environment (Sarkar and Bandyopadhyay 2013; Mitra et al. 2012). Therefore, to answer the research questions raised in this paper, the following objectives are taken into consideration, a) explore the status of the Hugli river based urbanization and adjacent urban environment in terms of land use patterns; b) assess the quality of ferry services that connect Howrah and Kolkata; and c) examine the status of water pollution in the Hugli river and people's perception of the possible causes. The Hugli river as a part of the Ganga action plan (National Mission for Clean Ganga, Ministry of Water Resources, River Development & Ganga Rejuvenation 2018) requires thorough investigation regarding human interference in Kolkata through the assessment of municipal solid and liquid waste management, agricultural effluents, ferry transportation services, idol immersion etc[1].

[1]www.nmcg.nic.in 2018

The nineteenth century ushered in a new era of development in commerce, which made Kolkata a centre of trade and capital. However, it was in 1690 when Job Charnock realised the potential of this region and laid the foundation of British Calcutta[1] on the site of the *Sutanuti, Govindapur and Kalikata* villages on the eastern bank of the Hugli river (Murphey 1964; Mitra 1977). With the growth of trade, attention was given to the improvement of communication systems, and mercantile activities in Calcutta received a tremendous stimulus with the opening of railways and other new lines of communications (Ghosh 1991; Bhattacharyya 2018). Naturally, the port of Calcutta called for further improvements, which led to the construction of docks (Bhatta 2009). It must be noted that up until 1860 the port of Calcutta had a very small hinterland[2] comprising only Howrah, Hugli, 24 Parganas, and a small part of eastern Bengal (Fig. 1). But the establishment of jute and cotton factories in Calcutta and its suburbs and the opening of the new lines of communication expanded this hinterland (Table 1). With the development of heavy machinery and production units, manufactured goods were distributed to various parts of India from Calcutta. The major items of export from this region were indigo, jute, cotton etc. (Bhaskaran 2014; Mitra and Mitra 2015).

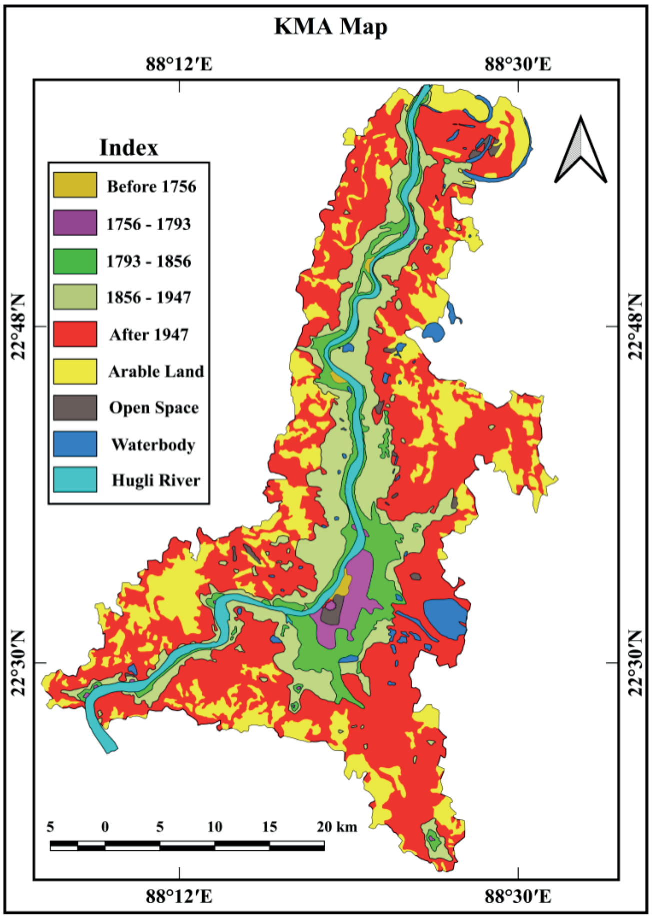


Fig. 1. Growth of Kolkata Metropolitan Area (KMA)

STUDY AREA

Kolkata Metropolitan Area (KMA) extends beyond Kolkata Municipal Corporation (KMC) area and stretches over the neighbouring districts like Howrah and Hugli along the right bank of the Hugli river, whereas, Nadia, North 24 Parganas and South 24 Parganas are located along the left bank. Since the Hugli river flows through the middle of the KMA area, it divides the area into western and eastern halves (Majumder 2020). The study area (Fig. 2) for the present paper stretches between Hugli bridge or *Vidyasagar Setu* in the south to Bally bridge or *Nivedita Setu* in the north, with Howrah bridge or *Rabindra Setu* in the centre. The total length of the right bank which is under the Howrah Municipal Corporation is 11.76 km. The left bank stretches about 12.42 km. Regarding the location of the linking bridges, Hugli and Howrah Bridge belong to the KMC area and Bally Bridge is located outside of KMC. The selected stretch of the river within the study area is meandering and concaving towards Kolkata.

MATERIALS AND METHODS

This paper is a blend of both quantitative and qualitative analysis based on both primary and secondary data. While studying the selected stretch, the area was divided into four zones. The criteria of classification of the zones are mainly based on administrative jurisdictions (KMC and KMA), distance from Central Business District (CBD) of Kolkata and orientation of the three main bridges passing through the river Hugli. With the help of GPS, ghats, bridges and riverside buildings were digitally observed to understand their geospatial pattern. A total of 11 ghats on the left bank (4 ghats in Zone I and 7 ghats in Zone II) and 3 ghats on the right bank (1 ghat in Zone III and 2 ghats in Zone IV) are taken into consideration in this study. The criteria of sub-grouping the ghats are mainly based on their accessibility in terms of taking bath, regular immersion of idols, sources of the toxic municipal outfall, religious site, burning ghats and availability of ferry service. Water samples were collected on a stratified random selection basis to measure the water quality and different water properties. The map of Land Use Land Cover (LULC) pattern showing its evolution from erstwhile Calcutta to contemporary Kolkata is referred from the National Atlas and Thematic Mapping Organization (NATMO) map which was prepared by P. Nag (1997)[3].

Table 1. Growth and Development of Kolkata Metropolitan Area along the Hugli River

TIMELINE	SPRAWL AND OUTGROWTH
Till 18^{th} century	Mainly colonial Calcutta was developed during this era. Along with it other colonial towns like Sreerampore, Chandannagar and Chunchura also developed in different isolated pockets
Early 19^{th} century	The outgrowth of urban areas in a linear pattern along both east and west bank of the Hugli river from Kalyani in the north to Uluberia in the south
Mid 19^{th} to mid 20^{th} century	Extensive urban development and spreading off to peri-urban areas of the adjacent districts away from the Hugli river
Late 20^{th} century to early 21^{st} century	Calcutta conurbation development because of increased linkage with neighboring towns along the Hugli river.

[1]Mitra 1952
[2]Kundu 2003
[3]NATMO 1997

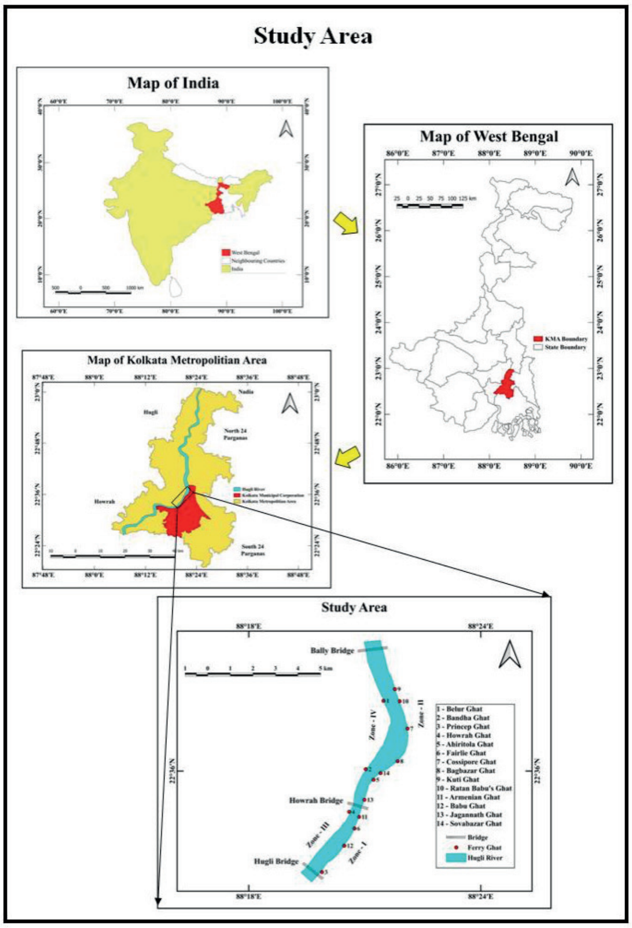


Fig. 2. Location of the Study Area in Kolkata, India

This land use land cover map comprises the historical evolution of Kolkata over the past 300 years. Location map is prepared and analysed using Q-GIS mapping software. Round-the-clock ferry service analysis was prepared based on the data collected from the West Bengal Transport Corporation Department (2016). A perception study on 488 respondents which is about 0.6 percent of the average daily number of passengers through a Ferry ghat was conducted to understand the ferry service quality. Another perception study on 209 respondents which is about 3.12 percent of the daily average number of visitors of a Ghat was conducted to understand water pollution in the Hugli River on a random sampling basis. The Average Weighted Index (AWI) technique was employed to verify the ground truth and correlate the opinions to combat the environmental challenges.

RESULTS AND DISCUSSION

Urban Morphology of Kolkata

Kolkata started developing around the Esplanade and BBD Bag area, which currently functions as the Central Business District (CBD) of the city. The area is occupied with the law and administrative offices, business and commercial centres, sports and entertainment venues, market and transport headquarters, which characterizes its land use pattern as that of a business district area. Over time, the urbanization process has achieved its highest rate and reached distant suburban places (Rajashekariah 2011), although the land value and demand decrease with increasing distance from the CBD area. The city has experienced rapid growth mainly in its south, east, south-east, and south-west direction (Fig. 1). Apart from horizontal expansion, the CBD area has experienced vertical extension with skyscrapers, high-rise administrative and residential buildings. Towards the north along the left bank of the Hugli river, Kolkata experiences a gradual and rapid transformation of land use from administrative to old and native residential type (Table 2). Jute, cotton, chemical industries etc. are found away from the CBD area and mostly along the river bank.

On the other hand, the scenario of urban development along the right bank of Hugli river under the Howrah Municipal Corporation area (HMC) is indeed different. The area is mainly covered by densely populated residential areas like Bally, Belur, Liluah, Salkia, Ghusuri etc. being the headquarter of the southeastern railway, Howrah station is located on the right bank of the Hugli river and extends over a vast area. Other than that, Avani riverside mall has come up as an alternate recreational destination. Peri-

Table 2. Zone-wise Land Use analysis along the Hugli River

ZONES	MAJOR LANDMARKS ALONG THE RIVER	MAJOR LAND USE TYPES
Zone – I (3.88 km)	Lord Princep memorial park, Victoria Memorial, Racecourse, Fort William, Esplanade, New Market, Shahid Minar, Eden Gardens, Netaji Indoor Stadium, Babu Ghat bus terminus, Ordinance factory headquarter, Calcutta high court, Calcutta swimming club, Raj Bhavan, St. Johns Church, New Secretariat building, GPO, Flotel, SBI headquarter, Millennium park, Laldighi, BBD Bag, Writers building, Lalbazar, Fairley place, Kolkata Port Trust headquarter, Bengal chamber of commerce, Armenian church, Barabazar, Mahatma Gandhi road, Mallick ghat flower market etc.	Law, Administrative and Defence, Business and Commercial, Sports and Games, Leisure and Entertainment, Market area and Transport
Zone – II (8.54 km)	Loha patti, Jorasanko, Jorabagan, Nimtala burning Ghat, Rambagan, Garanhatta, Ahiritola, Beniatola, Hatkhola, Rabindra Sarani, Kumartuli, Sovabazar, Hatibagan, Bagbazar, Canal and Lock gate, Circular railway, Chitpur, Ghoshbagan, Chunibabu Bazar, Cossipore, Paikpara, Tala, Swadagar Pally, Goshala Basti, Mitra Bagan, Satchasi Para, Ramlila Bagan, Sinthi, Sajye Bagan, Rabindra Bharati University, Baranagar, Baranagar Jute Mill, Bon-Hugli, Alambazar, Ashokegarh, U B colony, Dakshineswar Temple, etc.	Mainly pockets of old residential areas which are named after the occupation class of the natives. Mixed land use and partly Industrial
Zone – III (3.66 km)	Avani river side mall, Choura basti, Lichu bagan, Railway museum, Railway club, Howrah railway station, Howrah bus depot, Howrah taxi stand etc.	Rail transport and warehouses, partly residential
Zone – IV (8.10 km)	Gulmohar Railway Quarter, Pilkhana, Mali Panch Ghara, Salkia, Ghusuri, Bhotbagan, Vivekananda Pally, Liluah, Belur, Belur Bazaar, Belur Math, Barendra Para, BBD Nagar, Bally etc.	Mostly mixed residential and partly industrial

urban expansion along this bank has no limit as it has already reached the interior of the Howrah and Hugli districts. Apart from horizontal expansion, the vertical urban limit along this bank is inadequate, although newly built residential complexes are increasing the limit of the skyline.

It has been observed that the river Hugli which flows southward is gradually reaching sea level. The extension of the Hugli river towards its downstream between Bally bridge (MSL 14 meters) and Hugli bridge (MSL 05 meters) shows a trend of descending elevation. Contrary to it, from the CBD to the suburban areas, the vertical urban extension of Kolkata is gradually decreasing as we move upstream along the Hugli river. The majority of the high-rise buildings are located within the CBD area[1]. For example, Chatterjee International (91m, 24 floors), Tata Centre (79m, 18 floors), The 42 (245m, 62 floors), Everest House (84m, 21 floors), Birla House (60m, 16 floors), New Secretary Building (38m, 12 floors) etc. Peripheral areas do not only transform to residential land use, but the average height of buildings in areas like Shovabazar, Ahiritola, Cossipore, Baranagar, Bally, Belur etc. have shown gradual decrease (Fig. 3a and 3b).

Ferry Service over the Hugli River

Days before steamers and railways made their appearance in India, the principal means of transport in Bengal and the province of Hindustan was by boats, laboriously towed or sailed over the magnificent waterways of the Ganges and its affluent (Munsi 1980). The present study area is a part of the National Waterway – 1 (NW-1 runs 1620 km from Haldia in West Bengal to Allahabad in Uttar Pradesh) which passes through the Ganges, Bhagirathi and Hugli river systems[2]. A total of 28 ghats that are found within the study area are either used for ferry services and or for public bathing. Ferry service on the Hugli river is a transport breakpoint between Howrah and Kolkata. Compared to other modes of transport available in Kolkata, the ferry service is not the ultimate choice for passengers. Perhaps due to its nominal fare, it was initially used by industrial labourers to reach their workplaces which were situated along the bank of the river Hugli.

Perception study on the quality of the ferry service reveals that passengers are highly satisfied with low transport cost, level of comfort during journey and contribution of ferry service to mass transportation in Kolkata. They are also satisfied with the service frequency and connectivity of the ghats they commute through. On the other hand, the majority of people are partly satisfied with the surrounding environment of the Ghats, travel time and speed of the vessel. And lastly, people are not satisfied with the late-night security for both men and women due to increasing antisocial activities in the city (Table 3). Ferry service as a mode of transport is a dying sector in Kolkata. Since it connects the breakpoint of transport between Howrah and Kolkata, its significance cannot be denied.

Water Pollution in Hugli River

Wastewater discharges did not disturb the balance of the ecosystem since the nature has the capacity to degrade the wastes and restore. With the increasing pressure of

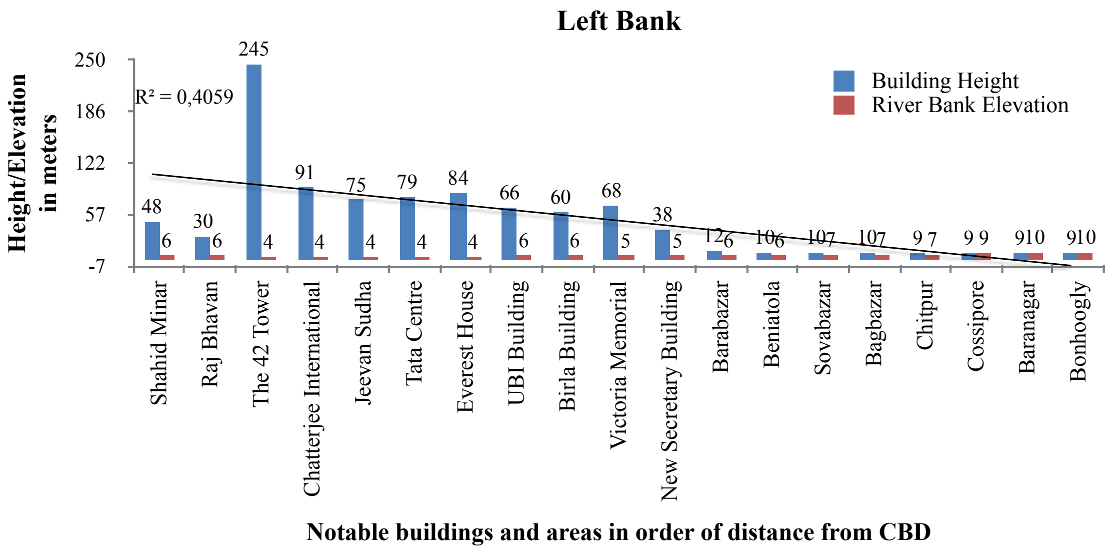


Fig. 3a. Comparing River Bank Elevation and Building Height in Kolkata along the Left Bank of the Hugli River

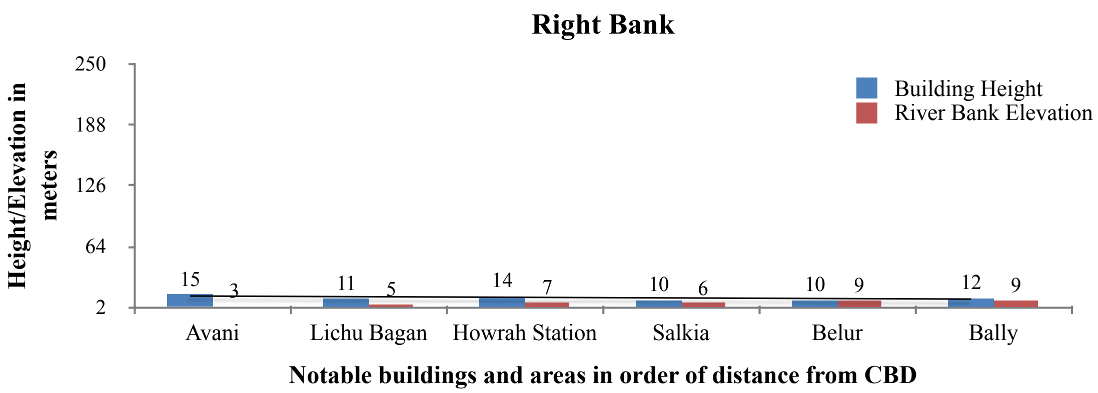


Fig. 3b. Comparing River Bank Elevation and Building Height in Howrah along the Right Bank of the Hugli River

[1]www.skyscrapercenter.com 2015
[2]www.iwai.nic.in 2021

Table 3. Passengers' Perception on the Quality of Ferry Service over the Hugli River

ISSUES	HIGHLY SATISFIED	SATISFIED	PARTLY SATISFIED	NOT SATISFIED	NOT AT ALL SATISFIED	AVERAGE WEIGHTED INDEX (AWI)
Service Frequency	124	182	125	49	8	0.069
Passenger Fare	252	101	75	46	14	0.077
Vessel Quality	127	113	162	80	6	0.064
Crowd and Queue	129	83	160	101	15	0.061
Travel time and Speed	92	110	189	81	16	0.060
Late night Security	53	74	129	162	70	0.044
Ghat Connectivity	141	147	110	90	0	0.067
Ghat Environment	49	109	243	70	17	0.055
Journey Comfortability	323	139	21	5	0	0.090
Contribution to Mass Transport	247	147	52	42	0	0.081
Total Number of Respondents						N = 488

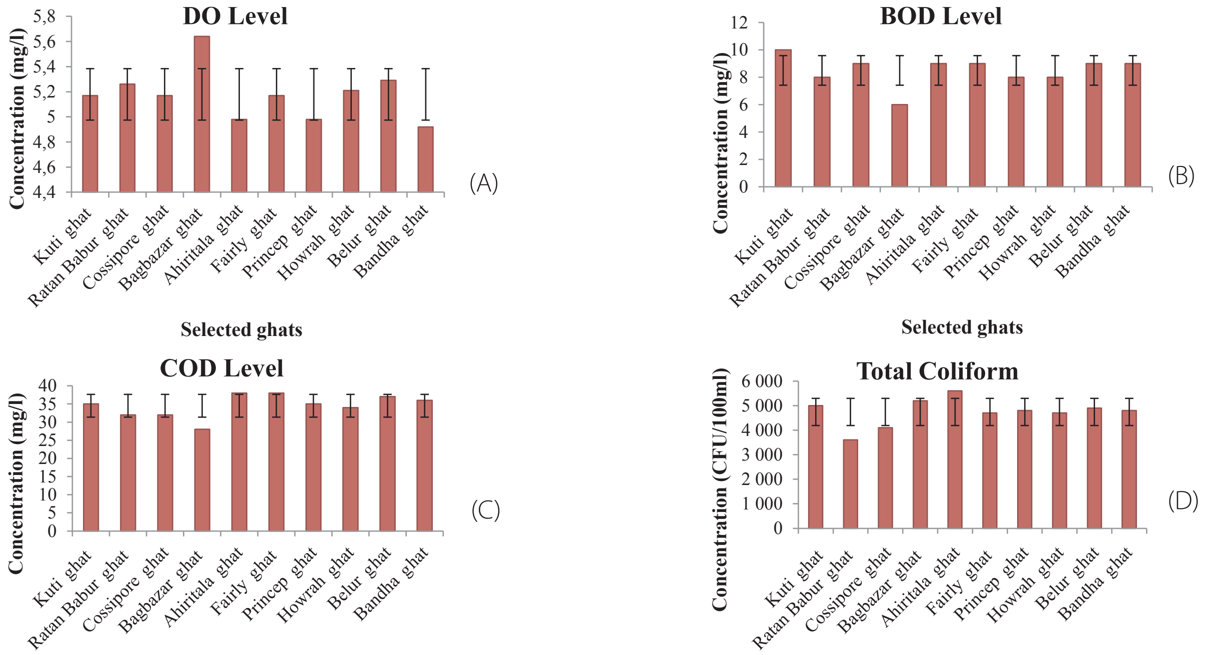
population and the shooting up level of pollution, the replenishing capacity of nature had gradually slowed down (Mohanta and Goel 2014). Municipal and industrial wastewaters are directly released into water bodies with or without treatment (Rudra 2015). In addition, other anthropogenic activities such as agriculture result in a non-point discharge of pollutants into rivers causing serious environmental problems and therefore posing a threat to human health (Table 4). This has led to deterioration in water quality rendering it unsuitable for human consumption and sustenance of aquatic life (Shaw 2005). Taking the selective parameters into consideration and their threshold limit, the Hugli river ghats exhibit an escalating pollution profile (Basu and Main 2001; Biswas 2003). Maximum and minimum values were recorded and the permissible limit was also noted to measure the vulnerability of ghats. These ghats are used by the local people for bathing, washing clothes and performing other daily rituals. Unlike Banaras ghats where people visit for religious ceremonies as well as for recreation, Kolkata ghats are not only devoid of such provision but are struggling for existence. (Bhaduri 2012). However, to commemorate the hundred years of Kolkata Port Trust (KPT), entire ghats, bridges and amusement parks were lit up for urban renewal and aesthetic beauty.

The Hugli river ghats are used for multiple purposes which has influenced the degree of association of people with it. Be it religious or domestic or transport, river ghats have turned into a dumping point. This has not only resulted in environmental imbalance but also negatively affected the levels of Dissolved Oxygen (DO), Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD) and Coliform bacteria. Excessive growth of algae and eventually lowering level of dissolved oxygen in water poses a serious threat to aquatic life. This can result in insufficient amounts of dissolved oxygen available for fish and other organisms. At sea level, typical DO concentrations in 100-percent saturated fresh water will range from 7.56 mg/L at 30 degrees Celsius to 14.62 mg/L at zero degrees Celsius[1]. An inter-ghat analysis of DO level shows that the aquatic system of the Hugli river is under serious threat (Fig. 4A). BOD test was also performed to determine the effect of dirty water containing bacteria and organic materials on

Table 4. Details of Selection Criteria of Water Sample Collection from different Ghats

SELECTED GHATS	SOURCE OF OUTFALL	CRITERIA OF SELECTION
Kuti ghat	Outfall from burning ghat	Burning Ghat, idol immersion
Ratan babur ghat	Outfall from burning ghat and local drains	Burning Ghat, idol immersion
Cossipore ghat	Outfall from temples and factory areas	Temples, small factories, ferry service
Bagbazar ghat	Outfall from temples and burning ghat	Temples, ferry service and circular railway
Ahiritola ghat	Outfall from burning ghat and local drains	Nimtala burning ghat, temple and ferry service
Fairly ghat	Outfall from parks and stations	Ferry service, frequent movement of boats, circular railway station and Millennium Park
Princep ghat	Outfall from army campus	Military camp, Hugli Bridge and circular railway station
Howrah ghat	Outfall from Howrah railway station	Ferry service
Belur ghat	Outfall from Belur math and surrounding areas	Ferry service
Bandha ghat	Outfall from Salkia area	Bathing ghat, idol immersion

[1]Minnesota Pollution Control Agency 2009



Source: Envirocheck 2009

Fig. 4A to 4D. Level of different Chemical and Biological Parameters in the Water of the Hugli River

animal and plant life when released into a stream or lake (Fig. 4B). Chemical Oxygen Demand is another important water quality parameter because it provides an index to assess the effect of discharged wastewater on the receiving environment (Fig. 4C). Higher COD levels mean a greater amount of oxidizable organic material in the sample, which will reduce Dissolved Oxygen (DO) levels. Therefore, DO is inversely correlated with COD and BOD. The presence of Coliform bacteria in water on the other hand indicates faecal contamination and can cause diarrhoea and other dysenteric symptoms. A minimum of 3600 to maximum 5600 mg/l threshold of Coliform bacteria presence is safe but the results of ghat-wise analysis shows an alarming state of the Hugli Rriver water for human consumption (Fig. 4D).

Peoples' views and concerns regarding the emerging environmental problems were analysed through a perception study on 209 individual respondents, randomly selected from different ghats. People strongly agree upon the threats arising due to industrial waste, garbage disposal, sewage disposal and idol immersion. People are unsure about their opinion on bathing and washing in the Hugli river but they agree that dead bodies and animal waste play a significant role in the contamination of the river Hugli. Thus, people indirectly blame the municipal discharge of sewage water and industrial waste but are not ready to take any voluntary initiative at a micro level to keep the Hugli clean. Ever-increasing pressure of population on either side of the Hugli river and escalating index of urban growth act as a catalyst towards further environmental decay (Table 5).

CONCLUSION

The discussion in the preceding paragraphs has directed attention to the changing trend and pattern of urbanisation in the Kolkata Metropolitan Area along the river Hugli, which will be insightful in guiding the future planning and policy execution for the city. Fundamentally, it was observed that

Table 5. People's Perception on Causes of Water Pollution in the Hugli river

CAUSES	STRONGLY AGREE	AGREE	PARTLY AGREE	NOT AGREE	NOT AT ALL AGREE	AVERAGE WEIGHTED INDEX (AWI)
Idol Immersion	118	50	37	4	0	0.084
Bathing	19	92	75	14	9	0.062
Washing	31	45	60	55	18	0.052
Animal Waste	45	59	25	65	15	0.056
Agricultural Waste	96	51	38	6	18	0.074
Industrial Waste	138	45	18	8	0	0.087
Garbage Disposal	129	66	14	0	0	0.089
Sewage Disposal	135	51	23	0	0	0.088
Ferry Service	31	43	61	41	33	0.050
Dead Bodies	22	74	81	19	13	0.059
					Total Number of Respondents	N = 209

urban dynamics and river hydrodynamics are negatively correlated. Horizontal urban sprawling along with skyscrapers and high-rise projects in Kolkata have extended the vertical limit of the city challenging the environment and urbanization balance during the last three decades. The urban morphology of Kolkata is therefore changing into a complex functional landscape due to growing interaction and direct dependence of people on the river Hugli. Crisscrossing bridges and river transport connectivity between both banks of the Hugli have influenced the urban economic opportunities for both Howrah and Kolkata. Due to the continental drift of the Indian plate in the northeast direction against the Asian plate, the Meghna basin is getting deeper and the river Hugli is suffering from a lack of water flow. The Ganga action plan is therefore of much significance to increase the navigability of this river, sustain the water flow and reduce bacterial concentration with seasonal variation. Symbiotic consideration of issues like urban development, environmental protection, economic growth, morphometric dynamics of the river, socio-cultural interaction etc. can make the city environmentally sustainable and develop as a complex urban morphology.

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RESEARCH PAPER

FOREST FRAGMENTATION AND LANDSCAPE STRUCTURE IN THE GUAMÁ RIVER BASIN, EASTERN AMAZON

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ABSTRACT. The Guamá River basin, in the northeastern state of Pará, eastern Amazon, Brazil, encompasses approximately 1,200,000 hectares. It presents great economic and social importance and is under significantly changes in land use and land cover. The objective of this work was to analyze and characterize the landscape structure of this basin through landscape ecology indexes (density, size, metric variability, shape, core area, proximity indexes, and patch area index). Land use and land cover maps were developed using images from the RapidEye system through supervised digital classification. The vegetation and landscape structure were quantified in patches, classes, and land cover. The forest patches were associated with partial conservation of some areas where production sectors had not yet directly affected, or those from natural regeneration of abandoned areas, mainly pastures. The class vegetated area was the second class most representative of the Guamá River basin covered about 37% considering the total area. The basin landscape presented more than 34,000 vegetated area patches It showing that this class are very fragmented by the presence of a large number of small patches, with this the basin landscape is compromised regarding its ecological integrity, since more than half of its forest patches are in edge environments. The indexes enabled a good joint analysis of the sub-basins of the Guamá River basin, resulting in a more detailed overview of the forest fragmentation process.

KEYWORDS: forest fragmentation, landscape ecology, land use

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INTRODUCTION

The Amazon region has presented increases in anthropogenic actions on natural environments in the last decades, intensifying processes that replace natural vegetation by other land covers. These interventions had converted extensive and continuous areas covered with forests into agriculture, urban areas, and other covers, causing environmental impacts. In many cases, the lack of planning for these processes threatens water sustainability of basins in the Amazon region (Yesuph & Dagnew 2019).

The maintenance of forest cover is essential, since it is responsible for several environmental services, such as soil physical and mechanical protection, climate and soil microbiota regulation, and protection of slopes against erosion, biodiversity, water sources, and groundwater (Mascarenhas et al. 2009). However, agriculture and cattle raising are, among others, the causes that contribute the most to the fragmentation of primary vegetation (Batista et al. 2012). Thus, studies on forest fragmentation have diagnosed factors and applied different indexes that assist in understanding the landscape dynamics and functions and the changes in the landscape caused by anthropogenic actions (Pereira et al. 2015). Studies on dynamics of land use and land cover (LULC), mainly in large areas such as the Amazon region, are based on the analysis of remote sensing data (Klimanova et al. 2017).

The sustainability and development of the Amazon region require deforestation diagnoses and LULC studies, in addition to public policies focused on environmental services, mainly for the recovering of degraded areas, biodiversity conservation, maintenance of water resources, and mitigation of climate changes (Freitas & Freitas 2018). In this context, the Guamá River basin, in northeastern state of Pará, Brazil, encompasses 19 municipalities which together form one of the largest agricultural production centers in Pará (Brazil 2010); it is also important for the historical and economical context of the production dynamics in the Amazon region (Rebello et al. 2011). Thus, the understanding of the landscape structure is needed, grounding the application of methods related to conservation and preservation of the forest cover. Therefore, the objective of this study was to analyze the forest structure of the landscape of the Guamá River basin, considering its sub-basins, and to determine its forest fragmentation patterns based on Landscape Ecology indexes.

MATERIALS AND METHODS

The Guamá River basin (Fig. 1) is between 03ºS and 1º40'S and 48º45'W and 46º45'W; it has approximately 1,200,000 ha, encompassing 19 municipalities of the state of Pará, Brazil: Ananindeua, Acará, Belém, Benevides, Bonito, Bujarú, Capitão Poço, Castanhal, Concórdia do Pará, Garrafão do Norte, Inhangapi, Irituia, Mãe do Rio, Marituba, Ourém, São Domingos do Capim, São Miguel do Guamá, Santa Izabel do Pará, and Santa Luzia do Pará. Together they host approximately 2,700,000 inhabitants (Brazil 2010). For analysis purposes, the Guamá River basin is divided into eight sub-basins: Lower Guamá River (163,960.76 ha), Apeú Creek (74,737.99 ha), Bujarú River (99,019.23 ha), Middle Guamá West Sector (142,137 ha), Middle Guamá East Sector (191,134.49 ha), Mãe do Rio Creek (155,244.52 ha), Sujo River (46,012.53 ha), and Upper Guamá River (331,639.30 ha).

Forty-three orthorectified satellite images of the RapidEye system were selected to cover this area and make the LULC classification. The image selection was based on cloudiness percentages (priority), data quality, data availability, and season. RapidEye images presented 5 m of spatial resolution and five spectral bands positioned at: 440-510 nm (Blue), 520-590 nm (Green), 630-690 nm (Red), 690-730 nm (Red edge), 760-880 nm (Near-infrared). The data of the selected images were: 06/29/2011, 07/28/2011, 08/04/2011, 2011, 10/23/2011, 07/31/2012, 08/02/2012, 09/13/2012, 10/24/2012, 08/01/2013, 09/04/2013, 08/17/2014, and 11/25/2014. The images were acquired from the Geo Catalog of the Brazilian Ministry of the Environment.

The algorithm of maximum likelihood classification (MLC) was used for the supervised classification, and 236 points collected during a fieldwork in 11 municipalities were used for the training. Training samples were selected by delimiting polygons around representative sites for each LULC type. The LULC classes found and their respective keys were:

a) Vegetated area: secondary vegetation in different succession stages, reforestation areas, and native forests;
b) Agriculture: permanent and temporary crops used for subsistence and commercialization;
c) Occupation areas: urban areas, villages, and commercial and industrial areas;
d) Uncovered soil: roads; access routes; paved, unpaved and gravel roads; and mineral extraction areas;
e) Pasture: intensive and extensive husbandry, with animals or abandoned, with predominance of forage species;
f) Water body: rivers, lakes, streams, and creeks.

In addition to these classes, we obtained the categories described as "non-bserved areas", represented by clouds and their shadows, and as "others", such as river banks, stretches of sand, and rocky outcrops, which were considered only as spatial representation classes. The processing included a sample quality accuracy analysis to quantify and evaluate the classification and to obtain a high Kappa index, which is used to evaluate, validate, and report the reliability level of the classification (Pan et al. 2020), and an evaluation in a cross-tabulation (transition) matrix (Twisa & Buchroithner 2019).

The vegetation and landscape structure were quantified in patches, use classes, and land cover (Mcgarigal & Marks 1994; Mcgarigal et al. 2009), considering the following indexes:

a) Density, size, and metric variability: number of patches (NP) - number of patches that comprise each class; patch density (PD) - number of patches per unit of area (100 ha);

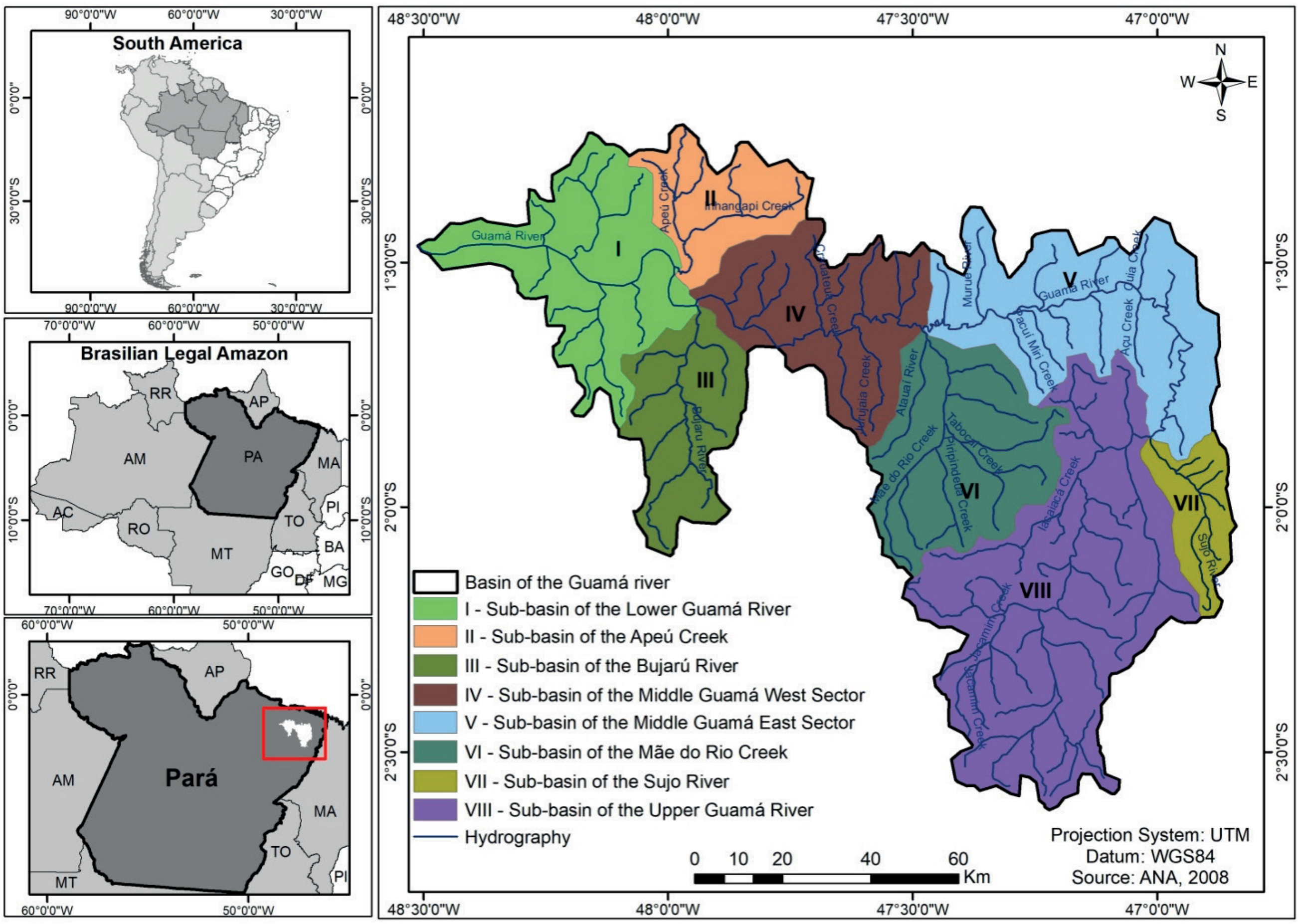

Fig. 1. Guamá River basin: division into sub-basins

mean patch size (MPS) - calculated based on the total area of the class and its respective number of patches; patch size standard deviation (PSSD) – a measure of absolute variation, which shows the variation of a patch size in relation to the mean; and patch size coefficient of variation (PSCV) – a measure of relative variation, which quantifies the variance of the data according to the mean.
b) Shape: mean shape index (MSI) - mean shape of the patches of the assessed class, according to mean perimeter to area ratio of their patches, compared to a standard shape; area-weighted mean shape index (AWMSI) - calculated similarly to the mean shape index; fractal dimension (FRAC) – the shape complexity of the patches that comprise the analyzed class; it varies from 1 (spots with simpler and more regular shapes) to 2 (spots with more complex shapes).
c) Core area: number of core areas (NCA) - number of patches that have a core area after the removal of the edge effect for each class; total core area (TCA) - sum of all core areas found; mean total core area (MTCA) - total core area divided by the number of patches that have core areas; total core area index (TCAI) - percentage of the class occupied with the core area after the removal of the stretch referring to the edge effect (edge = 100 m width).
d) Proximity indexes: mean proximity index (MPI) - mean distance between patches of different classes, based on a radius previously determined (100 m); mean nearest-neighbor distance (MNN) - mean distance between patches of the same class; nearest-neighbor standard deviation (NNSD) - variation of distance in relation to the MNN; nearest-neighbor coefficient of variation (NNCV) - variation of the data according to the mean.
e) Patch area index: area of each patch (ha).

RESULTS AND DISCUSSION

The Guamá River basin has a total area of 1,203,886.12 ha, which are distributed over eight sub-basins. The classes pasture and vegetated area covered, respectively, 49.78% and 37.43% of the total area (Fig. 2 and Table 1). This pattern, mixed by pasture and vegetated areas is usually found in opened areas in the Amazon region, where pasture areas are the predominant LULC (Pereira et al. 2015). All sub-basins analyzed had most of their areas with pastures, indicating a significant change in the original landscape due to the advance of animal husbandry, except for Lower Guamá River and Bujarú River. Watrin et al. (2009) point out that extensive and intensive pastures are the dominant land use in the northeast region of Pará. More than 20% of the areas in the Legal Amazon region were deforested (Castro & Andrade 2016). It is associated with large land properties that use this areas for grazing cattle. When the pasture yield reduce the pasture is abandoned and become a secondary vegetation (Carvalho et al. 2019). The sub-basins Lower Guamá and Bujarú (West region) have predominantly native forests and secondary vegetation, including reserve areas (80% of the forest cover is preserved in rural properties) and permanent preservation areas (forest cover in vulnerable areas, such as river banks, hilltops, and slopes), which is according to the Brazilian federal Law 12.651/2012 (Barroso et al. 2015).

The agricultural areas covered approximately 6% of the Guamá River basin, with the sub-basins ranging from 2% to 9%. According to the Agriculture Census of 2017 of the Brazilian Institute of Geography and Statistics (IBGE), these agricultural areas present mainly crops of orange (*Citrus sinensis*), manioc (*Manihot esculenta L.*), palm oil (*Elaeis guineenses Jacq.*), and black pepper (*Piper nigrum L.*), and this information was confirmed through

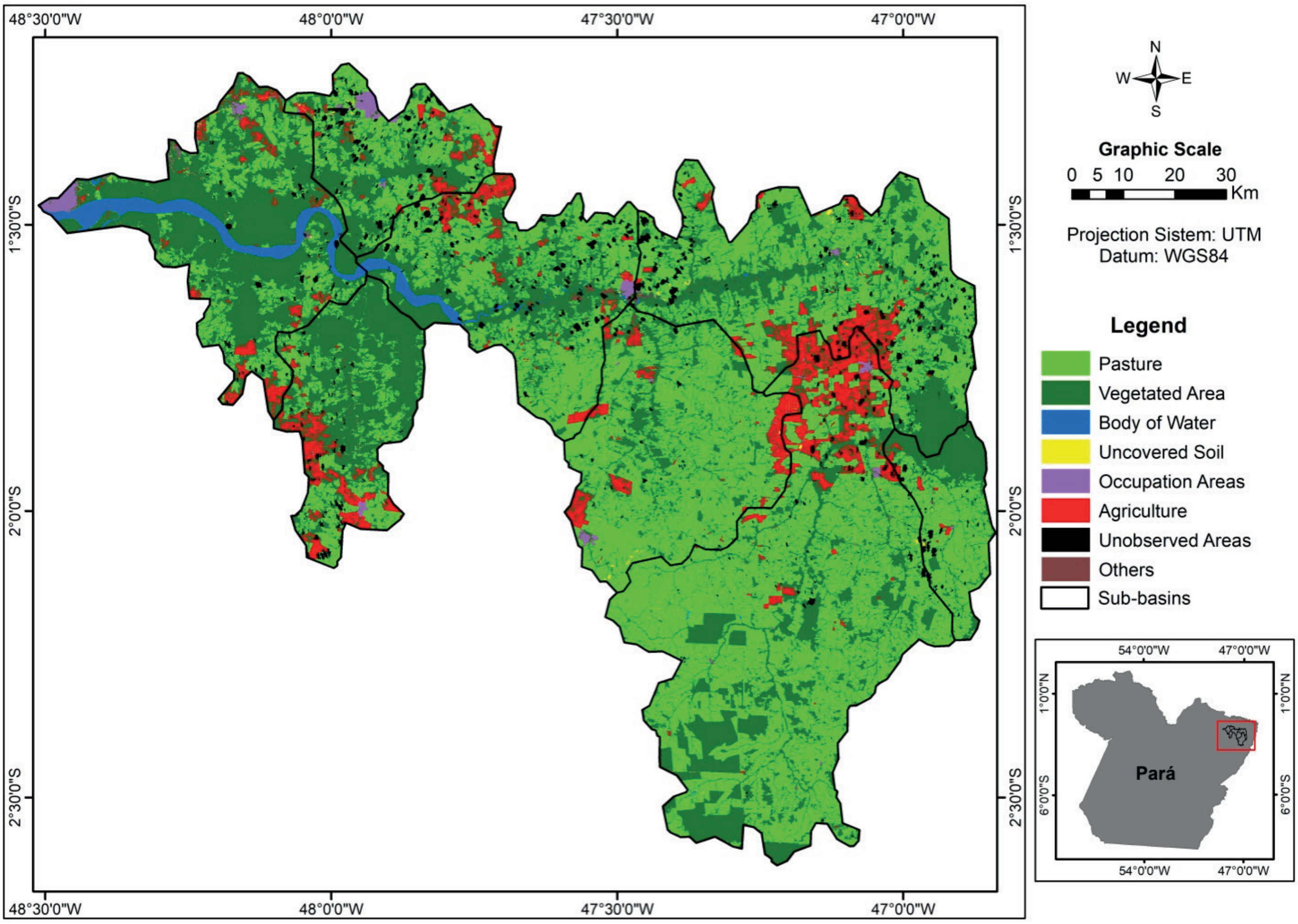

Fig. 2. Land use and land cover in the Guamá River basin

Table 1. LULC quantification matrix in sub-basins of the Guamá River

Land Use and land cover	Sub-basin area (ha)							
	Upper Guamá	Apeú Creek	Middle Guamá West	Lower Guamá	Mãe do Rio Creek	Middle Guamá East	Bujarú River	Sujo River
Vegetated Area	96,444.02	29,318.04	53,676.70	94,885.30	37,359.57	66,943.62	54,964.38	17,046.30
Agriculture	21,670.75	4,510.68	7,326.20	7,471.78	9,133.91	12,168.01	9,607.55	1,121.28
Pasture	204,207.79	32,601.57	65,790.25	38,121.28	104,811.65	97,848.97	30,131.77	25,761.48
Uncovered Soil	2,697.34	647.03	713.04	1,287.22	1,070.63	1,352.47	723.69	212.18
Occupation Areas	1,456.51	2,383.10	932.37	3,551.84	1,119.91	563.83	630.30	91.56
Water bodies	1,315.22	305.42	5,679.57	14,926.79	282.91	1,361.14	163.81	18.25
Others	149.97	104.04	614.94	346.94	122.74	484.29	156.21	73.02
Unobserved Areas	3,697.70	4,868.11	7,404.23	3,369.61	1,343.20	10,412.16	2,641.52	1,688.46
Total	331,639.30	74,737.99	142,137.30	163,960.76	155,244.52	191,134.49	99,019.23	46,012.53

field visits. The other classes had lesser representativeness in the basin, with less than 3% for each one of them.

The landscape presented 34,616 vegetated area patches, which was the second most representative class of the Guamá River basin, occupying an area of 450,637.93 hectares (Table 2). The analysis of the landscape structure was carried out considering only land covers shown by all vegetated areas.

The sub-basins that present the highest number of patches were those in the Upper Guamá (9,681) and Middle Guamá East (6,540), and the first had the largest area in relation to the vegetation areas. The data showed a high degree of fragmentation in the sub-basins, which represents the effects of human occupation. The sub-basins Sujo River (1,652) and Bujarú River (1,752) presented the lowest numbers of patches, and the Sujo River presented the lowest total vegetated area (17,046.30 ha).

The patch density index allows for the comparison of landscapes of different sizes. The sub-basins Mãe do Rio Creek, Sujo River, and Middle Guamá East showed the largest number of patches per area. The Lower Guamá River and Bujarú River had the lowest patch density and number of patches per area, denoting a minor degree of fragmentation.

The sub-basins Mãe do Rio Creek, Middle Guamá East, and Upper Guamá had greater fragmentation than the others, presenting the smallest sizes of forest patches (3.90 ha, 5.87 ha, and 5.96 ha, respectively), making them the most fragmented units of the basin. The distribution of vegetated areas is associated with land use, in this case, predominantly pastures. These sub-basins also presented the largest numbers of water sources; thus, forest preservation actions should consider it to increase the preservation of these areas.

The mean patch size is a good indicator of the degree of fragmentation because it is consistent with the number of patches and total area occupied by a class (Pirovani et al. 2014). According to McGarigal and Marks (1994), the lowest values of mean patch sizes found for a landscape characterizes it as the most fragmented one. The correlation between density index and mean patch size showed that the sub-basins that have a larger mean patch size and a lower patch density have higher patch concentrations than the mean. Thus, the correlation between number of patches and area occupied by them is inversely proportional.

The high standard deviation and coefficient of variation found indicated a large number of small patches in the areas. Thus, there is a wide difference between the sizes of forest patches of each sub-basin, denoting a spatial heterogeneity of spots in them. According to Azevedo et al. (2016), the mean patch size should be analyzed together with standard deviation and coefficient of variation because high values may represent the existence of large patches, even when their mean size is low. The assessment of these indexes shows a more detailed interpretation regarding

Table 2. Sub-basin areas, total area of the vegetated patches, number of patches (NP), patch density (PD), mean patch size (MPS), patch size standard deviation (PSSD), and patch size coefficient of variation (PSCV)

Sub-basins	Area (ha)	Total area - patches (ha)	NP	PD	MPS (ha)	PSSD (ha)	PSCV (%)
Upper Guamá	331,639.30	96,444.02	9,681	2.92	5.96	119.88	2,011.13
Apeú Creek	74,737.99	29,318.04	1,964	2.63	7.76	225.97	2,911.37
Middle Guamá West	142,137.30	53,676.70	4,107	2.89	6.91	157.00	2,272.18
Lower Guamá	163,960.76	94,885.30	3,105	1.89	13.83	600.86	4,344.12
Mãe do Rio Creek	155,244.52	37,359.57	5,815	3.75	3,90	58.42	1,497.23
Middle Guamá East	191,134.49	66,943.62	6,540	3.42	5.87	121.27	2,066.05
Bujarú River	99,019.23	54,964.38	1,752	1.77	14.77	716.60	4,850.35
Sujo River	46,012.53	17,046.30	1,652	3.59	6.25	209.26	3,347.79
Total	1,203,886.12	450,637.93	34,616				

the degree of fragmentation in the sub-basins. Tables 3 and 4 present the number of patches and their area distributed by class size for a better assessment of the forest structure in the landscapes.

The remaining patches are connecting elements (stepping stones) between large area patches and, together, they are essential for the maintenance of ecological processes (Mcgarigal et al. 2009). Patch size is an important factor for the population dynamics because it affects the richness of species. Larger patches usually shelter more complex biodiversity, allowing for the expansion and maintenance of the biodiversity.

The northeast region of Para presents a tendency of fragmentation; therefore, the restoration of forest cover is needed (Tamasauskas et al. 2016). Studies focused on water production, increase in connectivity between patches, and soil protection contribute to researches and analysis of landscapes for the conservation of natural resources (Moraes et al. 2015). The pasture management in the study area increases the edge effect. The distribution of patches in the landscape and their interaction with each other is important to reduce the impact of land use on vegetated areas and changes in the forest fragmentation pattern (Lustig et al. 2015; Vizzari et al. 2018).

Table 5 presents the shape and core area indexes. The sub-basins Bujarú River, Lower Guamá River, and Apeú Creek presented higher indexes of area-weighted mean shape; the larger patches had an elongated shape near watercourses. The shape index and fractal dimension (near 1) denote the regularity of most patches, which was also observed by Tuong et al. (2019).

Table 3. Number of vegetation patches

Patches (ha)	Upper Guamá	Apeú Creek	Middle Guamá West	Lower Guamá	Mãe do Rio Creek	Middle Guamá East	Bujarú River	Sujo River
< 50	9,519	1,934	4,043	3,078	5,710	6,418	1,722	1,625
50 - 100	73	11	31	8	55	57	11	14
100 - 200	43	10	17	7	30	26	8	8
200 - 500	20	6	8	5	16	24	6	3
500 - 1.000	16	0	3	3	2	6	4	1
> 1.000	10	3	5	4	2	9	1	1
Total	9,681	1,964	4,107	3,105	5,815	6,540	1,752	1,652

Table 4. Vegetation patches in hectares

Patches (ha)	Upper Guamá	Apeú Creek	Middle Guamá West	Lower Guamá	Mãe do Rio Creek	Middle Guamá East	Bujarú River	Sujo River
< 50	15,766.01	2,578.14	5,860.97	2,961.16	10,171.83	9,990.84	2,765.22	2,220.24
50 - 100	5,225.55	762.41	2,241.80	573.11	3,631.24	3,985.78	704.98	889.02
100 - 200	5,864.82	1,338.48	2,258.69	976.03	4,236.75	3,608.88	1,170.26	984.54
200 - 500	6,051.60	1,867.33	2,560.76	1,870.22	5,601.84	7,477.07	1,780.03	890.24
500 - 1.000	11,082.01	0.00	3,175.70	2,199.67	1,328.90	4,239.79	3,417.08	565.83
> 1.000	52,454.03	22,771.68	37,578.78	86,305.11	12,389.01	37,641.26	45,126.81	11,496.43
Total	96,444.02	29,318.04	53,676.70	94,885.30	37,359.57	66,943.62	54,964.38	17,046.30

Table 5. Mean shape index (MSI), area-weighted mean shape index (AWMSI), fractal dimension (FRAC), number of core areas (NCA), total core area (TCA), mean total core area (MTCA), and total core area index (TCAI)

Sub-basin	MSI	AWMSI	FRAC	NCA	TCA (ha)	MTCA (ha)	TCAI (%)
Upper Guamá River	1.34	8.82	1.05	160	43,452.70	271.58	45.05
Apeú Creek	1.32	26.57	1.05	53	10,419.70	196.60	35.54
Middle Guamá West	1.34	18.63	1.05	123	16,283.67	132.39	30.34
Lower Guamá River	1.25	39.39	1.04	61	42,763.30	701.04	45.07
Mãe do Rio Creek	1.35	11.16	1.05	180	6,222.96	34.57	16.66
Middle Guamá East	1.34	12.46	1.05	198	23,483.43	118.60	35.08
Bujarú River	1.29	41.91	1.04	45	19,472.32	432.72	35.43
Sujo River	1.32	12.70	1.05	34	7,469.86	219.70	43.82
Total				854	169,567.94		

The shape of forest patches is an important parameter, but it cannot be analyzed singly, since other aspects, such as the edge effect, should be considered. It determines the magnitude of the effect of external factors (Lustig et al. 2015; Vizzari et al. 2018). The core areas (Table 5) corresponded to the central (internal) areas of each patch, which were determined based on a continuous border of 100 m and according to the studies of Pirovani et al. (2014) and Pereira et al. (2015).

According to Herrmann et al. (2005), forest patches with square shape and edge effects are correlated as follows: patches with more than 100 m extension towards their interior presented 1 ha affected by the edge effect; those with 10 ha presented almost 90% affected area; those with 100 ha have 35% affected area; and those with 1,000 ha have more than 10% affected area.

Considering the patches with core areas, 854 patches (2.47%) could maintain the species in their interior. The sub-basins Middle Guamá East and Mãe do Rio Creek presented, respectively, 198 and 180 patches with core areas. Sujo River and Bujarú River presented the smallest number of patches.

The Guamá River basin had 62.37% forest patches exposed to edge effect. Patches that had no core area should not be disregarded in the landscape analysis, since they are important for the conservation of the forest composition, biological flow corridors, and connectivity between patches.

Core area is a better indicator of patch quality than its total area (Mcgarigal & Marks 1994). The sub-basins Upper Guamá River (43,452.70 ha) and Lower Guamá River (42,763.30 ha) presented the largest total patch areas with no direct impact of the edge effect, and the smallest core areas were found in the sub-basins Mãe do Rio Creek (6.222,96 ha) and Sujo River (7,469.86 ha).

According to Metzger (2003), the minimum mean core area required for the maintenance of sustainability of species and integrity of their natural structure is around 25 ha; all sub-basins analyzed had higher values than this minimum mean. Lower Guamá River and Bujarú River had the largest, and Mãe do Rio Creek and Middle Guamá East had the smallest mean core areas.

The sub-basins Lower Guamá, Upper Guamá, and Sujo River presented core area indexes of approximately 45.07%, 45.05%, and 43.82%, respectively. Mãe do Rio Creek presented the lowest core area index (16.66%), denoting that it is the most vulnerable to the edge effect and most affected by anthropogenic impacts.

Similar results were found for the mean distance from the nearest patch (defined as the mean length between patches of the same class), and the sub-basins Upper Guamá River and Sujo River presented 118.72 m and 118.68 m, respectively, denoting a high degree of isolation, which makes them more vulnerable to the edge effect (Table 6).

The degree of isolation of a patch affects the forest quality. It shows the dynamics of the circulation and dispersion of species and the degree of proximity between forest fragments. The sub-basin Upper Guamá River had the highest, and the Lower Guamá River and Bujarú River had the lowest variability of distance between forest patches. A high degree of isolation of a forest patch denotes an increase in the development of species (Souza et al. 2014). The proximity indexes found for the sub-basins Lower Guamá River (26,957.84) and Bujarú River (21,899.02) showed a low interaction with the other uses and covers that comprise their landscapes. Mãe do Rio Creek (660.02) and Upper Guamá River (904.95) were the most fragmented sub-basins, presenting a higher integration between classes. Metzger (2003) described two forms to reconnect populations of forest fragments for the recovery of fragmented forest environments: the first is to improve the network of corridors, and the second is to increase the permeability of the landscape matrix.

The evaluation of indexes and zoning by hierarchical analysis (Sun et al. 2019) described the sub-basins in two groups: (1) those that show the number of patches (NP), patch density (PD), mean patch size (MPS), patch size standard deviation (PSSD), patch size coefficient of variation (PSCV), mean proximity index (MPI), mean nearest-neighbor distance (MNN), nearest-neighbor standard deviation (NNSD), and nearest-neighbor coefficient of variation (NNCV); and (2) those that show the relationship between shape and preservation of core areas: mean shape index (MSI), area-weighted mean shape index (AWMSI), mean fractal dimension (FRAC), number of core areas (NCA), total core area (TCA), mean total core area (MTCA), and total core area index (TCAI) (Figure 3).

Despite the differences between the sub-basins of the Lower and Upper Guamá rivers, they presented similar responses. The Lower Guamá River had presence of conservation units and some areas were not exposed to the expansion of the Metropolitan Region of Belém (MRB); and the Upper Guamá River presented a large number of dispersed forest fragments, which contributed to make the other metrics similar to those of the Lower Guamá River.

Physical modification and unrestricted water extraction cause considerable degradation of springs.

Table 6. Mean nearest-neighbor distance (MNN), nearest-neighbor standard deviation (NNSD), nearest-neighbor coefficient of variation (NNCV), and mean proximity index (MPI)

Sub-basin	MNN (m)	NNSD (m)	NNCV (%)	MPI
Upper Guamá	118.72	76.18	64.17	904.95
Apeú Creek	105.66	65.64	62.12	7,190.69
Middle Guamá West	106.64	60.47	56.70	2,876.13
Lower Guamá	97.11	51.35	52.87	26,957.84
Mãe do Rio Creek	116.53	74.62	64.04	660.02
Middle Guamá East	111.32	67.56	60.69	1,499.01
Bujarú River	105.10	51.61	49.10	21,899.02
Sujo River	118.68	70.93	59.77	1,244.31

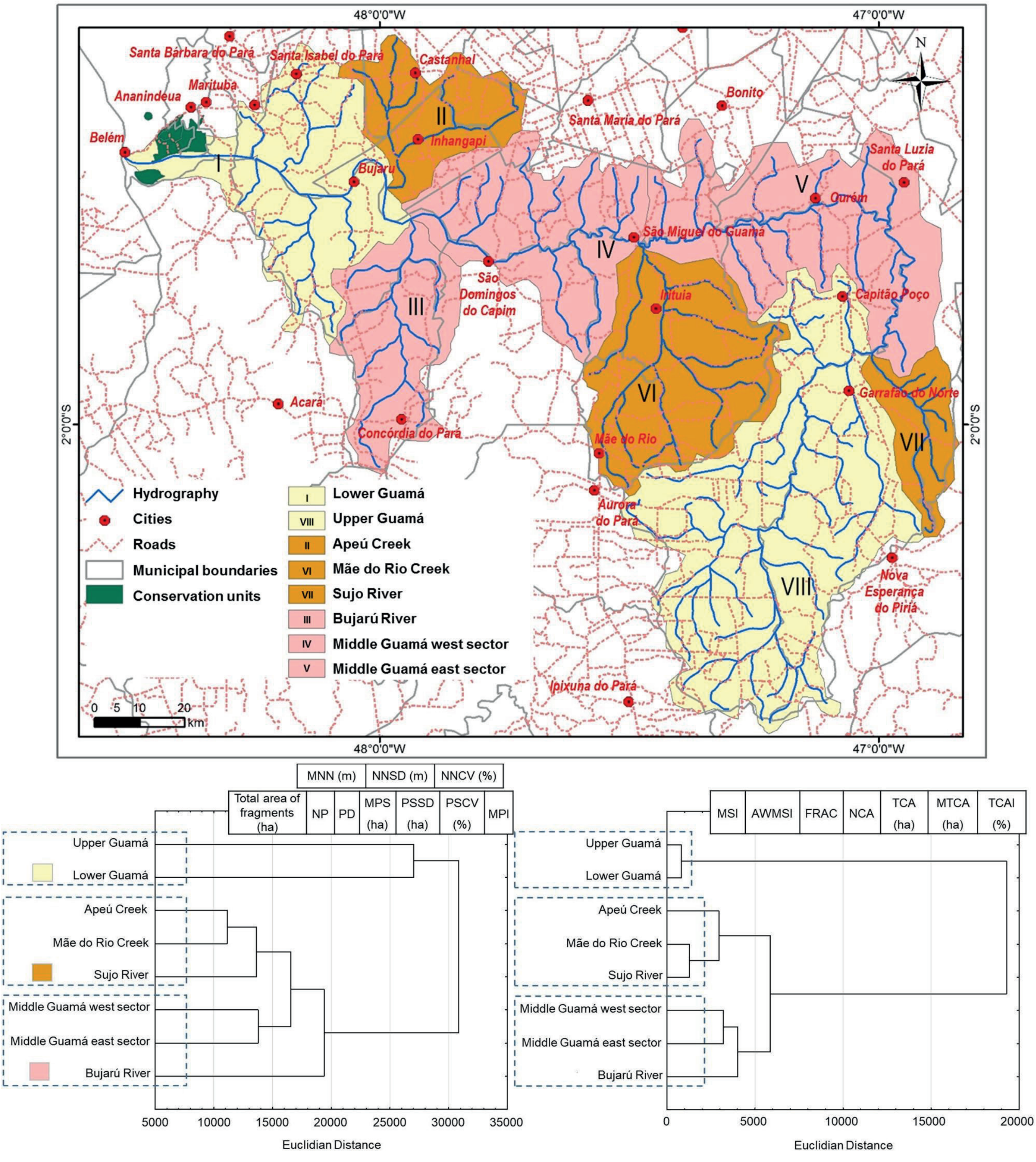

Fig. 3. Zoning of the basin according to the components of landscape metrics

Therefore, groundwater drawdown has been one of the losses in ecosystem services. Therefore, there is an interest in preserving natural resources, preventing housing and agricultural expansion, or only maintaining the traditional farming practices in areas with big changes in LULC (Rossini et al. 2018; López &, Saavedra 2021).

LULC change the relationship between land surface and atmosphere, soil and vegetation, vadose zone and groundwater, surface water and groundwater, and soil and stream. These interfaces interact with different variables and dynamic system compartments in a watershed, including social and economic factors (Reiss & Chifflard 2017).

The sub-basins Apeú River and Mãe do Rio Creek are directly affected by the urban occupation component, denoted by an intense anthropogenic action in forest fragmentation, which reflects in the spatialization and geometry of the forest fragments. Vale et al. (2015) reported that the sale of lands by small farmers to large ones caused the migration of these small farmers to urban areas in the basin region.

The degree of dispersion of forest fragments found denoted a region formed by several municipalities along the Guamá River and tributaries, which is affected by expansion of production sectors (mining, cattle raising, and agriculture) and opening of access roads to integrate the territory (Vieira et al. 2007; Enríquez 2009; Coutinho et al. 2012; Alves et al. 2012; Castro & Castro 2015) and can be considered a zone of great threat to water sustainability due to changes in the land cover pattern.

Mello et al. (2009) pointed out the existence of commercialization chains of secondary forest products, which ensures the maintenance of secondary vegetation as a rural income source associated with economic sectors (wholesalers, retailers, agribusiness). This factor may contribute to the maintenance of vegetation cover in the region. According to Nascimento and Fernandes (2017), the dynamics of the classes pasture and secondary vegetation area in this region denote the formation of a cycle of land use and occupation where the inactive pasture areas can favor the regeneration of the vegetation.

CONCLUSIONS

The fragmentation of vegetated areas in the Guamá River basin is associated with land occupation processes in the eastern Amazon. Pasture areas are more expressive in the landscape matrix, corresponding to almost 50% of the total area of the Guamá River basin. Vegetated areas are very fragmented by the presence of a large number of small patches, confirming the great impact of anthropogenic activities.

The zoning, which was carried out considering the grouping of metrics, shows that changes in land cover in the Guamá River basin have not met the basic criteria for the maintenance of recharge areas and watercourse margins, which are essential to ensure the hydrological potential of the region. The sub-basins that comprise the central axis of the Guamá River basin require greater attention from society, since actions for the planning, use, and management of these areas are essential for the processes of conservation of forests and recovery of degraded areas and for the maintenance of ecological processes.

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RESEARCH PAPER

SPATIO-TEMPORAL ANALYSIS OF URBAN EXPANSION AND FUTURE GROWTH PATTERNS OF LAHORE, PAKISTAN

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ABSTRACT. Lahore, a metropolis and 2nd largest city of Pakistan, has been experiencing rapid urban expansion over the past five decades. The socio-economic development and growth of the urban population have caused the rapid increase of urban expansion. The increase in the built-up area of Lahore has seen remarkable growth during the past five decades. This study is aimed at detecting the Spatio-temporal changes in land use land cover and evaluating the urban expansion of Lahore since 1973. The conversion of land to other uses is primarily because of growth in urban population, whereas the increase in economic activities is the central reason for the land-use changes. In this study, temporal Landsat imageries were integrated with demographic data in the GIS environment to quantify the spatial and temporal dynamics of land use land cover (LULC) changes and urban expansion of Lahore city. The supervised image classification of maximum likelihood algorithm was applied on Landsat MSS (1973 and 1980), TM (1990), ETM+ (2000), TM (2010), and OLI/TIRs (2020) images, whereas a post-classification comparison technique was employed to detect changes over time. The spatial and temporal analysis revealed that during the past five decades, the built-up area of Lahore city has expanded by ~ 532 km^2. It was found from the analysis that in Lahore city the urban expansion was primarily at the cost of loss of fertile agricultural land, vegetation, and other cultivable land use. The analysis further revealed that the structure and growth pattern of Lahore has mainly followed road network and linear expansion. The results indicate that this accretive urban expansion is attributed to socio-economic, demography, conversion of farmland, rural-urban migration, proximity to transportation routes, and commercial factors. This study envisions for decision-makers and urban planners to devise effective spatial urban planning strategies and check the growth trend of Lahore city.

KEYWORDS: Land use change, urban expansion, monitoring, growth pattern, Lahore

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INTRODUCTION

Cities are central places for socio-economic activities and human survival (Chen et al. 2021). In recent past decades, fast urbanization has been accompanied by momentous increases in the urban population in cities (García-Nieto et al. 2018; Yang et al. 2018). Expansion of cities has been continuous for several decades (Taubenbock et al. 2009). Expansion of towns and cities mostly observed in the developing countries is causing the loss of fertile agricultural, farmland, and urban green spaces (Mundia and Aniya 2006; Jat et al. 2008). According to the United Nations, the percentage of the urban population in cities during the period of 1950–2018, increased from 30% to 55% and projected that in 2050 urban population proportion will increase to 68% and 90% of the projected urban population increase would take place in developing countries (United Nations 2018). Today, most regions of the world are highly urbanized like 82% of Northern America, 81% of Latin America and the Caribbean, 74% of Europe, and 68% of Oceania. The urbanization level in Asia is now approaching 50%. In contrary to that, 43% of the African population is urban and 57% population is rural (United Nations 2018). Pakistan as a developing country is facing rapidly increasing urbanization and in Pakistan, the proportion of the urban population living in cities increased from 17.8% to 36.4%, from 1951 to 2017 (GoP 2000, 2017). According to the level of urbanization, within the Asia-Pacific region, Pakistan is experiencing a moderate level of urbanization. In comparison with other countries of South Asia, Pakistan has the maximum number of urban dwellers because 36.4% of its human population settled in towns and cities (GoP 2017). Pakistan is one of the fastest urbanizing countries in South Asia and the share of the urban population is increasing significantly. The other countries of South Asia are far behind Pakistan in terms of the urban population. It is projected that by the year 2030, the proportion of the urban population of Pakistan will increase to 50% (GoP 2015). Like other developing countries, the annual urbanization rate of Pakistan is 3% and is rapidly increasing in South Asian countries (Kugelman 2013).

Urbanization is the most powerful force that results in land-use change (LUC) around the world (Simwanda and Murayama 2018). By way of continuing development in urban areas, lands consist of the resources such as agriculture, farmland, woodland, and forest areas have been altered to built-up areas

(Son et al. 2017; Vasenev et al. 2019). Due to the increase of urban population, the fertile land use for agriculture is being encroached by industrial areas, infrastructural development, educational purposes, housing, and commercial usages (Quasem 2011). According to the report of UNFPA (2007), the recent developments of the urban expansion emphasize peripheral areas and most of the urban areas are located at the prime agricultural lands (Arif and Hamid 2007). Agarwal et al., (2002), reports that globally and over a longer period, nearly 1.2 million km2 of forest and woodland and 5.6 million km2 of grassland and pasture have been converted to other land uses during the last three centuries. However, urban land covers only 3% of the Earth's land-living surface and expansion of urban areas has important influences on ecosystems and climate change (Liu et al. 2014; Zang et al. 2017) in urban areas due to urban expansion (Kim et al. 2016). Perhaps, the alteration of natural land to urban built-up uses is one of the greatest irreversible anthropological effects and all over the world it is detected that urban land had enlarged of 58,000 sq. km during the period of 1970 to 2000 (Seto et al. 2011). Several studies (Chen 2007; Bagan and Yamagata 2014; Ahmad et al. 2016) show that high rates of urban expansion are occurring during the last three decades all around the world with the example from China, Egypt, United States, Turkey, India, Pakistan, and other Asian and African countries. Internationally, future urban expansion is projected to alter 27 to 35 million hectares of croplands during the period between 2000 and 2030 from which about 80% of worldwide loss of cropland due to urban expansion will take place in Africa and Asia (Bren d'Amour et al. 2017).

One of the characteristics of urbanization urban expansion has been getting significant consideration in different disciplines, such as urban planning and geography (Liu et al. 2005; Li et al. 2014; Song and Deng 2015). There is no doubt that the constant expansion of urban surfaces has caused a massive burden on sustainable urban development. Due to the significance of urban expansion and its everlasting effects, it has become an alarming issue in integrated socio-economic and ecological research (Kaza 2013; Li et al. 2018). Therefore, it is worth evaluating the spatial and temporal urban expansion dynamics, which can help in decision-making and urban planning efforts associated with sustainable development. Urban population growth and socio-economic development cause urban expansion (Wilson et al. 2003; Epstein et al. 2006). Computing the temporal and spatial urban expansion patterns is significant for understanding its effects on ecological processes. To get a detailed understanding of processes of urban expansion, current issues interrelated to urban expansion have been highlighted. Most studies have been accompanied to analyze and monitor the status of rapid expansion of urban areas in developed nations (Seto et al. 2002) as well as developing nations, which include India and particularly Pakistan (Sudhira et al. 2004; Ghaffar 2006; Anwar and Bhalli 2012; Shirazi and kazmi 2014; Bhalli and Ghaffar 2015), China (Weng 2002; Seto and Kaufmann 2003; Xiao et al. 2006), and Mexico (Muñoz-Villers and López-Blanco 2008). Several studies have been devoted to revealing how the expansion of urban areas modifies the spatial configuration of cities' landscape patterns (Estoque and Murayama 2013; Benza et al. 2016; Kirillov et al. 2019).

In recent decades, there has been an increasing trend in the use of GIS, photogrammetric, and satellite remote sensing (SRS) data retrieval procedures for mapping, intelligent navigation, as well as simulation modeling of urban expansion and future patterns of urban growth. These methods have been used extensively in the identification of variations in land use as well as the growth of cities (Batisani and Yarnal 2009; Bhatta 2010). Most of the conventional methods of field surveys were time taking; the procedure of Remote Sensing and GIS have facilitated scientists to do broad spatial and temporal investigation in a comparatively short period (Lo and Yang 2002). The applications of RS and GIS techniques confirm the accuracy, flexibility, authenticity, and easiness of data collection, storing, and study of important digital data for revealing, and timely observing of spatial features at local to global level (Wu et al. 2006). Lahore is the second biggest metropolitan city after Karachi in Pakistan and haphazard urban expansion creates several issues related to the conversion of agricultural land into a built-up area, water quality deteriorating, air pollution, urban heat islands, and others. In this study, an attempt has been made to apply multi-temporal images while analyzing the urban expansion and its impact on land use and for monitoring the future growth patterns of Lahore.

Study Area

The study area of Lahore extends between 31°15′ N to 31°42′ N and between 74°01′ E to 74°-39′ E, (Nasar-u-Minallah 2020) spread over an area of 1772 sq. km. (Fig. 1). The average elevation of Lahore is 150 to 200 m above sea level with the annual mean temperature varies from 18°C to 38.8°C and the average annual rainfall is about 628.7mm (Nasar-u-Minallah and Ghaffar 2020).

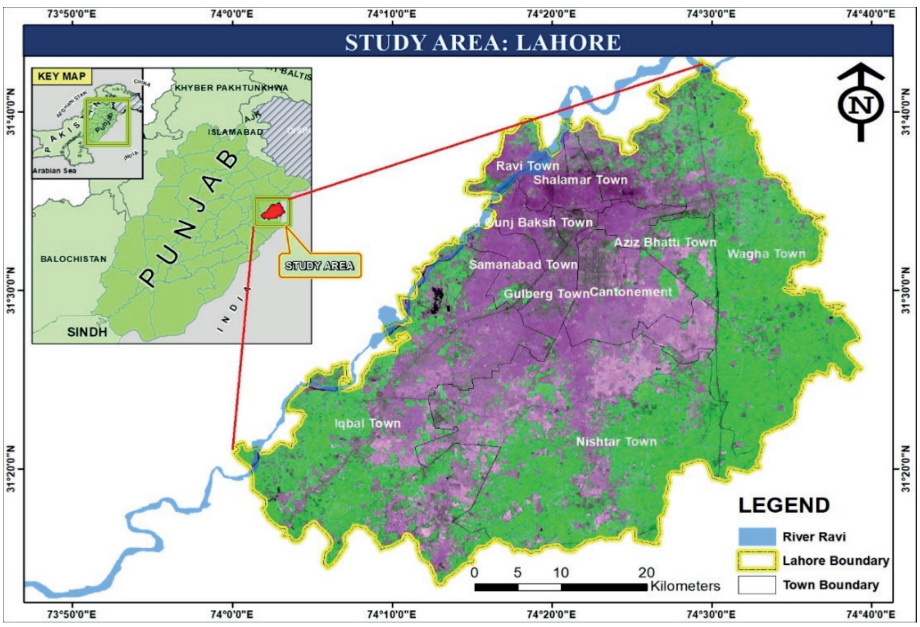


Fig. 1. Depicting the geographical location of the study area (Lahore)

Land use profile within Lahore is unevenly distributed into a built-up area, agricultural land, vacant land, and water bodies. However, much of the agricultural land, vegetation cover, and green spaces have been removed as a result of land-use change due to urban expansion. The urban population of Lahore has grown considerably, according to the population census reports it increased from 1.12 million in 1951 (GoP 2000) to 11.12 million in 2017 (GoP 2017). The population density of Lahore estimated in the 2017 census is 6275 persons/sq. km (GoP 2017).

MATERIALS AND METHODS

Data acquisition and preparation

This study is based on Spatio-temporal satellite data along with non-spatial data accessible from different sources for different periods. Urbanization has led to the expansion of the city landscape of Lahore, leading to land-use variations. The present study precisely emphasizes understanding the patterns of land-use change and dynamics of expansion based on demographic and satellite data. Satellite digital data is used to extract the land use statistics of Lahore comprising of six Landsat images. The Landsat 4, 5, 7, and 8 data sets were created by the USGS and acquired in GeoTIFF format. The Landsat satellite images were acquired as standard products, i.e. geometrically and radio-metrically rectified (Ifatimehin 2008; Bhatta 2009). In order to achieve the desired objectives of the study, the earliest available Landsat image was acquired on 23 March 1973, and the rest of the images with the interval of ten years were acquired on 04 March 1980, 16 March 1990, and 19 March 2000 while the up-to-date two images were acquired on 07 March 2010 and 18 March 2020. The data specification of Landsat images is shown in Table 1. The optical bands of Landsat images have been used to extract land use information. It is worth mentioning that the thermal bands of satellite images were not considered for the analysis. High-resolution Google earth image was used as reference data for land use classification and geographic data (GPS points) were also collected for all the various land-use types to assess classification accuracy. Other reference data includes topographical maps and aerial photographs, district and town boundary of the study area which was obtained from the office of the urban unit, Lahore. The data collected from the Survey of Pakistan (SOP) includes topo-sheets (scale, 1:50,000) of Lahore. Socio-economic data consist of primarily statistical information regarding the population of city and land use data as well as road infrastructure also used in this study was acquired from population census organization and Punjab development statistics respectively. The data manipulation and image processing were accompanied using procedures provided by ERDAS, which also integrates GIS functions. ArcGIS is utilized for overlay analysis. ArcGIS and ERDAS Imagine are used as GIS and satellite remote sensing software to analyze the digital data and acquire the final output during the entire study.

Methodology

The whole procedure of the present study has been illustrated in a flowchart as shown in Fig. 2. The image processing procedures comprised of pre-processing of the image, classification of the image, scheme of classification and design, overall accuracy assessment, and dynamics of urban expansion and exploration of land-use changes (LUC). To achieve the objective of the existing research, satellite images of the Landsat system of MSS, ETM+, and OLI/TIRs modes were acquired in GeoTIFF format from the USGS website free of cost. At first, different optical bands of Landsat images were stacked by the procedure of layer staking to develop false-color composite imagery (Jensen 1996; 2009). The satellite Landsat imageries were geo-referenced to a common coordinate system of UTM43 and datum WGS84 (Almas 2005). The vector layer of Lahore was utilized to subset each image for clipping the study area from the complete scene. All the subset images were enhanced by the histogram equalization technique to raise the volume of visible information and to increase a higher level contrast in the peaks of the original histogram (Shalaby and Tateishi 2007). This procedure is important for helping the identification of GCPs and the rectification process (Weng 2001).

Image classification is a process whereby all pixels in the image are categorized into a theme or different land-use class (Lillesand and Kiefer 2004). Supervised image classification technique has been extensively utilized in remote sensing satellite applications. A supervised image classification procedure by maximum likelihood algorithm (MLA) is subsequently applied for mapping of land-use changes on the six Landsat satellite imagery. Training sites for supervised image classification were defined with the help of field acquired data (Almas 2005). After the scheme of land use organization has been selected, training areas are wisely chosen inadequate homogeneity to increase the image classification accuracy assessment. This phase is perhaps the vital part of supervised image classification, to extract the spectral signature from the training sample to

Table 1. Detail of Landsat satellite imagery

Date of Acquisition	Sensor	Spectral Band	Spatial Resolution	Path/Row
23-03-1973	MMS	1-4	60m	160/38
04-03-1980	MMS	1-4	60m	160/38
16-03-1990	TM	1-5 & 7	30m	149/38
19-03-2000	ETM+	1-5 & 7	30m	149/38
		Pan (8)	15m	
07-03-2010	TM	1-5 & 7	30 m	149/38
18-03-2020	OLI	1-8	30m	149/38
		Pan (9)	15m	

Source: http://landsat.usgs.gov/

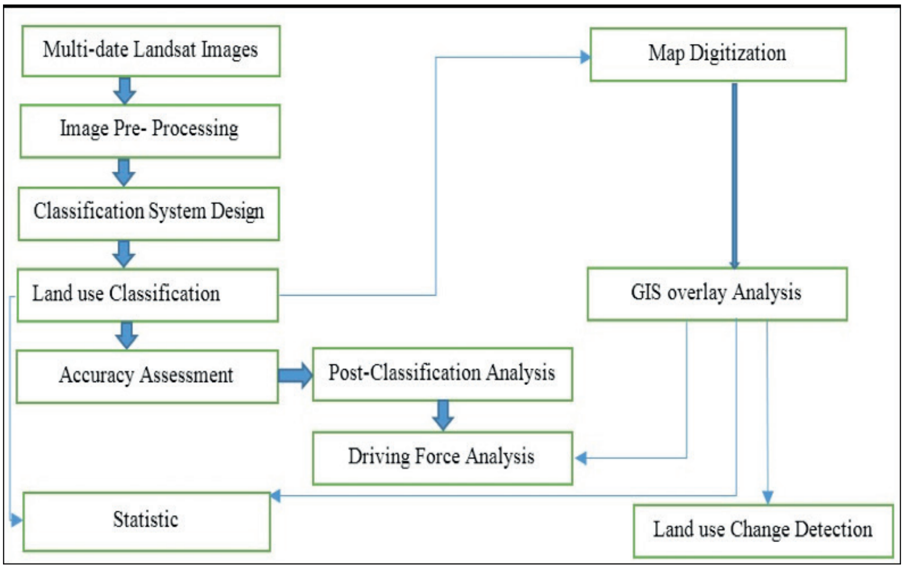


Fig. 2. Flowchart depicting the outline of the general methodology

determine the overall classification accuracy, and thus the utility of the creation of the thematic map. An altered form of the Anderson classification scheme of land use (Anderson et al. 1976) is utilized to classify the different types of land use. Although the Anderson land use classification scheme was formerly designed for the USA land-use type, after that it is frequently utilized to classify the land use all over the world (Dewan and Yamaguchi 2008). The Anderson land-use system determined that the classification of land use of level I and II classes can be mapped over large areas from Landsat data. So, Anderson's land use classification scheme of levels I and II is taken and referred to as the land use scheme in the present study. Land use types and schemes of classification are given in Table 2.

To detect the land-use change, there are two basic approaches for the analysis of multi-temporal data i.e.; post-classification comparisons and simultaneous analysis (Singh 1989). Both above-mentioned approaches have their own benefits and drawbacks (Mundia and Aniya 2007). In the present study, the first approach post-classification comparisons were selected, because the post-classification approach is very helpful when available data is acquired in different sensors and spectral and spatial resolutions are not the same (Alboody et al. 2008). Moreover, it is a common method for comparing land-use dynamics (Congalton 1991). It is used for change detection of different types of land use, by associating individually produced classified land use maps (Mundia and Aniya 2007). The major benefit of this approach is its ability to offer descriptive land information on the nature of changes that occur during the study span (Alboody et al. 2008). It is significant to note that this procedure depends on the outcomes of the classification of all classified images and digital data stored in the GIS catalog. The GIS functional abilities permitted the comparison of post-classification and helped qualitative calculation of the factors inducing urban expansion. Accuracy assessment of classification determines the value of the information derived from satellite remotely sensed (SRS) data. The accuracy assessment of the classification of six land use maps of Lahore is determined using the techniques of random sampling. Stratified random sampling techniques, where the points were stratified according to the distribution of land use classes were accepted (Mundia and Aniya 2006). By permitting the reference pixels to be selected at random, the probability of business is reduced. For satellite images of MSS, ETM+, and OLI a total of 500 points were selected. The overall accuracies of the classified images were 85%, 89%, and 90% for MSS, ETM+, and OLI, respectively.

RESULTS AND DISCUSSION

Dynamics of urban expansion and analysis of Land use changes

The history of development and land use planning in Lahore city has been reported in several studies in the previous decades (Rana and Bhatti 2018). This study, however, highlights the existing as well as the projected state of the urban built-up area of Lahore in future decades. Urban built-up area measured as being reflective of urban expansion. Urban expansion is a difficult process determined by a range of spatial and temporal constituents (Deng et al. 2009). The rapid increase in urban expansion of Lahore city is largely attributed to natural increase, migration, area annexation in urban boundary,

Table 2. Description of satellite-derived Land use classes modified after Anderson, 1976

Level I	Level II	Explanation
Key land use	Sub-land use	
Urban	Built-up land	Residential, industrial, transportation, commercial and services, communications and utilities, and mixed-use of land.
NON-Urban	Vacant Land	Open space, fallow land, construction sites, excavation sites, bare soils, and exposed areas.
	Vegetation/ Agriculture	Trees, natural vegetation, forest, grassland, gardens, parks and play areas, agricultural land, and crop fields.
Water Body	Water	River, streams and canals, open water, ponds, lakes, reservoirs.

reclassification, and merging of villages in urban territory. Urbanization is the main cause of land conversions and land-use changes. It creates unpredictable and long-term modifications to the city landscape. A significant aspect of change detection is to determine what is changing to what i.e. which land-use class is changing to the other (Weng 2002; Xiao et al. 2006). Exploring the spatial and temporal changes in land use is one of the most effective methods to recognize the existing ecological status of an area and to monitor land variations (Yuan et al. 2005). The present study examined urban expansion and future growth patterns of Lahore through the built-up area employing Landsat satellite data for the period from 1973 to 2020.

The results of the study indicated that there is a rise in the urban built-up area in the direction of the south and east of Lahore. The increase in urban population intensified the pressure on the residential and commercial sector which caused the expansion of new, and extensions of existing residential colonies in these areas of Lahore. The built-up area increased from 223 sq. km to 756 sq. km during the study period primarily at the cost of vegetation, agricultural and vacant areas. The areas recognized as built-up in 2020, but not developed in 1973 had a vegetation cover in the 1973 satellite image and thus had no built-up areas in the 1973 time period. Remarkably, the rise in the built-up area from 1973 to 2020 in the fringes of the city was considerably higher than that in the core regions. About 80% increase in the urban built-up area is observed in the outskirts region as contrasting 20% of that change is observed in the central region indicates rapid urban expansion in the peripheries of the city. There is a prediction that in the future the possibility of urban expansion will be in the direction south and east of the city by 2025 and predominantly at the cost of vegetation, agricultural and vacant land; On the other hand, some extensions in the urban built-up area is also projected to the west by 2035. The overall trends in all land-use change types are presented in Table 3.

Urban expansion of Lahore from 1973 to 2020

The spatial and temporal land-use dynamics from 1973 to 2020 were derived from the examination of multi-spectral satellite imageries. Prompt increase in the population of towns and cities and constant urbanization is the leading factor of massive growth in the change of land use in Lahore. From 1973 to 2020, the overall changes that took place in land use are shown in Table 3 and Fig. 3a-f. The urban built-up area of Lahore that has enlarged significantly during the period between 1973 and 2020 has been illustrated in Fig. 5. The analysis revealed that the urban built-up area of the city was estimated to increase from about 223.96 sq. km in 1973 which enlarged to 445.12 sq. km in 2000 and further expanded to 756.44 sq. km by the year 2020 (Table 3). In addition to this, it is also revealed that the agricultural land of the city, however, reduced from 1213.23 sq. km in 1973 to 825.23 sq. km in 2020 (Table 3), whereas the vacant land also reduced from 320.02 sq. km in 1973 to 175.10 sq. km in 2020 (Fig. 3). This expansion of built-up area had engulfed the surrounding agricultural and vacant land. With the rapid growth of the urban population, the demand for new houses scheme and commercial purposes also increased and the neighboring cropped and farmland was transformed into a built-up environment. The spatial distribution of land use profile for the three most significant classes includes built-up area, agricultural and vacant land are illustrated in Fig. 3a-f.

The study revealed that in Lahore urban population growth over the period has affected great changes in existing land use. The comparison of land use maps revealed in Fig. 3a-f and Table 3 shows that the built-up area of Lahore has extended by 532.48 sq. km during the period of 1973 to 2020. From 1973 to 2000, the built-up area grew about 221.16 sq. km while the vacant land decreased 77.79 sq. km, whereas, agricultural land also reduced 150.98 sq. km (Table 3). The important aspect of rapid expansion in cities is the increase in the urban population. According to the census report of 1972, the city population was 2.58 million

Table 3. Lahore city: Land use change, 1973 to 2020

Year		Land-use Type				Total Area
		Built-up Area	Vacant Land	Agricultural Land	Water Bodies	(in sq. km)
1973	Area sq. km	223.96	320.02	1213.23	14.79	1772
	Percentage	12.64	18.06	68.47	0.83	100
1980	Area sq. km	273.29	305.44	1170.57	22.70	1772
	Percentage	15.42	17.24	66.06	1.28	100
1990	Area sq. km	352.75	277.74	1117.82	24.17	1772
	Percentage	19.91	15.67	63.08	1.36	100
2000	Area sq. km	445.12	242.23	1062.25	22.40	1772
	Percentage	25.12	13.67	59.95	1.26	100
2010	Area sq. km	517.43	230.69	1004.99	18.89	1772
	Percentage	29.20	13.02	56.72	1.07	100
2020	Area sq. km	756.44	175.10	825.23	15.23	1772
	Percentage	43%	10%	46%	0.86%	100

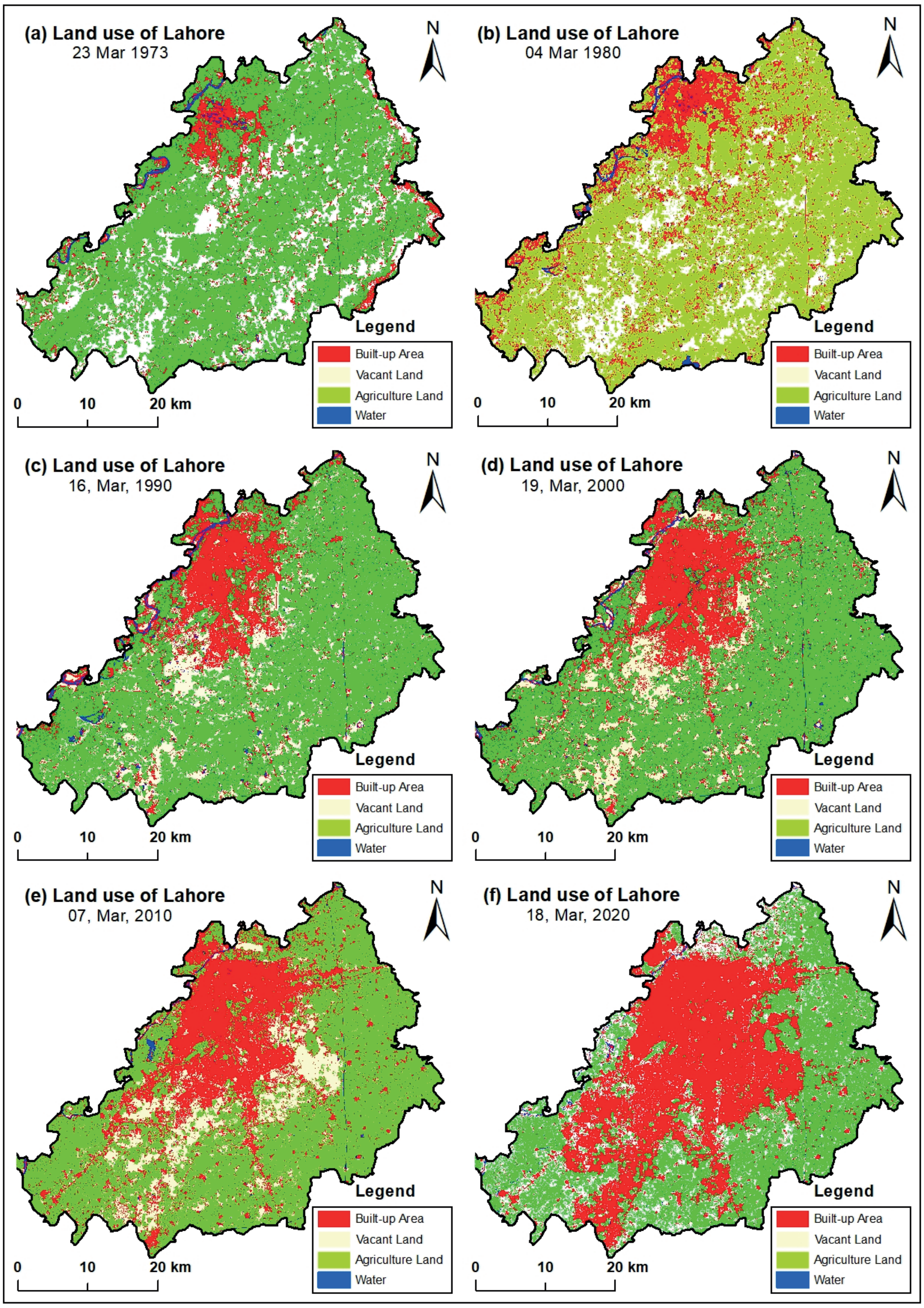


Fig. 3. Land use map of Lahore from 1973 to 2020

which increased rapidly and reached up to 3.54 million in 1981. Within the one decade, about 1 million population was increased. There is a great demand for new residential areas due to the increase in the urban population and its growing income. The population of the cities has been increasing rapidly due to two main reasons; one is rural to urban migration and the other one is a natural increase of population. Population from the countryside has moved to Lahore in search of better health, educational facilities, and employment opportunities.

From 2000 to 2020, remarkable growth in the urban expansion of Lahore was observed. According to the population census statistics of 1998, from the total population of the city which is 6.3 million in 1998 around one million of the population includes migrated people. The statistics also reveal that the bulk of the migrated population inhabited the urban regions of Lahore city (GoP 2000). From 2000 to 2020, the built-up area increased about 311.32 sq. km while agricultural land reduced 237.02 sq. km whereas, the vacant land also decreased 67.13 sq. km (Table 3 and Fig. 4). That is the time when the government decided to consider the whole of Lahore as the city district and in the provisional population census statistics of 2017, the whole of Lahore has been declared as an urbanized area (GoP 2017). The settlements which are located nearby the limits of Lahore are also considered urban areas. Due to the conversion of land, the land values inside the city boundaries have accelerated several times.

The rate of expansion of urban/built-up areas and land conversion on other land uses has increased rapidly, with fragmented patches of urban development distinguishing urban sprawl. This type of urban sprawl, with its irregular spatial directions, could have been encouraged by not conforming to the rules and guidelines of the local

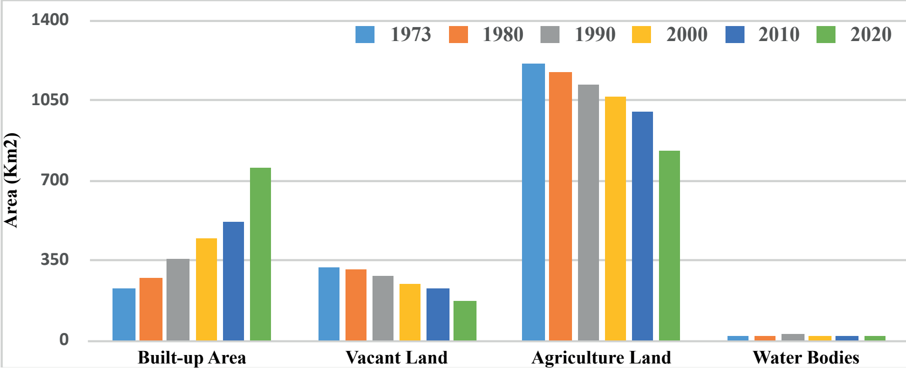


Fig. 4. Trends of urban/built-up area, agriculture, and vacant land-use change

government. The urban growth of Lahore does not follow the classical models of urban spatial structure views, for example, multiple-nuclei by Harris and Ulman (1945), sector model by Hoyt (1939), and concentric zone model by Burgess (1925). Since ancient times, the growth of Lahore had been haphazard and does not follow the regular pattern as mentioned above in many development western models. However, after British Raj, many sections of Lahore were developed and do follow some patterns of radial growth. The growth has not occurred equally everywhere and in all directions but rather it has occurred rapidly and further along with specific directions in a haphazard manner. The expansion of Lahore has taken gradual growth around the periphery where new developmental activities have occurred along with increasing the density of the built-up area in the city center.

The urban expansion of Lahore has grown around the node of the major transportation routes originating from the center of the city (Fig. 5). Transportation and accessibility are perhaps significant factors in the process of urbanization in Lahore. In the same fashion, as other Asian urban centers expand, Lahore's rate of land-use change has been quite rapid, primarily because of the huge number of migrants (1 million) from the countryside (GoP 2000, 2017). Lahore's urban built-up area expanded by 171.83 km2 from 1980 to 2000 compared to the 311.32 km2 during the period between 2000 and 2020. According to the predictions, urban expansion can occur mostly at the coast of land covered by agriculture and urban green spaces towards the south and east of Lahore by 2025; a certain increase in the urban built-up area is also predictable to grow in 2035 by the west.

Factors Influencing Urban Expansion

The land-use changes shown for Lahore occurred as a consequence of the relationship of many demographic as well as socio-economic and environmental factors. The process of urbanization of Lahore has been quite rapid as compared to other big cities of Asian counties. Some of the key aspects that have caused the urban expansion of the city are as follows.

Population growth: Lahore's urban population has increased significantly during the past five decades. The population census reports state that it has increased from 1.12 million to 11 million during the years 1951 and 2017 respectively (GoP 2000, 2017). Population estimate of 2016 shows that most of the population that live in an urban area is 82% (GoP 2016), which has remarkably grown to 100% in 2017 as shown in the provisional population census report when the district

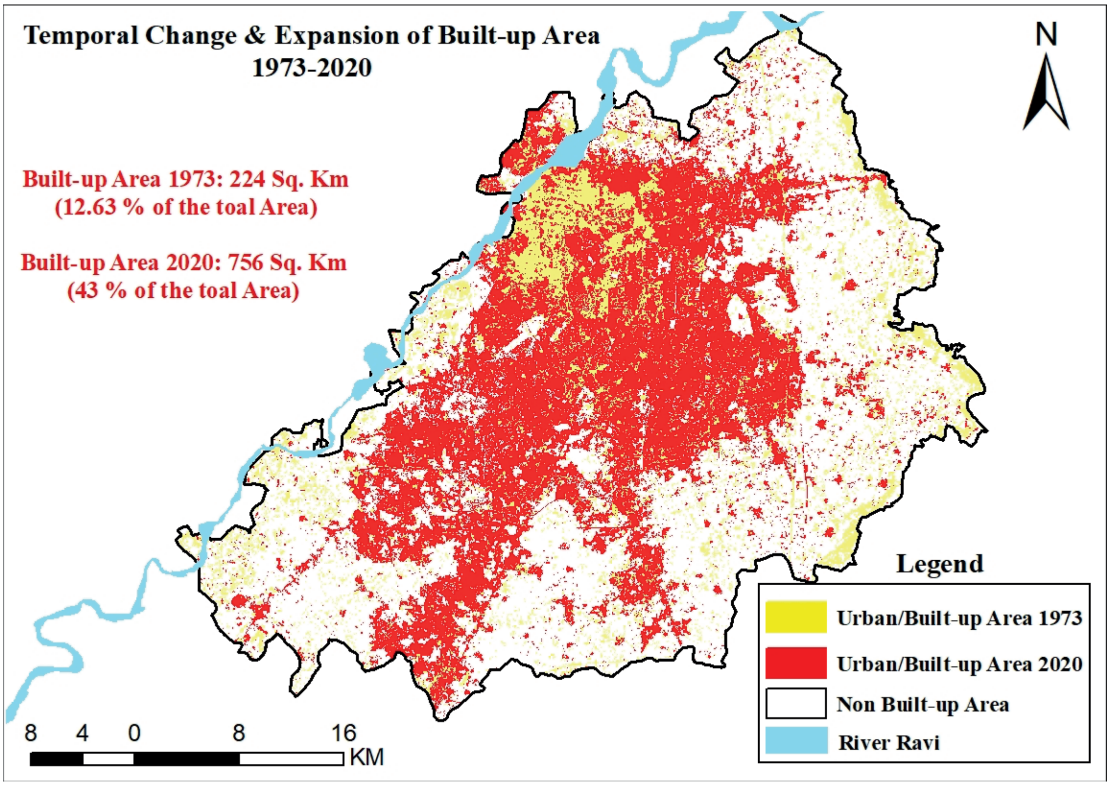
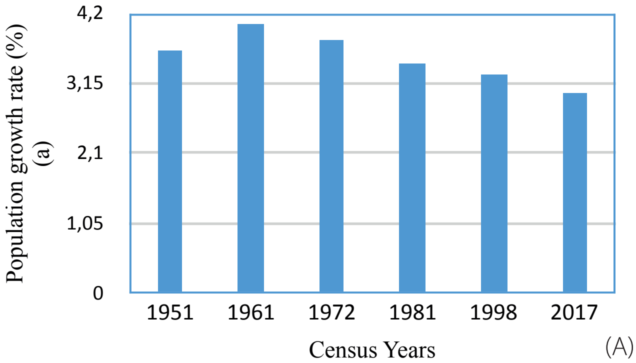


Fig. 5. Temporal change and expansion of the built-up area of Lahore between 1973 and 2020

Lahore has been stated as an urbanized area (Table 4) (GoP 2017). The population density of Lahore is 6300 people/sq. km. in 2017, while in 1951, the population density was 641 persons/sq. km (GoP 1951, 2017). The average household size of Lahore is about 6.1, which is relatively high related to the other cities of the same size. Although the average annual growth rate of the population of Lahore reflects a declining trend. As revealed in Fig. 6, the growth rate of Lahore declined from 4.1% between 1961 and 1972 (GoP 1972) to 3% between 1998 and 2017 (GoP 2000; 2017). A decreasing growth rate of population states that it is not the only main cause for urban expansion but rural to urban migration is a leading cause of urban population growth (GoP 2000; Shirazi and Kazmi 2014; Nasar-u-Minallah 2017; Rana and Bhatti 2018). According to the 1998 population census statistics, about 16.4% (1 million) of the total population of Lahore (a total of 6.3 million in 1998) consists of migrated people (GoP 2000; Rana and Bhatti 2018). The data of migrated people also revealed that migrated people majority which is 86% (GoP 2000), reside in the urban areas, which indicates that they increased the burden on the infrastructure of the city (Rana and Bhatti 2018). The significant population growth in Lahore during the last 5 decades is responsible for the conversion and changes of land use patterns. This growing population demands increased residential and commercial areas and has caused an increase in land-use change and development of the city. The growing population at a rate of 3% annually and the high rate of incoming migrants, have contributed to the urban sprawl, which caused an increasing number of mushrooming slums and settlements in a squatter manner (Rana and Bhatti 2018). This population growth combined with lack of planning are interrelated with each other and has caused the worsening of already prevailing socio-economic, physical, and environmental complications. Additionally, with the observing of infrastructural development and growth of the built-up area, it is also essential to obtain and examine the



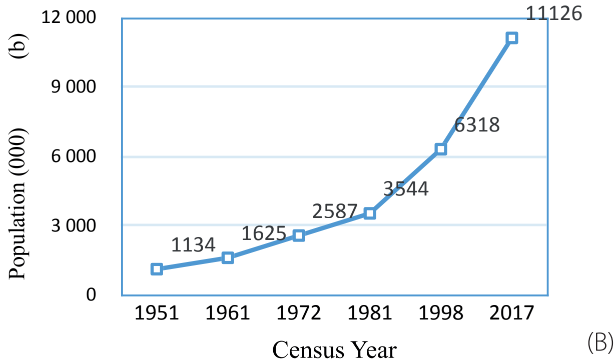


Fig. 6. (a) Average annual growth rate and (b) Population growth from 1951 to 2017

Table 4. Proportion of urban population of Lahore from 1951–2017

Census Year	Population		The proportion of Urban Population (%)
	Urban Population	Total Population	
1951	861,279	1,134,757	75.90
1961	1,312,495	1,625,810	80.73
1972	2,189,530	2,587,621	84.62
1981	2,988,486	3,544,942	84.30
1998	5,209,088	6,318,745	82.44
2017	11,126,285	11,126,285	100

Source: GoP 1951; 2000; 2017

Table 5. Lahore district and urban migration trends 1981–98

	1981		1998	
	District (%)	Urban (%)	District (%)	Urban (%)
Same province	49	50	52	53
Different province	7	7	6	6
AJK/NA	1	*	1	1
International	38	38	20	21
Not reported	5	5	21	19

Source: GoP 1981, 2000

population authentic data with the help of a census survey from the recent population census 2017 which will significantly assist in this regard.

Road infrastructure: The urban built-up area's spatial pattern has a geometry that has primarily been molded by the road network. The provincial highway department appraisals that there are about 1265 km roads in Lahore city (GoP 2015) and Lahore city is connected by a thick road network in terms of approachability. Due to ease of access, people migrate to Lahore and settle there. Major roads that connect Lahore with other cities are Multan road, G.T. road, Ferozepur road, Raiwind road, Jaranwala road, and Sheikhupura road. While the main railway line of Lahore connects it to many settlements along northern and southern routes and also to the bordering country-India, through Wagha in the east. Lahore is also connected with other parts of the country particularly in the north through a network of Motorways (M-2, M-3, M-1, M-4). It has developed the historic route which links central Asia with the sub-continent. The high number of transportation routes has encouraged the urban sprawl, which results in linear growth along the major roads of Lahore. The recent infrastructure development of Lahore i.e. metro bus system (27 km) and orange line train system (27.1 km) would probably affect the future patterns of urbanization, and it is significant to observe and comprehend the local dynamics of urban growth from time to time so that more informed decision can be made accordingly.

Commercial and trade Centre: Lahore being a higher-order commercial and trade Centre, has customers across the country. This sector of the urban economy has provided the city of Lahore with a concrete stimulant to the energetic activities of the metropolis. Currently, a unified commerce and trade nucleus is established in and around the Walled City of Lahore and adjacent to the urban and sub-urban areas of Lahore mostly in the south and southeast direction. As the pressures on the infrastructure continue to increase, prospects of commercial and trade activities in the central business district will be at stake. Lahore's gross domestic product (GDP) due to the purchasing power parity (PPP) was assessed at $40 billion in 2008, and the estimated GDP growth rate is at 5.6% by the year 2025 (Rana and Bhatti 2018). Lahore contributes to the provincial economy of Punjab at an estimate of 19% and 11.5% to the national economy has extraordinarily expanded in both human population growth and process of industrialization and spatial extent owing to the economic development. The creation of some prospects of employment in several sectors of the economy such as business, commercial, transport, and industrial growth gave rise to the growth of an urban population of Lahore. This urban population explosion played a significant role in the change of land use patterns and expansion of the built-up area of the city. This tremendous growth influenced the urban area of Lahore and captured the hinterland of the city. It is also stated that the city has experienced noteworthy industrial growth over the past few decades and Punjab development statistics reveal that about 2233 factories are government registered (GoP 2015a; Rana et al. 2017).

Professional and educational Centre: Lahore is an extraordinary seat of learning and scholarly people in Pakistan. As a specialized, professional, scientific, technical, and educational Centre, the city makes a noteworthy influence on the academic circle of the country. According to the most recent statistics, the city of Lahore has 657 primary, 219 middle, and 327 government high schools as well as several private schools (GoP 2015a). In addition to these, there are 47 government colleges and 28 public and private universities that offer higher education respectively. Better educational and professional facilities are also causing the population growth and expansion of Lahore city.

Constraints to the Expansion of Lahore

It is apparent from the analysis of urban expansion, there are many considerable directions for the expansion of the city, for which there are favorable factors. Contrary to that, there are unfavorable factors that would discourage the future expansion of the city. The development and growth of a city are usually affected by certain constraints and Lahore is no exception to this. River Ravi is one of the main physical constraints and manipulating factors in the expansion of Lahore. However, the presence of the Ravi River together with the risk of flood plain possibly threatens built-up area extension by the directions of north and north-west. Other major physical constraints to the built-up area expansion of Lahore comprise the closeness of the Indian border (Wagha) in the East direction which facilities the city expansion only in the direction of the South and Southwest (Fig. 5). Furthermore, there are several imperceptible constraints, which are not easy to measure but can be observed which include traffic problems, solid waste management, exhausted housing environments, and city congestion within the heart of the city that dynamism forces people to travel to the peripheries of Lahore. The city area and its vicinity comprise of flat land that slopes gently towards south and south-west. So we can say that there is no physical difficulty in the expansion of these areas of the city. As a result of these physical constraints, city development has been generally limited towards a southerly direction (Fig. 7). Growth strategies for Lahore are also being constrained by these physical barriers in the east, north, and north-west and the future growth trends towards the south will have to be accepted.

Future Patterns of Growth

In the light of the above-mentioned potentials and constraints, the future growth of Lahore in various forms is as follow follows:

Densification and vertical growth: The built-up area of Lahore which is presently being densified by sub-division of larger plots into smaller ones to fill the vacant pockets of land and by adding new rooms and stories to the existing housing units, this trend can be seen in the form of vertical growth in the city Centre (Shirazi and Kazmi 2014). This way of in-fill land along with financial affordability of the people, the process of densification will be affected by now allowing the congestion and strain the existing physical and social infrastructure (LDA and NESPAK 2004). Vertical growth is one of the forms of future growth of Lahore like elsewhere in the world.

Peripheral growth: Along with densification within the built-up area, peripheral growth is persistently growing informally and haphazardly in the form of the creation of new commercial and residential schemes. This trend can be detected in areas including south of

Khaire Distributary areas, Harbanspura, along both sides of Ferozepur Road, Shahdara, and riverbed across Bund road. Irrespective of the facilitation of basic amenities in these areas which are encroaching upon the fertile agricultural land, the natural vegetation of these areas can be protected by some legislation to protect the indigenous vegetation of Lahore.

Growth across Ravi: Before encouraging development along the River Ravi banks, a thorough study is needed by flood management because of the vast patches of vacant land across the river Ravi are available for commercial and residential purposes which are adjacent to the central core of Lahore (LDA and NESPAK 2004; Shirazi and Kazmi 2014).

Growth in the South-West: There are numerous housing schemes in the offing, in and around Lahore, which are consuming the large agricultural land. Cheap-land is the main reason behind the mushrooming of such housing schemes in the peripheral and suburban areas of the city. This can pave a way for the future expansion of the city. This growth corridor is more popular in the southwestern direction where the major housing schemes are flourishing in dispersed form. This sprawl wave further increases ribbon development along the major roads like Multan, Ferozepur, and GT road. These areas are getting centrifugal from present city Centre which is furthering chaos and congestion on the roads with every coming day. This situation demands decentralization and development of new commercial, trade, and institutional Centres in the area (LDA and NESPAK 2004).

Future Direction of Growth

Lahore has been experiencing quite a rapid population growth since 1951 and is now home to about 11 million people in 2017 (GoP 2017). The growth of the urban population constantly acts as an

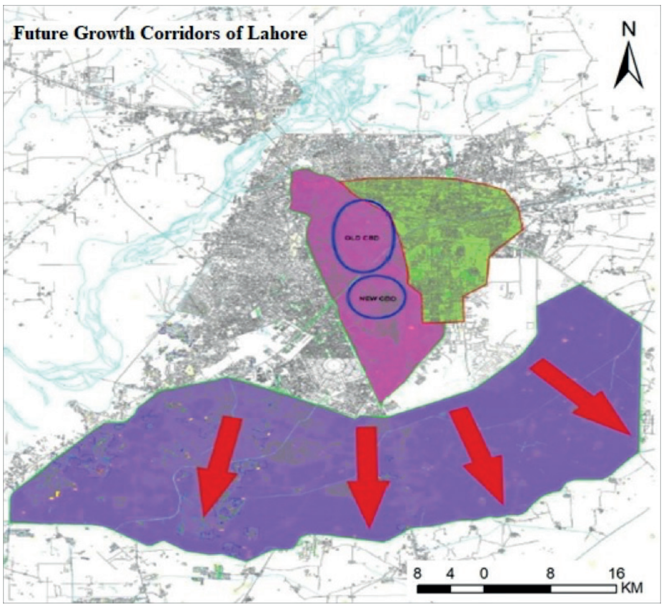


Fig. 7. Future Growth Corridors of Lahore

attribute to the development of Lahore. Future growth directions of the city of Lahore are towards the south-east and south-west, as displayed in Fig. 7, these two growth corridors are potentially more favorable for future development and expansion of the built-up area of the city as shown in Fig. 7. Although the city of Lahore has the prospective to grow all-around that comprises its sprawl in the direction of Wagha border (east) and towards River Ravi (north-west), from 2000 onwards, much of the development has been in the eastern and southern parts of the city and to some extent, in the north-western area across the river, Ravi has largely been in the form of approved new housing schemes (Shirazi and Kazmi 2014). It is apparent from the expansion analysis and identified that south-east and south-west directions as recognized future growth corridors for the city of Lahore and Gulberg Main Boulevard, Jail Road, MM Alam Road recommended as new CBD for the city of Lahore as shown in Fig. 7. This will not only reduce pressure on old business centers but also help in decreasing travel distance from far-flung areas of the city in the south to the core areas.

CONCLUSION

The study used post-classification techniques along with the GIS techniques to integrate multi-spectral data with socio-economic and demographic data to examine changes in land use and the Spatio-temporal dynamics of urban expansion. The present study has proven the effectiveness of GIS and remote sensing techniques in producing precise land use maps and detailed change statistics of Lahore, which provides a database for the site suitability for further urban expansion of the rapidly growing metropolis of the country. This valuable information is also crucial for the suitable provision of facilities and infrastructures for sustainable urban planning. The land-use profile of Lahore has changed over time considerably. Specifically, the built-up areas have enlarged by 532 sq. km, which is a major attribute to the rapid population increase due to the great influx of migration, signifying loss of agricultural land and green spaces by 702 km2 over the period from 1973–2020. Reduction of agricultural land, loss of vegetation, and the issue of urban sprawl have attuned the urban expansion. The network of roads has affected the structure of urban development, due to which the expansion has ribbon growth along the main roads of the city. This study helps a lot in the better understanding of spatial and temporal dynamics of urban expansion of Lahore and will facilitate in the better planning and effective spatial organization of urban infrastructural activities, which is essential for development in future leading to improve the environmental conditions, quality of life and living standards of the millions of people living in the city of Lahore. In the future, studies exploring the hidden patterns of urban growth and loss of vegetation, urban green spaces, and agricultural land can probe the future changes through high-resolution satellite imagery of Lahore.

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RESEARCH PAPER

TOURISM INDUSTRY IMPACTS ON SPATIAL INEQUALITY IN THE DEAD SEA REGION

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ABSTRACT. This research examines the impact of the tourism industry on spatial inequality in the Dead Sea region in terms of income, employment and changes in urban forms. The research assumes that this inequality results from the Dead Sea Development Zone (DSDZ) creation and focuses on the local level of urban analysis with the case study of a small Jordanian village Sweimeh, Quantitative data is used in this study for exploring these changes, uncovering persistent and obvious patterns of land use and exhibiting perspectives for the landscape, while satellite images offer extensive advantages over verified maps. The qualitative analysis combines field observations, a structured questionnaire survey with 270 randomly selected households and semi-structured interviews with 30 purposively selected participants. The results of the research showed that the DSDZ creates spatial inequality between the hotel touristic district and the village due to the high level of place-based development differences associated with urban characteristics, such as infrastructure and services provision. The results revealed that there has been a notable increase in population and area of Sweimeh as well as the locals' income. The population doubled from 2054 in 1994 to 4448 in 2019, the area has increased from 0.15 km^2 to 4.40 km^2, and the share of jobs in the tourism sector and businesses in the village jumped from 10% to 50% in the same period. This study is important since urbanization and spatial management programs received little attention in the DSDZ development agendas. At the academic level, the findings of this research help to establish an assessment tool for testing the socio-economic impact of tourism development on disadvantaged local communities.

KEYWORDS: Dead Sea; Jordan; Tourism industry; Spatial planning; Spatial inequality; Urban forms; Local communities

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INTRODUCTION

The Dead Sea (DS) is a lagoon located between Jordan, Israel, and the West Bank Authority (Fig. 1). It attracts thousands of local and international tourists and is one of the main Jordanian tourist destinations. Major attractions of the DS include its mineral-rich, reputedly therapeutic hypersaline waters, the year-round warm climate, and historical and cultural heritage. To serve these attractions there are thousands of hotel rooms around the DS on the Jordanian and Israeli coasts, with thousands more proposed after the Treaty of Peace (1994) between Jordan and Israel, which had a positive impact on the tourism industry of the Dead Sea Region (Friends of the Earth Middle East [FoEME], 1998). In July 1994, the first public meeting of Israeli and Jordanian leaders was held at the Jordanian Dead Sea Spa Hotel. In 2009 the Dead Sea Development Zone (DSDZ) was created to facilitate a safe touristic hub between Jordan, Israel, and the Palestinian Authority.

The tourism industry continued to develop rapidly from the late 1990s (El-Naser 2020). Despite notorious intermittent conflicts, the overall number of tourists in Israel (not including day excursionists) increased by 27%, from 2.2 million in 1995 to 2.8 million in 2015. In the same period, the number of tourists in Jordan increased by 370% and reached 5.3 million (Wendt 2016). Israel welcomed over 4.55 million tourists in 2019, 48 % of whom visited the DS area. In the same year, the number of tourists in Jordan was 4.2 million, which is less than previous years.

In addition to the Treaty of Peace, a number of factors helped to accelerate the urban development and tourism industry of the Jordanian DS shore. On one hand, the Israeli plans to develop up to 5,000 new hotel rooms along the northern shore were halted in part due to fear of sinkhole formation (FoEME 1998). On the other, the Palestinian Authority was deprived of normative rights and control of its DS shoreline. Palestinian tourism is restricted since Israel

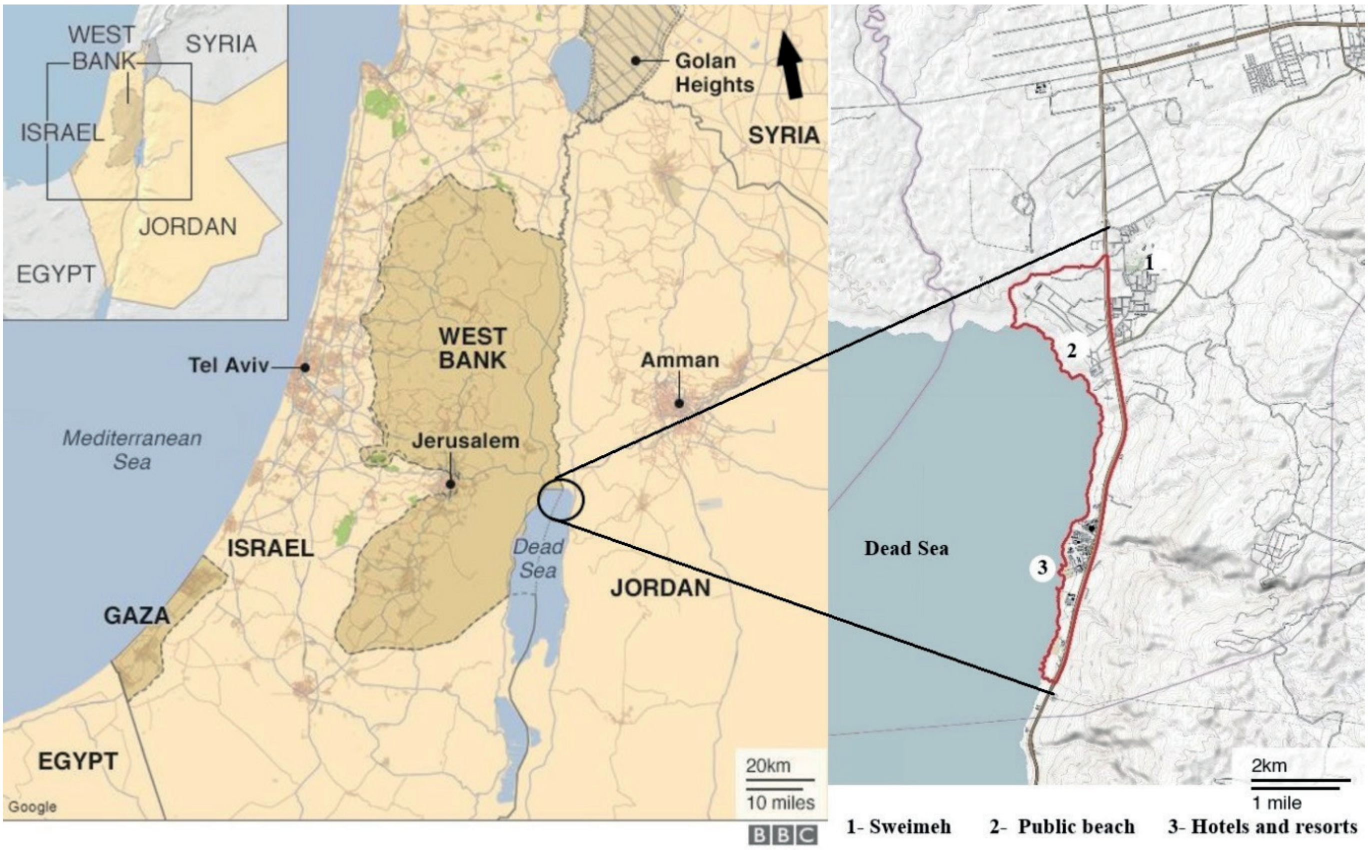

Fig. 1. Three states bordering the north Dead Sea shore and the study area
Source: Google (2021) (left), Alfuqaha et al. (2020) (right)

took control of most tourist sites on the northern shore of the DS, depriving the Palestinians of direct access to it. The western shore of the DS is about 54 km, of which 18 km are occupied by Israel, while the remaining 36 km are located within the West Bank (El-Naser 2020) (Fig. 1).

Israel controls tourist access to Jericho, which negatively affects the tourism industry in the city (B'Tselem 2011). Also, Israeli plans for developing infrastructure, such as transportation roads and bridges, are limited due to the geological and rough topographical formation of the sea area, which is prone to collapse and leads to the high costs of construction and maintenance. As a consequence of these challenges, residential development in the area is minimal (Becker and Katz 2006).

Development zones (DZs) provide many benefits, including the attraction of foreign investments, creation of employment opportunities, and distribution of development gains, which eventually leads to the improvement of local living conditions and supports local and national socio-economic development (te Velde 2001). Jordan, as a developing country in the Middle East and North Africa (MENA) region, has adopted a DZ policy since 2008 to encourage economic development and liberalization. By 2014 the government had established a DZ in each of Jordan's twelve governorates in an attempt to develop regional economic production (JFDZ Group 2016). This economic policy was a part of a larger development program known as the Decentralization and Local Development Support Program (DLDSP), sponsored by the European Union, and executed by the United Nation Development Program (UNDP) (Erdmann et al. 2016; USAID 2016). (Fig. 2) shows the spatial distribution of the development zones in Jordan, including the DSDZ within the Balqa governorate (number 6).

Despite the Jordanian governmental efforts to achieve economic growth using the DZ model, the geopolitical location of Jordan plays a fundamental role in its economic development policies. For example, the Jordan Valley Region was a site of conflict and wars until the signing of the Jordanian Israeli Peace Treaty in 1994. In addition, political instability in neighboring countries after the Arab Spring in 2011 discouraged many foreign investors from investing in Jordan. This research argues that despite this economic instability, the DSDZ has achieved its touristic development goals on the national level, but failed to materialize benefits at the level of local communities, which are the focal point of this research.

Fig. 2. Jordan's tourism development zones (numbers 3 & 6)
Source: Google (2021)

Jordan has always considered tourism development to be a key national economic sector, due to the country's abundant natural and historical tourism resources. The government took serious decisions to promote tourism through the DSDZ as a national model (Jordan Investment Commission 2014). This research aims to study the impact of the DSDZ on socio-economic and physical planning aspects with a case study of the village of Sweimeh to answer the following questions:

• What is the urban impact of the DSDZ on local communities?
• What is the socio-economic and physical impact caused by the touristic planning development of the DSDZ?

MATERIALS AND METHODS

The research methodology is based on a mixed-method approach, which includes both qualitative and quantitative strands. Descriptive statistics and content analysis were used to analyze the collected data. The research assumes that the DSDZ has a socio-economic impact on the tourism industry in Jordan and aims to explore how the DSDZ affects the emergence of new urban forms.

The quantitative data is based on previous studies and comprises data sets derived from satellite images, maps, and aerial photographs. The strategic master plan of the DS was used to extract data and get a more precise mapping and classification of the existing shoreline conditions and land-use patterns of the north shore. The qualitative analysis combines field observations, questionnaire surveys, and semi-structured interviews with 30 purposively selected participants (10 officials from the DSDZ, 10 officials from the local authorities, and 10 business investors in hotels and restaurants).

The structured questionnaire survey was based on a simple two-point dichotomous scale (Yes or No questions), which was deliberately simple to ensure that participants from the case study village of Sweimeh understand the questions and answers clearly. The sample of the questionnaire survey from the village was based on household units rather than individual respondents, considering each family as a single unit.

The suitable sample size for the field survey questionnaire was calculated using Raosoft Sample Size Calculator, with a 95% Confidence Level (Z Score = 1.96), 5% margin of error (0.05), and sample proportion of 50% (= 0.5):

$$sample\ size = \frac{N * \left(\left(Z_{\frac{\alpha}{2}} \right)^2 * p * (1-p) / MOE^2 \right)}{\left(\left(\left(Z_{\frac{\alpha}{2}} \right)^2 * p * (1-p) / MOE^2 \right) + N - 1 \right)}$$

Where
$Z\alpha/2$ is the critical value of the Normal distribution at $\alpha/2$ (e.g. for a confidence level of 95%, α is 0.05, and the critical value is 1.96), MOE is the margin of error, p is the sample proportion, and N is the population size.

According to official statistics, the population of Sweimeh is around 4448. The average household size is 5.5 people per house. Accordingly, there are approximately 4448/5.5 = 803 households in Sweimeh, thus the sample size for the needed questionnaire survey is:

$$sample\ size = \frac{803 * \left((1.96)^2 * 0.5 * (1-0.5) / 0.05^2 \right)}{\left(\left((1.96)^2 * 0.5 * (1-0.5) / 0.05^2 \right) + 803 - 1 \right)} = 261\ households$$

The researchers distributed questionnaires during field visits to randomly selected households. The data gathered from 270 questionnaires were translated by the researchers from Arabic into English, transcribed and coded. The questions of the questionnaire were categorized into two major themes: the first measured socio-economic impact of the DSDZ; and the second measured physical impact. The results are shown in Table 1.

Table 1. Questionnaire results

Survey Questions	Percentage	
	Yes	No
Socio-economic		
Do you think that jobs in the tourism sector are stable and permanent?	11.3	88.7
Do you think that jobs in the tourism, business, public sectors are better than working in agriculture?	88.9	11.1
Have you participated in discussions about your needs with the developers before the tourism development projects?	10.3	89.7
Do tourism development projects increase options for shopping, entertainment, and restaurants?	65.4	34.6
Do tourism development projects increase your income?	70	30
Did the new residential projects increase the social inequality between the local residents and the new settlers?	84	16
Do you think that tourism development projects can generate negative cultural problems due to the cultural and moral differences between tourists and the local communities?	20	80
Physical		
Are the conditions of infrastructure (roads, sewage, and drainage) in Sweimeh after the development project better than the conditions before?	75.2	24.8
Did the newly annexed parts of the Sweimeh municipal boundaries at the borders of the development zone affect your living conditions?	34.6	65.4
Are the service facilities such as showers, restrooms, and changing rooms enough on public beaches?	5.9	94.1
Is there periodic cleaning for public beaches?	20.0	80.0

Source: Authors

DISCUSSION AND RESULTS

Socio-economic impacts

Eraqi (2007) reported both positive and negative socio-cultural and economic impacts of tourism development on local communities in neighboring Egypt, measuring the impact of tourism development on the standard of living of local Egyptian communities and their attitudes. The cultural, socio-economic, and climatic similarities between local communities in Egypt and agricultural communities in the DS Jordan Valley make these findings pertinent. Tsundoda and Mendilinger (2009) noted that tourism is a total social event, which may be beneficial to cultural life in communities. Locals at the DS are encouraged to share their culture with tourists in a celebratory and proud way. This cultural interaction helps in educating young locals to take pride in their origins. In contrast, tourism development projects can also generate negative impacts, causing cultural problems due to the differences between tourists and host communities (Ap 1992). These projects can damage local social and cultural values due to the possible increase of social problems associated with tourism development, such as crime, prostitution, and drugs, which affects local communities.

Mathieson and Wall (2006) argued that the negative social impact of tourism can be categorized into three groups: social change, tourism and health, tourism and language. The extent of such influences varies from local residents to owners of hotels and restaurants on the DS. 80% of the resident participants emphasized that there is no direct social interaction between foreign tourists and themselves, since the latter stay in the five-star gated hotel district. Interviews with investors in the tourism sector, such as hotel and restaurant owners, revealed that young, educated, and trained local people who worked for hotels and restaurants were culturally influenced by wealthy foreign tourists; in addition, this cultural interaction enhanced their language and communication proficiency.

The economic impact of tourism affects the production, distribution, and consumption of wealth in human societies (Ashley and Mitchell 2010). The host community is usually quite happy to see the influx of tourists into their living areas where many recreational activities are organized and planned to welcome people, who subsequently spend their money there, generating revenue for the community (Allen et al. 1988). According to Edgall (2006), the economic impact of tourism includes new commerce, job creation, new products, increased income, enhanced infrastructure, economic diversification, and economic integration of the local economy, as well as linkages between local services and products and the tourism sector (Gnanapala and Sandaruwani 2016).

Murray Simpson (2009) has listed a set of positive impacts of tourism on the local economy, including direct opportunities of employment in administration, guiding, tours and transport, construction, hospitality, management, accommodation, shopping, food and beverage outlets. He also added a number of impacts of tourism on the governmental level, such as indirect employment opportunities (including environmental management, entrepreneurs, and other supportive industries), support of the development of multi-sector or mono-sector non-profit community-based enterprises, provision of alternatives to changing or fading traditional industries, and increase in land value.

According to the JFDZ Group (2016), the existing hotels of the DSDZ provide about 3,700 jobs. It is expected that the new developments will provide around 8,800 job opportunities upon the construction of the recreational and touristic facilities proposed in the Dead Sea Master Plan (DSMP). This more than doubles the current number of direct opportunities, aside from other indirect employment opportunities. There are significantly more male Jordanian workers in the DS tourism industry, which has been the case since 2004. Given the education and gender characteristics of the local community, people of the area can generally only fill low-grade service jobs (e.g., concierge, clerk, baggage porter, bellman, valet and so on), while managerial and leadership roles in the hospitality industry typically go to Jordanian locals with superior educational background from the major cities (Amman, Zarqa, and Irbid), or international employees appointed by multinational hotel chains (Fig. 3).

Conversely, tourism can generate negative economic impacts. For example, tourism is an unstable and highly unpredictable income source (Tosun 2001), influenced by political instability (Russel and Faulkrar 2004). Furthermore, a booming tourism industry places great pressure on local resources, such as food, land, transport, electricity and water supply, etc., limited in the host economy, increasing the demand and facilitating inflation of prices for local communities. 75% of respondents agreed that uncontrolled commodity prices doubled or even tripled over the weekends and in the tourist seasons. Tourism creates jobs that are not sustainable (Munt 1994), do not require professional skills, and do not provide a sufficient salary to afford family expenses (Mathieson and Wall 2006; Page and Connell 2006). Questionnaire responses regarding job stability and income revealed that 88.7% of participants employed in the DSDZ did not feel job stability, and they were mainly working on short-term contracts without any health insurance or social security benefits.

Another negative aspect reported by participants was that most owners of stores and service facilities were reorienting their businesses towards serving tourists rather than locals, seeking increased profitability. Expensive tourist restaurants are generally beyond the spending reach of local people; for example, residents of Sweimeh village are visibly poor. According to the survey, only 6.0% of the respondents could afford to sit and eat in these restaurants. Page and Connell (2006) indicated that poor local communities may not benefit from tourism development, as their income may be accrued by tourist businesses and governments, without trickling down to local people. While the income from tourism is often syphoned away from local people, they are always subject to price increase due to tourism development, including land and property values, especially when there is a sustained demand for building tourism facilities. This creates inflationary effect on local economy with increasing land and property prices often making young people unable to afford to continue residing in their local communities, while local residents are forced to pay more for their homes and taxes (Mathieson and Wall 2006).

Physical impacts

Urban forms in the DSDZ nowadays undergo

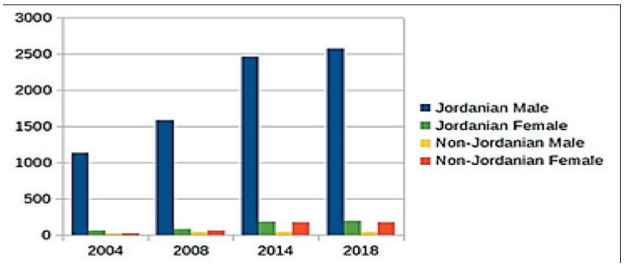

Fig. 3. Number of employees at the DS hotels according to gender and nationality
Source: JFDZ Group (2019)

immense changes in their character and land use, with expanding levels of tourist economic development in the region. Collected data in this research plays a significant role in exploring these changes, uncovering persistent and obvious patterns of land use and exhibiting perspectives for the landscape, while satellite images offer extensive advantages over verified maps, as explained in this section. The main focus is on the local level of urban analysis, with the case study area of Sweimeh, a small village about 74 km from Amman, located on the northeast shore of the DS within the DS Strategic Development Plan Zone (Fig. 2). The village makes an ideal case for the current study as it is the smallest and poorest settlement in the DS area and the closest urban settlement to the touristic development zone. Furthermore, there are few urban studies on the relationship between poor settlements and tourist development programs in Jordan.

According to Pivo (1992), two basic components of urban form are consistently debated. One component includes a variety of physical elements encompassing configurations of land use, urban design aspects, and transportation networks. The second component treats urban form as an ever-changing process. In general, the physical elements are in a constant state of change due to political, social, and economic forces. The interrelation between the two components in the DS area illustrates the complexity of its urban form. In this section, we focus on the individual village of Sweimeh as part of the new DS shoreline strategic master plan produced in 2011.

Sweimeh is part of the Balqa governorate. It is a poor rural settlement with inadequate basic services and infrastructure (Fig. 4). The modern urban history of Sweimeh dates back to the beginning of the twentieth century. It was originally considered a retreat for a group of clans (herders and farmers) who came from the southern Jordan Valley. It gradually became a permanent settlement of mud-brick houses and then concrete bricks from the early 1940s. Previously, the site was inhabited due to the abundance of water. The residents planted vegetables, as well as wheat and barley. Nevertheless, the recently mechanized agriculture operated by investors put an end to the traditional local agricultural production over the last two decades. The survey results indicated that 88.9% of the respondents believed that the economic future for younger generations was very much framed around urban context, with a clear demand for non-agricultural employment and income.

The DSDZ generates wage income for the local workers higher than the increase in the local cost of living in the old village. The local residents have experience in developing their small family businesses, including selling handicrafts, reed baskets and so on. Those who owned land close to the hotel district started with tourist stores selling souvenirs and traditional restaurant services along the main road. 65.4% of the survey respondents agreed that tourists increased options for shopping, entertainment, and restaurants. Their perception is that tourists contribute to sustaining local businesses, which are also used by local people. These small businesses increased their family income and encouraged the villagers to construct concrete homes or expand their existing households, own private cars, and have electrical and solar photovoltaic panel devices fitted to their homes for sustainable and cheap green energy (Fig. 4).

To control this urban growth, the Jordanian government approved the amendment of the development borders of the DS region from the northeastern side in 2016. It annexed parts of the municipal boundaries of Sweimeh to the development zone over an area of approximately 327 hectares (Fig. 5). The normal growth and the new expansion increased the area of the village from 0.15 km^2 in 2004 to 4.40 km^2. A limited number of the local people (34.6%) were able to benefit from this emerging urban development (Rumonline 2018). There were considerable economic opportunities for the local people to profit from selling their agricultural land.

There has also been a notable increase in the population of Sweimeh since the 1950s as it grew from 267 people in 1953 to 2054 in 1994, while between 1994 and 2019 the population more than doubled reaching 4448, as reported by the Jordanian Department of Statistics (DoS 2019). According to a study conducted by

Fig. 4. Sweimeh village
Source: Aledwan (2019); Jordanzad (2019)

the Directorate of Social Development, 40% of the town population are aged 1-15 years, 10% are in secondary school, 30% have permanent jobs, and the rest are over 50 years old (Jordanzad 2019). This visible increase is attributable to normal population growth and the new emergent local economic business development, which attracted more young local people to stay close to their homes in Sweimeh (Table 2).

Over the past 15 years, the Jordanian government has focused on an equitable approach in terms of heritage preservation and tourism development. The main spatial planning strategy target was to maximize the benefits from tourism and provide improvements to local communities, so they held a design competition commissioned by the Jordan Development Zones Company (JDZC) to develop a master plan for the Dead Sea shoreline in 2011. The plan was produced by the well-known American planning and design firm Sasaki Associates, which won first place in the competition. Their spatial planning strategy revolved around the creation of 12 investment districts that address the conservation of natural and economic resources of each investment area. The detailed master plan covers 4,000 hectares and aims to provide the area with various investment opportunities for the upcoming 25 years. It aims to conserve the natural DS environment, embody the concept of sustainable development, and take all possible measures towards it (Sasaki Associates 2019).

In this study, we focused on two out of thirteen districts indicated in this plan: the Sweimeh urban district (Maroon) and the hotel district (Ochre). The color chart in the Dead Sea Master Plan Districts ranges from green to yellow, indicating the spatial distribution of the nine existing districts and the four new proposed ones (Fig. 6). Before the 1990s, the northeast coast was in the area now comprising the luxurious hotel district, the convention center, Amman shore, and the DS Porto districts, while the newly proposed four districts (The Panorama, North Zara, South Zara, and Mujeb Reserve) are set apart in a single zone on the east coast with fewer observable features.

According to the technical report of the DS Strategic Plan (Sasaki Associates 2019), there are four reasons behind not including the village of Sweimeh in the detailed development zone master plan. Firstly, the presence of Sweimeh in the upstream part of the northwest zone is hidden behind the hotel district, and separated by the DS high-speed highway (the maroon polygon); secondly, Sweimeh has few publicly controlled lands; thirdly, the village is located on flat land, and does not have a panoramic view towards the DS; and finally, the surrounding area of the village has low touristic development value. In return, the hotel zone is located on the seashore next to the sandy beach and has many access points from the service road of the DS highway. Additionally, the coastal lands are owned and controlled by the government and investment companies.

The Dead Sea Master Plan Districts (DSMPD) was only partially implemented, with a number of new housing projects being constructed by the individual private sector or foreign investors to the southeast of the old village, close to the local community's homes, on land that was once theirs. The result was the creation of planned residential areas of varying quality and standards. 84% of the respondents considered that the new housing projects had increased the division between the disadvantaged local residents and the privileged newcomers. The projects exacerbate social disparity due to the glaring contrast in levels of facilities

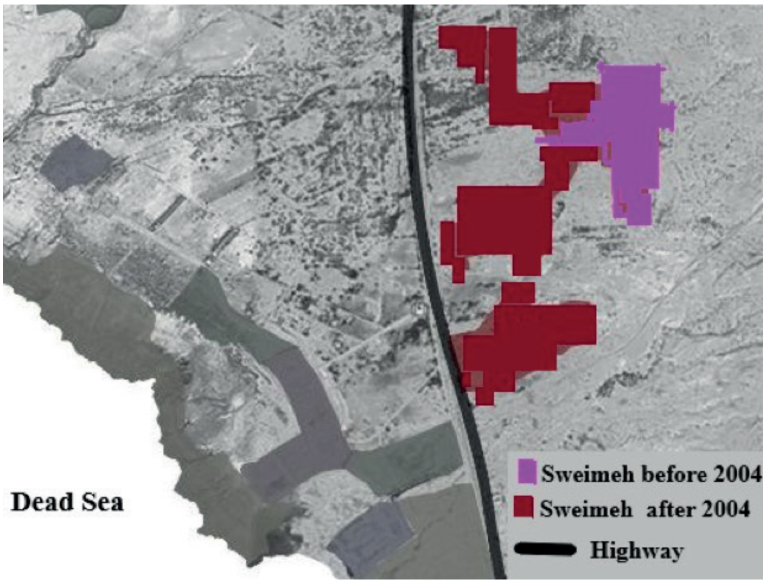

Fig. 5. Sweimeh urban growth, before and after 2004

Source: Alfuqaha et al. (2020)

Table 2. Sweimeh population growth

Year	Population	Household no.	Average household	Growth percentage		Annual percentage growth		Tourist jobs/ business percentage
1953	267	49	5.4		217		4.4	0
1994	2054	270	7.6	769		9.6		10
2019	4448	803	5.5					50

Source: Authors

between the two residential groups (Fig. 7). Conversely, one of the investors in these projects said that a large number of the new flats were not sold due to the poor conditions and attributions of the neighboring houses of local people in the old village of Sweimeh. The officials of the local authority of Sweimeh considered it to be their responsibility to provide services for the new housing projects, such as electricity, road construction, garbage collection and transportation, while there are no financial returns from these services since payments of these property tax bills are governed by a patchwork of state investment commissions and paid to the state, not the local governments which rely on property taxes to fund the services.

The DSDZ creates spatial inequality resulting from the high level of place-based development differences associated with urban characteristics, such as poor infrastructure and service provision. This spatial inequality is visible in the shoreline service provision, which is divided into luxurious private resort shorelines and unpleasantly overcrowded public beaches. The use of facilities and accommodation in the resorts and spa treatments are very expensive and unaffordable for the middle and lower class, while the free public beach is dirty and faces intense problems caused by coastal erosion, landslides, and sinkholes. It has no sandy beach and is frequently exposed to geological hazards (Fig. 7 & Fig. 1) (Abu Khalil 2019). In addition, the public shore forms an environmental challenge to the local authority of Sweimeh, which suffers from financial problems and does not have enough garbage compressor trucks and sweepers to clean the shore.

In general, the DS shore is irregular along the coastline and has no beachfront due to the rough rocky terrain and narrow passes to beaches (Abou Karaki et al. 2019). The shore fails to function in terms of recreation or providing social and cultural activities (Abu Khalil 2017). In contrast, the DS resort beach, managed by the private sector, comprises various luxurious facilities in proximity to hotels. The beach has an aesthetically pleasing sea view, which plays an important role in the choices made by tourists, as well as in their willingness to pay higher hotel prices (Fig. 7).

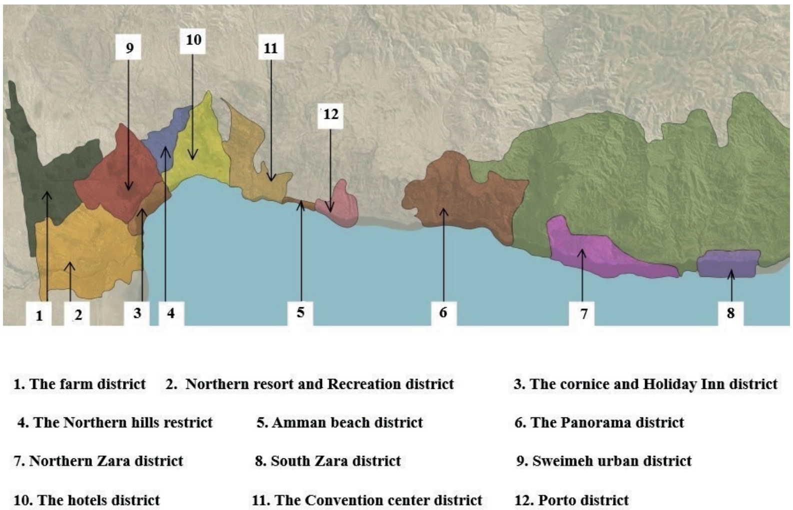

Fig. 6. Dead Sea Master Plan Districts

Source: Sasaki Associates (2019) illustrated by Alfuqaha et al. (2020)

Fig. 7. Sweimeh spatial inequality

Source: Aledwan (2019) (top left); authors (2021) (down left); Abu Khalil (2019) (right)

Finally, the Dead Sea Master Development Plan fails heavily in terms of land use planning. It was largely a technical process, executed out of the public domain, with expenditure skewed towards elite interests, displaying negligible concern for the socio-economic development of local people. New hotels and their associated resources, including the modified natural shoreline from which local people are now excluded, are clearly valued over new roads, schools, and hospitals for local citizens. Consequently, the inhabitants of Sweimeh exhibited a generally negative attitude towards the DSDZ because of the great attention paid to the development of the hotel district, while Sweimeh lacks basic services such as electricity and water.

CONCLUSIONS

The analysis demonstrates the general success of the DSDZ and its positive socio-economic impact on the national level, with negative social impact and unequal outcomes on the local level. Although tourism development zones inevitably generate some negative social and economic impacts, they can be extremely beneficial in helping to develop regional economic potential and in alleviating poverty. The researchers believe it is crucial to study the impact of the development zones through their social, environmental, spatial, and economic effects. It is important for planners to study and analyze worldwide case studies for a better understanding of the specificity of each project and the attributes that lead to either success or failure of such projects. Furthermore, local communities should be consulted and considered in every stage of planning and execution to avoid the kind of two-tier, discriminatory, and exclusive outcomes seen in Sweimeh.

This paper is important for two main reasons. Firstly, with urbanization and urban management receiving little attention in the DSDZ development agenda, it is necessary to understand why new forms of urban management are needed to address increasingly divisive urban inequality. Secondly, there is little interest of governments, investors, and other national agencies in the context of tourism development programs in the urban sector at the local level. At the academic level, the findings of this research help to establish an assessment tool for testing the socio-economic impacts of tourism development zones.

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RESEARCH PAPER

LAND SUITABILITY MODELING FOR RICECROP BASED ON AN INTEGRATED MULTI-CRITERIA DECISION MAKING IN QUANG TRI PROVINCE OF VIETNAM

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ABSTRACT. The present study was aimed to determine the potential cultivated lands for rice crop production in Vietnam. Analytic Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) were employed in order to analyze the structure of an ideal solution in agriculture that focuses mainly on environmental, economic, and social sustainability. A final ranking of alternative development solutions was also accomplished. Three major factors were taken into consideration during the process, including the economics, social concerns, and the environment, in order to develop a sustainable plan for rice and other grain crops in the future. The obtained results demonstrate that the area under investigation in Quang Tri province, which encompasses 192.49 km^2 of land area, was extremely conducive to growing rice crops, with the majority of the arable lands suitable for cultivating rice varieties concentrated in Trieu Long District (63.14 km^2) and Hai Lang District (56.87 km^2). The main findings of the present work indicated that, it can link decision makers with the influencing variables of rice crop growing utilizing a hybrid method that can be successfully used based on GIS technique. To expand production, chemical soil characteristics and agricultural development strategies should be investigated further, particularly in the studied areas with greater success potential.

KEYWORDS: Evaluation, GIS, AHP, land suitability, rice crop, TOPSIS

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INTRODUCTION

During the period from 2008 to 2017, the GDP growth rate of the entire agricultural sector of Vietnam reached a striking average of 2.66% per year with the rate of 2018 hitting a record figure of 3.76%. In 2019, despite many hurdles, Vietnamese agriculture continued to maintain its growth momentum of 2.2% (Ministry of agriculture and rural development 2019).

Rapid urbanization and urban expansion have resulted in the inevitable depletion of agricultural land resources leading to reduced rice-crop growing areas. An integrated approach to improving the ability to increase rice-crop productivity is needed for planning of land resources (Quang Tri Provincial Committee 2020).

The geographic information system (GIS) provides the necessary support for management and the analysis of large volumes of data concerning complex geography (Stefanidis 2009; Tang 2009; Jamil 2018). The analytic hierarchy process (AHP) has been increasingly applied as a technique for multi-criteria decision analysis in multipurpose tasks (Stefanidis et al. 2013; Akıncı et al. 2013; Bagheri et al. 2013; Jiuquan et al. 2015; Kazemi 2016; Estrada et al. 2017; Seyedmohammadi et al. 2019). It can support the decision-making process to arrive at a decision that the panel members trust. Disagreements in judgments can indicate, that the judgments can be adapted until the group members are satisfied with the decision outcomes (Hummel et al. 2014).

Over the last decade, a large number of studies, researches, institutes and projects have been carried out in an attempt to construct a comprehensive procedure for the optimal use of agricultural land (Jeffrey et al. 2009). Multiple criteria decision analysis (MCDA) has been considered the high feasible technique for solving complicated issues. MCDA techniques, such as analytic hierarchy process (AHP) based on GIS, is an effective framework to assess for the strategic placement of cropping (Seyedmohammadi et al. 2019). Many years ago, GIS-based research was carried out to develop new arable lands for the cultivation of rice and other crops in efforts of environmental conservation and efficient management of natural resources, which was proved essential for ensuring adequate food supplies and sustainability in agricultural development (Dengiz et al. 2013; Al-Yamani et al. 2013). The application of GIS and multi-indicator assessment techniques in land adaptation assessment have captivated numerous scientists the world over (Rahmanipour et al. 2014). There has been an urgent need to apply the principles of sustainable production to land resources and land use and to meet the requirements of society while conserving fragile ecosystems (FAO 1993). The potential and limitations of land usage for plant production were predicted through assessment of land suitability for cultivation in Azadshahr Township – Iran, utilizing an analytic hierarchy process (AHP). This study provides a special methodological approach to evaluation of suitable areas that can appear useful for decision makers and farmers to adopt as a planning (Maleki et al. 2017). AHP is becoming more and more utilitarian in agricultural planning. Vietnam located in tropical climatic zone and is evident to have had favorable conditions to grow agricultural products in various locations, including lowlands, mountainous areas, highland, and even coastal ecological sub-regions. Vietnam's agricultural productivity has invariably maintained an average annual growth rate of approximately 3.5%, translating to one of the most significant proportions among all Asian countries in general. After a prolonged period of food scarcity since 1989, Vietnam has, since then, gradually become the world's rice export powerhouse.

In Vietnam, initial research on applying GIS to land adaptive assessment was carried out in the 90s of the twentieth century. Studies have used GIS technology in zoning for either the adaptability or adaptation to land use types based on GIS application and MCA multi-standard analysis method in the AHP – IDM technique. Today, GIS and AHP technique have been proven effective for their application in agricultural production planning (Vy et al. 2014; Huynh et al. 2015; Chau et al. 2017; Dieu et al. 2107; Huynh et al. 2015).

Quang Tri is a region requiring an outsized amount of attention due to its outdated agriculture practices and low urbanization rate. Rice and crops are the major agricultural product in Quang Tri province (Quang Tri Statistical Office 2019). The needs for optimal land usage are of pivotal important here in due to various complicated social aspects and a broadly low domestic product in this province. Assessment of suitable land is therefore rendered largely necessary for rational management of land use in future planning. The present study is a novel, which focuses on the potential cultivated lands for rice crop production using Analytic Hierarchy Process (AHP) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) aiming to analyzed in agriculture based on environmental, economic, and social sustainability. This study was aimed to modeling the land suitability for rice and crops affecting province's ecological assets. The majority of these criteria have to be evaluated by linguistic terms rather than numerical values (Suder and Kahraman 2018).

MATERIALS AND METHODS

Study area

A humid tropical climate, typical of the inner tropical ring of the Northern Hemisphere, prevails in Quang Tri, which receives significant influence from the sea. Mountains, hills, plains, sand dunes, and beaches make up the diverse topography, which is positioned in a northwest-southeast orientation and comprises primarily of mountains and hills. Mountainous landscape with altitudes ranging from 250 to 2000 meters. The landscape has been extremely dissected, with steep hills on all sides. The landscape is hilly, with altitudes varying from 50 to 250 meters above sea level (Fig. 1). Several crops, including rice, sweet potatoes, pineapple, soy beans, groundnuts, and melons, contribute to the province's economic well-being.

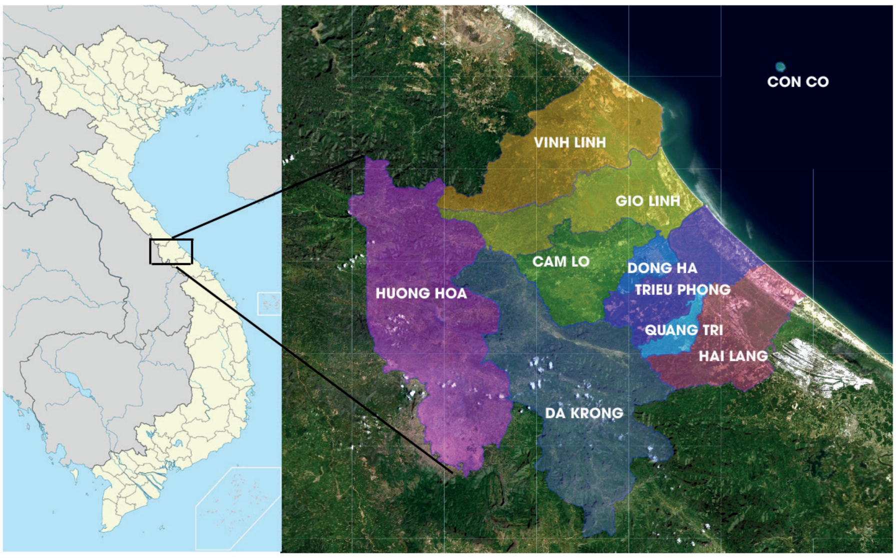

Fig. 1. Location map of study area

Source: Map background is taken from Open Street Map (OSM), Arcgisonline, Google Map, Wmflabs… Administrative boundary data is compiled from Database of Global Administrative Areas, Global Map of Vietnam ©ISCGM, Ministry of Natural Resources and Environment – Vietnam

MATERIAL

The climate data was gathered from three weather stations located within the study province and its neighboring areas. The climatic means were calculated based on data from period of 2000-2008 years. The mapping of the climatic variables was completed with the help of the ArcGIS 10.0 program. During a survey conducted in April 2020, soil samples from 120 profiles around the province were gathered at random. Maps showing the geographical distribution of soil depth and waterlogging were created for the study provincial region. Vietnam's National Soil Maps (2010), which were used in the research, were acquired from the Ministry of Natural Resources and Environment's website. The elevation layer was obtained from the website (http://srtm.csi.cgiar.org/). With the help of ArcGIS 10.0, we were able to calculate the slope from the DEM (resolution 30x30m). It was possible to get land use data from Ministry of Natural Resources and Environment (MONRE, 2015), which contained presently rice-crop land that was gathered utilizing remote sensing images taken during the wet and dry seasons. These previously mentioned statistics were incorporated into the model in order to map the suitability of land for producing rice crops.

METHODOLOGY

Identification of criteria

Two groups of experts were designed as follows:
Group work N^{0}1 (GW1) was organized with members of the provincial local authorities and a research team to determine criteria that include environmental, economic, and social conditions influencing rice and crop land suitability. Upon discussions, criteria had been selected and included in questionnaire sent to committee (to 5 decision-makers: D_1, D_2, ..., D_5). The purpose of this work was to rank possible site alternatives (A1, A2,..., A10) in the Quang Tri province for an ideal solution. This model used the TOPSIS method, which used multi-criteria from C1, C2,..., C9 (Fig. 2, Table 3).

Group work N^{0}2 (GW2) was comprised of 10 members. Among these, there were 5 local experts and 5 local farmers who joined the council to determine the criteria for the natural conditions influencing the rice crop growth. Upon discussion, criteria were selected and included in the questionnaire, then delivered to the aforementioned experts and local farmers. The goal of this work is to weigh the criteria. Each criterion is categorized into four levels (S1, S2, S3, N) based on the ecological requirements of rice crop cultivation of the Instruction for agricultural production land evaluation of Vietnamese Standard ISO (8409:2012). The integration of AHP-GIS was used in this model. This approach may be graphically formulated as follows (Fig. 2, Table 9).

The results of two teams of researchers (GW1 and GW2) were explored in detail discussion.

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)

Step 1: Construct a set of criteria for evaluating rice-growing areas in Quang Tri. The information utilized in this study was gathered through in-depth interviews with members of the decision-making and site-selection committees. Following the decision-making process, criteria for evaluating the rice growing location in Quang Tri were established.

Step 2: Determine the relative importance of each criterion. Using a metaphor, each individual decision-making committee (D1, D2, D3, D4, D5) evaluates the significance of a set of evaluation criteria after creating a set of assessment criteria. The weights assigned to each standard were established.

Step 3: Calculate the average proportion of alternatives available based on each of the criteria. During this stage, the decision-making committee will consider each site (A1, A2, A3, A4, A5, A6, A7, A8, A9, and A10) in agreement with the set of criteria that has been determined before. In agreement with each criterion, the decision-making council evaluated the rating scale and significance size of each site. Applying the formula in Eq. (1):

$$x_{ij} = \frac{1}{k} \times (x_{ij1} + x_{ij2} + \ldots + x_{ijt} + \ldots + x_{ijk}) \quad (1)$$

Step 4: Calculate the weighted average of the results. The fuzzy-decision matrix with weights and normalization should be calculated. by formula in Eq. (2):

$$w_j = \frac{1}{k} \times (w_{j1} + w_{j2} + \ldots + w_{jk}) \quad (2)$$

Step 5: Standardize the way in which alternatives are presented in relation to objective criteria. The result of the evaluation stage was used to obtain at the normalized values of choice Dt with respect to each criteria Cj for each Ai in this step.

Step 6: Calculate the value of the normalized standard in given case. The normalized scoring weight value Gi is obtained by multiplying the weight values of the criterion by the normalized rating weight value Gi. Formula in Eq. (3):

$$G_j = x_{ij} \times w_j, i = 1, \ldots, m, j = 1, \ldots, n \quad (3)$$

Step 7: Calculate The optimal fuzzy positive ideal solution A + and the optimal fuzzy negative ideal solution A- are selected (Table 1).

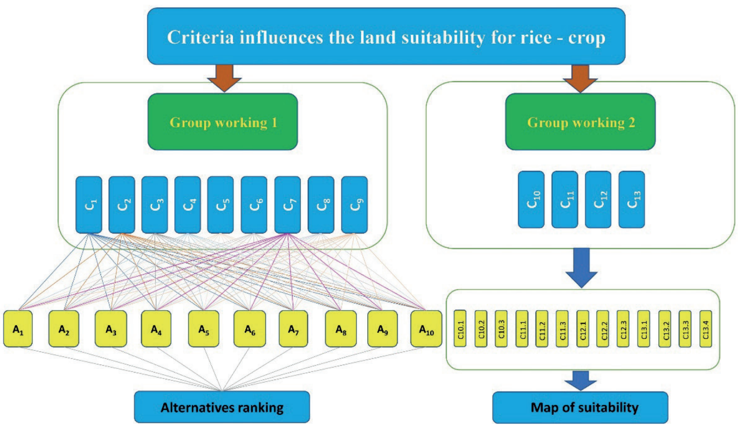

Fig. 2. The study process analysis

Table 1. Optimal dimming solution

A+	1	1	1
A -	0	0	0

Step 8. Calculate the distance between each solution as well as the coefficients in close proximity by formula in Eq. (4):

$$d_i^+ = \sqrt{\sum_{j=1}^{n}\left(G_i - A^+\right)^2}$$
$$d_i^- = \sqrt{\sum_{j=1}^{n}\left(G_i - A^-\right)^2} \quad (4)$$

The closeness coefficient (CCi) is used to evaluate which alternatives should be favoured in the ranking process. Formula in Eq. (5):

$$CC_i = \frac{d_i^-}{d_i^+ + d_i^-} \quad (5)$$

Step 9: Determine the order in which alternatives should be ranked based on respective coefficients. This was the last step in the process of evaluating the alternatives. The best alternative sites have the highest closeness coefficients, while the worst alternative sites are the furthest away from the positive ideal solution and the closest to the negative ideal solution in terms of distance and closeness coefficients.

Analytic hierarchy process (AHP)

A credit scoring model based on this expert judgement can be developed using a technique of analytic hierarchy process (AHP). For this type of model, the validation requirement can be problematic. The judgments made then converted into a scale of 1 to 9 that reflected the relative importance of one element over others in relation to attribute of the element in query (Saaty 2008; Saardchom 2012; Hummel et al. 2014; Table 2) In order to determine which criteria affect to land-use suitability for rice and crops, ten experts are invited to process to provide judgments on pair comparison question, which assisted in the determination of the importance of each criteria of natural conditions. Overall, priorities can be made through synthesising or pooling together the judgement made in the pairwise comparisons (Saardchom 2012). Consistency Ratio (CR) (< 10 %) was used to check the accuracy of comparisons (Malczewski 1999; Saaty 2000; Saardchom 2012; Bozdağ 2016; Maleki 2017).

Score for each criterion (X_i'') on each land mapping unit was determined, importance of criteria i' are converted to criteria weights (W_i''), in which i' rang from 1 to m, where m was the total number of criteria involved in the process. The weighted linear combination of W_i'' and X_i'' give suitability index (SI) for each land mapping unit (LMU). By above process, land-use suitability map is produced. Score of each level criterion is computed for each LMU. These values are combined with the above mentioned overall weight to provide suitability value for each LMU corresponding to each land-use type. This process was done in ArcGIS through the composite map of land mapping units using the formula in Eq (6).

$$SI = \sum_{i'=1}^{m}\left(W_{i'} \circ X_{i'}\right) \quad (6)$$

According to the FAO (1993), the most suitable index was SI_1 (with a value > 80%), followed by SI_2 (40% -80%), which was a moderately suitable index, and then SI_3 (20%-40%), which was a marginally suitable index, and finally N (with a value less than 20%), which was not a suitable index.

Geographic Information System (GIS)

To estimate an appropriate piece of land, utilize aggregated values of inputs and weights. GIS and AHP were demonstrated in an evaluation of land suitability. The approach was originally designed as a logically and systemically quantitative framework, in which priorities are set, options are selected, and a connection is made with other participants. GIS technique was used to increase geographic fuzzy decision making. Using the structured AHP, expert perspectives are applied to establish the weights of given criteria. TOPSIS weights the potential for rice cultivation on the land to generate a ranking. GIS is used to run the Spatial Analyst module, and it is also used to determine suitability variables. This technique led to the assessment structure in Figure 3, 6. A questionnaire was used to gather information on importance of each criterion from local experts. Specifically, the goal of this study is to produce 13 component maps in raster format. All raster layers were targeted at WGS84-Zone 48N, and the AHP algorithm, which collected weights for all criteria, was used to apply the weights to the layers. The appropriateness of land for rice cultivation was determined by overlaying (superimposing) 13 raster component maps, which were created using ArcGIS 10.0 software. The map of land suitable for rice crops was finally obtained and categorized into four groups based on its classification (SI1, SI2, SI3, N).

Table 2. Nine-point scale using in AHP

Intensity of importance	Judgments of verbal attribute labels
9	Absolute importance
7	Very strongly importance or preferred
5	Strong importance or strongly preferred
3	Weak importance, moderately important or preferred
2, 4, 6, 8	Intermediate values between adjacent judgments of two
1	Equally preferred more important or preferred

Source: Saaty 2008

RESULTS AND DISCUSSION

Evaluation of land suitability from the Group Working N⁰ 1 (GW1)

The factors influencing rice crop growth were determined using data from detailed interviews with committee members (D1, D2, D3, D4, D5).Table 3 displayed nine criteria that were pointed out by the council, including: Income from rice crop production (C_1), Rate of return from rice crop production (C_2), Local policy (C_3), Financial resources (C_4), Farmer skills (C_5), Farming habits (C_6), Labor force (C_7), Technology improves rice production (C_8), Natural condition (C_9).

The regions included in the assessment are A_1: Dong Ha City, A_2: Quang Tri Town, A_3: Vinh Linh district, A_4: Huong Hoa district, A_5: Gio Linh district, A_6: Dakrong district, A_7: Cam Lo district, A_8: Trieu Phong district, A_9: Hai Lang district, A_{10}: Con Co district. Table 3 shows the data obtained from discussions with committee members (D1, D2,..., D5) to determine the factors affecting rice growing.Three major criteria for this assessment were: economic sustainability, social sustainability and environmental sustainability. Nine sub-criteria were choiced to involved in the model. Table 4 shows the weights of the standards (C1, C2,..., C9). Opinion of decision maker Dt on criterion Ci is EI is mean Ci is extremely important criterion than other, or MI is mean Ci is medium important one compared to others. This results also reveal that fuzzy set theory (Zadeh 1965) allows decision-makers to incorporate unquantifiable information and non-obtainable information into the model.

Table 5 shows the distance values of each option (A1, A2,..., A10) from the positive ideal and the negative ideal. The ultimate ranking of alternatives was decided by the closeness coefficients of the alternatives in question (CCi). The most suitable alternatives are those that are closest to the positive ideal. As measured by the closeness coefficient, the Hai Lang district rank was the highest for rice crops cultivation ($CC_{(A9)}$: 0.6354), followed by Trieu Phong ($CC_{(A8)}$: 0.6150), and Gio Linh ($CC_{(A5}$: 0.6025). These are districts that are less suitable for rice crops cultivation such as: Con Co district ($CC_{(A10)}$: 0.5426), followed by Dakrong district ($CC_{(A6)}$: 0.5563), Quang Tri Town ($CC_{(A2}$: 0.5669), Huong Hoa district ($CC_{(A4)}$: 0.567), Dong Ha City ($CC_{(A1)}$: 0.5712).

Evaluation of alternatives from the Group Working N⁰2 (GW2)

The data from detailed interviews with 10 experts determined the factors effecting rice crop growing, Table 6 indicated that there were 4 main criteria obtained by council, which were: Soil (C_{10}), topography (C_{11}), hydrology (C_{12}), climatic characteristics (C_{13}); 13 sub-criteria include: Soil type ($C_{10.1}$), soil depth ($C_{10.2}$), soil composition ($C_{10.3}$), elevation ($C_{11.1}$), slope ($C_{11.2}$), terrain ($C_{11.3}$), irrigation conditions ($C_{12.}$1), flooding ($C_{12.2}$), average annual rainfall ($C_{12.3}$), average annual temperature ($C_{13.1}$), annual maximum average temperature ($C_{13.2}$), annual average minimum temperature ($C_{13.3}$), number of sunny hours per month ($C_{13.4}$).

Table 3. Criteria involved in TOPSIS model

Criteria	Sub - Criteria	Definition
Economic sustainability	C_1 : Income from rice crop production	Income from rice crop production calculated by Vietnam (dong/ha per year)
	C_2 : Rate of return from rice crop production	The net gain or loss of an investment over a specified time period
Society sustainability	C_3 : Local policy	Local policy is a principle that guides local farmers making decisions result in positive outcomes enhance the living
	C_4 : Financial resources of household	Household capital may be ready for use in agricultural investment.
	C_5 : Farmer skills	Farmer skills are considered as the density of households who are proficient in farming
	C_6 : Farming habits	The activity of working on a farm is ancient
	C_7 : Labor force	Number of employees cultivating rice
Environmental sustainability	C_8 : Technology	Technology improves rice-crop production
	C_9 : Natural condition	General assessment of the potential of land, climate and water resources for rice production

Table 4. Decision matrix using Fuzzy linguistic variables

	D_1	D_2	D_3	D_4	D_5	Wij
C_1	EI	EI	EI	EI	MI	(0.740, 0.860, 0.980)
C_2	MI	EI	EI	EI	EI	(0.680, 0.860, 0.980)
C_3	EI	EI	EI	MI	EI	(0.740, 0.860, 0.960)
C_4	MI	EI	MI	MI	EI	(0.620, 0.780, 0.920)
C_5	MI	MI	MI	MI	MI	(0.500, 0.700, 0.900)
C_6	EI	MI	MI	MI	MI	(0.560, 0.700, 0.900)
C7	MI	MI	MI	MI	EI	(0.560, 0.740, 0.920)
C8	MI	MI	MI	EI	MI	(0.560, 0.740, 0.940)
C9	EI	MI	EI	EI	EI	(0.740, 0.860, 1.000)
EI: extremely important, MI: Medium important						

Table 5. The distance values and the final rankings

Alternatives	Separation from Positive Ideal solution (d^+)	Separation from Negative Ideal solution (d^-)	Closeness Coefficient (CCi)	Rank
A_9 (Hai Lang district)	0.6906	1.2038	0.6354	1
A_8 (Trieu Phong district)	0.7498	1.1977	0.615	2
A_5 (Gio Linh district)	0.7912	1.1993	0.6025	3
A_3 (Vinh Linh district)	0.8172	1.2045	0.5958	4
A_7 (Cam Lo district)	0.9087	1.223	0.5737	5
A_1 (Dong Ha City)	0.9321	1.2416	0.5712	6
A_4 (Huong Hoa district)	0.9368	1.2269	0.567	7
A_2 (Quang Tri Town)	0.9436	1.2353	0.5669	8
A_6 (Dakrong district)	0.9891	1.2399	0.5563	9
A_{10} (Con Co district)	1.0781	1.2787	0.5426	10

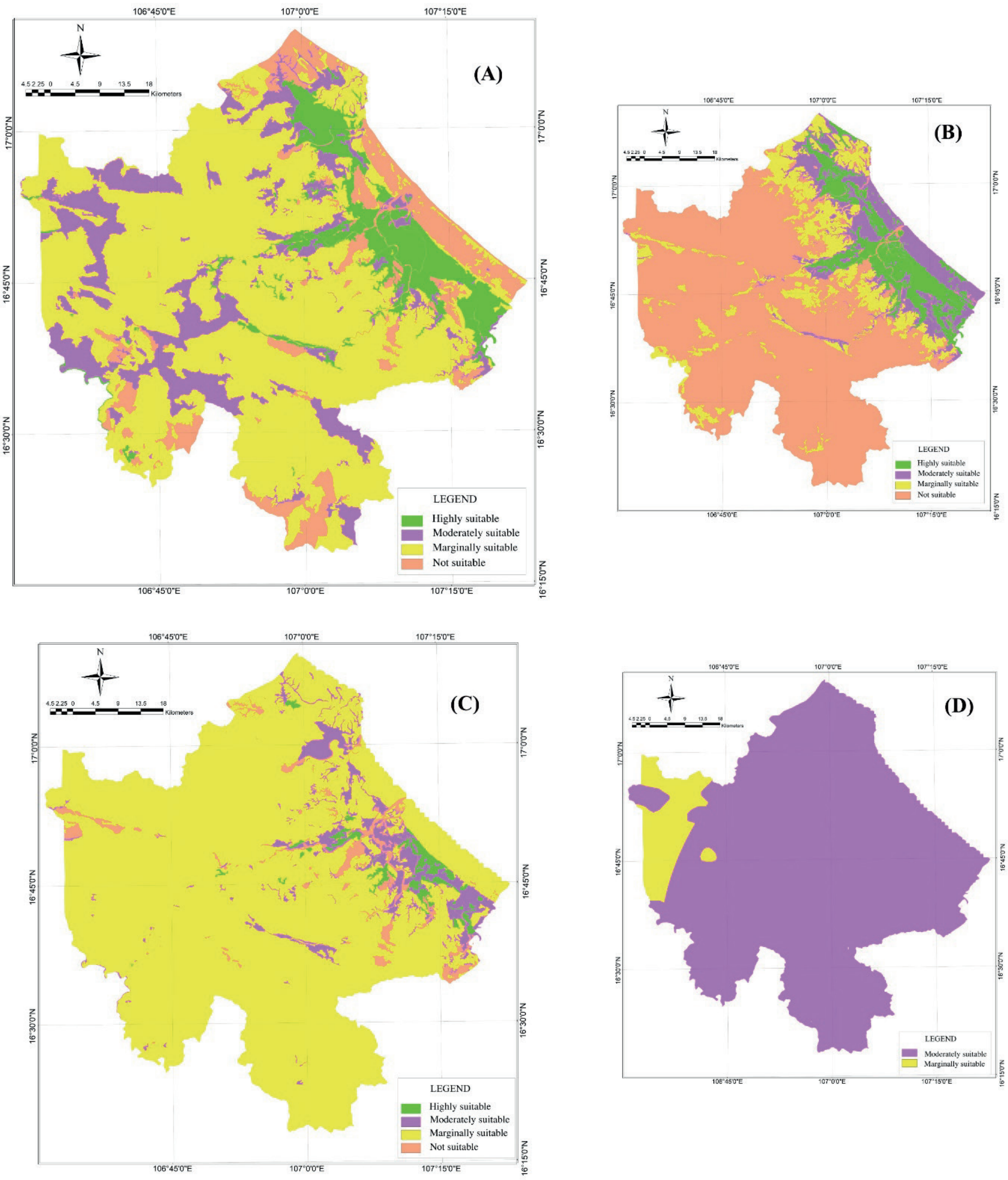

Fig. 3. Map of main criteria assessment for rice crops in Quang Tri province, Soil (A); Topography (B); Hydrology (C); Climatic

Table 6. Criteria involved in model of integration of GIS and AHP

Criteria	Weight (W1)	CR	Sub - criteria	Weight (W2)	Category				Source
					High suitable (S_1)	Moderate suitable (S_2)	Low suitable (S_3)	Not suitable (N)	
C_{10} : Soil	0.399	0.0058	Soil type group	0.426	Podzols (National soil type: Pb, Pf, Pg, Pe)	Cambisols, Ferralsols, Podzoluvisols, Reyzems (National soil type: B, Fl, Fp, Mi, D, Py)	Andosols, Chernozems, Xerosols (National soil type: Fj, Fq, Fs, Fu,M, Mn, T, C, X)	Other soil types	FAO, 1974, 1983, 1985, Vietnamese Standard ISO 8409:2012
			Soil depth (cm)	0.164	> 100	> 70 - 100	> 30 - 70	< 30	Local farmer
			Soil texture	0.138	Loam, Clay loam	Sandy loam, heavy clay loam	Clay	Sandy	Vietnamese Standard ISO 8409:2012
			Fertilization	0.272	High	Moderate	Low	Eroded soil with bare gravel, rocks, rivers	Local farmer
C_{11} : Topography	0.104	0.0027	Elevation	0.293	>3-10	>10-20, <3	>20-50	>50	Local farmer
			Slope (^{0})	0.419	0-3	>3-8	>8-15	>15	Local farmer
			Terrain	0.288	Dune	High dune	Low dune	Very low, very high dune	Vietnamese Standard ISO 8409:2012
C_{12} : Hydrology	0.408	0.0032	Irrigation conditions	0.523	Active irrigation		Difficult irrigation	Not irrigation	Vietnamese Standard ISO 8409:2012
			Flooding	0.257	Not inundated		Not inundated	Rivers	Local farmer
			Average annual rainfall (mm)	0.220	> 2000 - 2500	>1500-2000; > 2500	>1300 - 1500	< 1300	Vietnamese Standard ISO 8409:2012
C_{13} Climate	0.089	0.0001	Average annual temperature	0.222	>25-30 (^{0}C)	> 20 – 25 (^{0}C)	> 30, > 15 - 20 (^{0}C)	<15 (^{0}C)	Vietnamese Standard ISO 8409:2012
			Annual maximum average temperature	0.188	> 30 – 35 (^{0}C)	> 25 - 30 (^{0}C)	> 20 - 25; >35 (^{0}C)	< 20 (^{0}C)	Vietnamese Standard ISO 8409:2012
			Annual average minimum temperature	0.188	> 20 – 25 (^{0}C)	> 15 - 20 (^{0}C)	> 10 - 15, > 25 (^{0}C)	< 10 (^{0}C)	Vietnamese Standard ISO 8409:2012
			Number of sunny hours per month	0.402	>200	>150-200	>100-150	<100	Vietnamese Standard ISO 8409:2012

Table 7. Suitable land as assessed by main criteria

Category	Soil		Water		Topography		Climate	
	Area (Km^2)	Area (%)	Area (Km^2)	Area (%)	Area (Km^2)	Area (%)	Area (Km^2)	Area (%)
Highly suitable (SI_1)	419.07	8.83	75.11	1.58	87.75	9	4391.82	92
Moderately suitable (SI_2)	771.27	16.25	308.09	6.49	413.94	11	331.17	7
Marginally suitable (SI_3)	3012.48	63.46	4199.17	88.46	4004.12	13	24.00	1
Not suitable (N)	544.17	11.46	164.62	3.47	133.76	67	0	0

Table 8. Ranking the high suitable land

Sites	High suitable area (km^2)	Percentage of high suitable area per currently field rice crop	Rank focus on coverage of large area suitable
A_8 (Trieu Phong district)	63.14	69.13	1
A_9 (Hai Lang district)	56.87	53.49	2
A_3 (Vinh Linh district)	29.80	16.18	3
A_5 (Gio Linh district)	16.38	18.36	4
A_7 (Cam Lo district)	14.72	19.66	5
A_2 (Quang Tri town)	7.08	78.63	6
A_2 (Dong Ha city)	6.05	26.96	7
A_6 (Dakrong district)	1.04	2.55	8
A_4 (Huong Hoa district)	0.10	0.14	9
A_{10} (Con Co district)	0	0.00	10

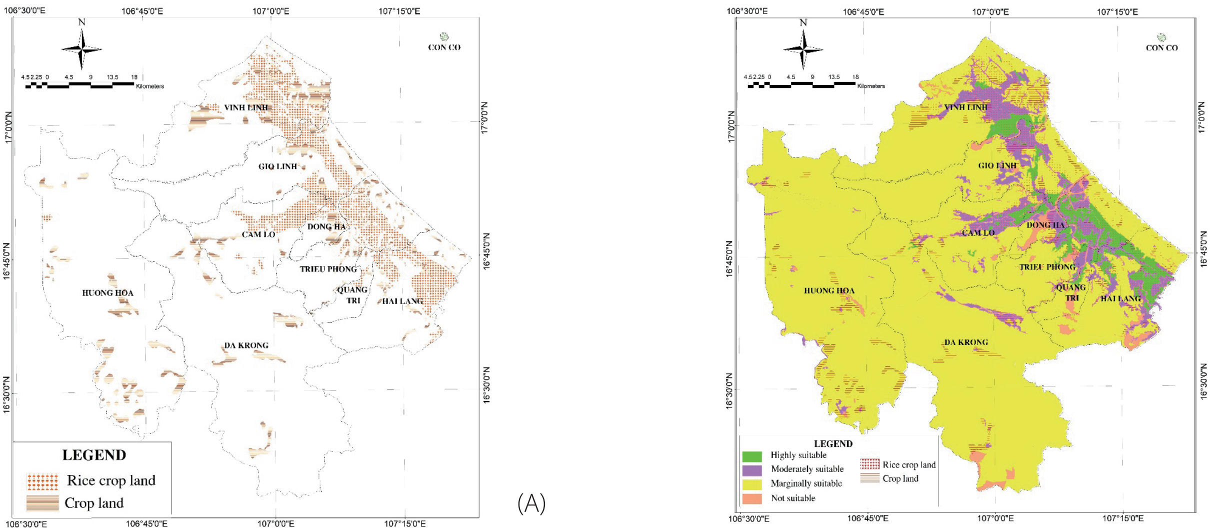

Fig. 4. (A) The actual currently rice fields and other crops land; (B) Land suitable area for rice crop

For rice crops, the results of the pairwise comparisons revealed that hydrological criteria (0.408) has the greatest weighting followed by soil (0.399), topography (0,104), and climate (0.089) in order of importance (Table 6). There were a number of important factors to consider, including soil, topographic, and hydrological requirements. The hydrological criterion and irrigation conditions were the only two to receive significant attention, whereas the average annual rainfall appeared to take the least attention. The soil types and soil texture have the largest and lowest weights, respectively, among the overall soil sub-criteria. Additionally, the number of sunshine hours per month was the most important climatic sub-criteria to consider when describing land suitability for rice crop production among the climatic sub-criteria. Out of the four main criteria, there was a consistency ratio (CR) of 0.005 for the matrix. Once it related to soil, topographic, hydrological, and climatic conditions, the correlation coefficient values (CR) were 0.0058, 0.0027, 0.032, 0.0001, respectively. This demonstrated the accuracy of the matrix result are mentioned in (Table 6). Due to the fact that their threshold values were on the narrow side for rice crops, hydrological criteria (2% of the province's total area) and topographical criteria (9% of the province's total area) restrict the amount of appropriate land for rice crop production (Table 7, Fig. 3). It has been shown that irrigation conditions and soil type have a stronger influence on rice crop development than any of the other variables involved. It was discovered that 28.3% (192.49 km^2) of the total field area in the study province was very favourable to the production of rice. The districts of Trieu Phong, Hai Lang, Vinh Linh, and Gio Linh had the largest appropriate land areas with areas of a very suitable index, 63.14 km^2, 56.84 km^2, 29.8 km^2, and 16.38 km^2 in area, respectively (Table 8, Fig. 4). Kihoro, (2013) carried out a research work in Kenya's Kirinyaga, Embu, and Mberee counties with a special emphasis on biophysical characteristics such as soil, climate, and terrain, which were taken into account for suitability analysis. In this study, topography and soil texture were 2 criteria that had the highest weight. Hydrology is what they are not took into consideration. Meanwhile, we consider that hydrology is the most essential option to address (highest weight). In Vietnam, the irrigation system remains underdeveloped and has not been modernised, the state of the irrigation system has an effect on rice production in the province. Some other studies on the evaluation of suitable potential areas for agricultural activities in the semi-arid terrestrial ecosystem in the Central Anatolia Region, terrain properties and soil features also were used to identify sites suitable for agriculture lands, the authors used both physical and chemical factors of soil to evaluate soil nutrition and soil quality index (Sezer et al 2014, Özkan et al 2020, Seyedmohammadi 2019, Rath et al 2018). The information was gathered through a variety of methods, including literature reviews, a structure-questionnaire, focus group discussions with local stakeholders, and individual interviews, all of which were conducted using the techniques of Participatory Rapid Appraisal and conceptual content analysis to gather the information. As a consequence, the diagnostic criteria for sustainable land management were developed in accordance with the framework for assessing sustainable land management, and they are as follows: productivity, security, protection, viability, and acceptability (Rath et al 2018). It is possible to apply and assess the sustainability indicators identified in these study in rice crop production regions of our study, which might result in the development of a strategic plan and increased sustainability in the future. Seyedmohammadi (2019) developed a similar model using the soil physical criteria. But erosion degree criteria were used instead of hydrology criteria. In high elevations, the source of erosion is rainfall; however, in lower elevations, the source of erosion is the river and creeks. Thus, the selection factors for evaluation are quite diverse. However, farmers are the most important people who have an understanding of their work. As a result, the findings of this study reflect cultural farming, with locals focusing on such criteria when deciding where to farm.

CONCLUSIONS

This study aimed to identify the high-suitable areas for rice-crops cultivation in terms of multiple potential factors by experts' opinions. Results show that soil irrigation conditions and soil type are the most important factor influencing the suitable index of land, followed by slope, and then the number of sunny hours per month. Hai Lang and Trieu Phong districts are ostensibly the worst sites because they are nearest to the negative ideal solution and it is of necessity to pay increased attention to varying purposes of using rice crop lands in Cam Lo, Quang Tri, Dong Ha, Dakrong, Huong Hoa, Con Co districts. These study revealed that the AHP and TOPSIS techniques arrived at identical predictions of land potential for rice cultivation, with a particular emphasis on four districts in the highest echelon of the rankings. Our results validated previously reports from the Ministry of Agriculture and Rural Development of Vietnam that Hai Lang and Trieu Phong were linked to the greatest agricultural areas in the province of Quang Tri, which resulted in the best rice crop output in the province. Within the study area, the land suitability evaluation is considered now as a vital link to sustainability of society, regarding productivity and environmental stability. Study reveals that integration of multi-criteria analysis (AHP and TOPSIS) has been used as an effective method of supporting the administration decision-makers who could base on ranked decision to decide on the planning of agricultural programs with environmental, economic and social sustainability.

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RESEARCH PAPER

THE TEMPORAL AND SPATIAL CHANGES OF BEIJING'S $PM_{2.5}$ CONCENTRATION AND ITS RELATIONSHIP WITH METEOROLOGICAL FACTORS FROM 2015 TO 2020

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ABSTRACT. Currently, Beijing is facing increasing serious air quality problems. Atmospheric pollutants in Beijing are mainly composed of particulate matter, which is a key factor leading to adverse effects on human health. This paper uses hourly data from 36 environmental monitoring stations in Beijing from 2015 to 2020 to obtain the temporal and spatial distribution of the mass concentration of particulate matter with a diameter smaller than 2.5 μm ($PM_{2.5}$). The 36 stations established by the Ministry of Ecology and Environment and the Beijing Environmental Protection Monitoring Center and obtain continuous real-time monitoring of particulate matter. And the 36 stations are divided into 13 main urban environmental assessment points, 11 suburban assessment points, 1 control point, 6 district assessment points, and 5 traffic pollution monitoring points. The annual average concentration of $PM_{2.5}$ in Beijing was 60 μg/m^3 with a negative trend of approximately 14% year^{-1}. In urban areas the annual average concentration of $PM_{2.5}$ was 59 μg/m^3, in suburbs 56 μg/m^3, in traffic areas 63 μg/m^3, and in district areas 62 μg/m^3. From 2015 to 2020, in urban areas PM2.5 decreased by 14% year-1, in suburbs by 15% year^{-1}, in traffic areas by 15% year^{-1}, and in district areas by 12% year-1. The quarterly average concentrations of PM2.5 in winter and spring are higher than those in summer and autumn (64 μg/m^3, 59 μg/m^3, 45 μg/m^3, 55 μg/m^3, respectively). The influence of meteorological factors on the daily average value of $PM_{2.5}$ in each season was analysed. The daily average $PM_{2.5}$ in spring, summer, autumn and winter is significantly negatively correlated with daily average wind speed, sunshine hours, and air pressure, and significantly positively correlated with daily average rainfall and relative humidity. Except for autumn, the daily average $PM_{2.5}$ is positively correlated with temperature. Although Beijing's $PM_{2.5}$ has been declining since the adoption of the 'Air Pollution Prevention and Control Action Plan', it is still far from the first level of the new 'Ambient Air Quality Standard' (GB309S-2012) formulated by China in 2012.

KEYWORDS: $PM_{2.5}$, Beijing, temporal and spatial changes, meteorological factors

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INTRODUCTION

When the particle size is less than 2.5 μm, it can both enter and reach the end of the bronchus, thereby interfering with gas exchange in the lungs. When the particle size is less than 1 μm, it can even penetrate the alveoli and enter the blood circulation of the human body, passing through and affecting other organs. Therefore, fine particles are more harmful to human health than larger ones. Concern about the hazards of particulate matter only started in the 1970s (Lave et al. 1973). According to statistics, the number of deaths caused by particulate pollution in the United States before 2000 was approximately 22,000 to 52,000. In European countries, the death toll is as high as 200,000. A long-term study of 500,000 people in large cities was conducted in the United States (Pope et al. 2002) and showed that for every 10 μg/m^3 increase in the concentration of fine particles, the mortality rate of all diseases, cardiovascular diseases and lung cancer increased by 4%, 6% and 8%, respectively. The hazards of particulate matter mainly depend on the toxic substances that it adsorbs. For example, adsorbed carcinogens, organic pollutants, and heavy metals will have toxic effects on the human reproductive system. Studies have also shown (Pope et al. 2009) that for every 10 μg/m^3 decrease in particle concentration, the average life span of the human body will increase by 0.61 years. In addition, a large number of studies have shown that particulate matter can affect the integrity of vegetation and natural ecosystems (Whitby et al. 1978), visibility (Chestnut et al. 1997), and man-made materials (Baedecker et al. 1997), while climate change (Warren et al. 2006) has direct and indirect effects.

In the past few decades, Beijing has conducted many studies on $PM_{2.5}$. The mass concentration of $PM_{2.5}$ in Beijing is highest in winter and lowest in summer (Yang et al. 2009). In 2000 and 2001, the main sources of $PM_{2.5}$ in Beijing were coal burning and dust, motor vehicle emissions, construction dust, biomass combustion, secondary nitrate, sulfate and organic matter. Compared with 1989–1990, pollution sources underwent certain changes (Zhu et al. 2005). Using the continuous observation data of $PM_{2.5}$ in Beijing from 2003 to 2004 and using the source analysis method of positive matrix decomposition, the pollution sources of fine particulate matter in Beijing were analysed as soil dust, coal, transportation, ocean, aerosol and the steel industry (Xu et al. 2007). We collected and analysed the $PM_{2.5}$ samples in different seasons in Beijing from 2009 to 2010 and discussed the main sources. The 6 main categories were soil dust, coal, biomass combustion, automobile exhaust, industrial pollution and secondary inorganic aerosols. Average contributions to PM2.5 were 15%, 18%, 12%, 4%, 25%, and 26%, respectively (Zhang et al. 2013). Research on Beijing's $PM_{2.5}$ in 2007 and 2008 found that the concentration of $PM_{2.5}$ in urban areas was higher than that in suburbs, and the concentration of $PM_{2.5}$ in urban areas increased significantly under foggy weather. During the Olympics, $PM_{2.5}$ pollution was significantly lower than that before the Olympics (Zhang et al. 2010). Using the two monitoring stations of the Beijing Urban Ecosystem Research Station to study $PM_{2.5}$, the results showed that the $PM_{2.5}$ of the two monitoring stations during the Olympics dropped by 26% and 27% compared to before the Olympics. During the Olympics, human control factors impacted $PM_{2.5}$ (Zhang et al. 2013). A similar study was also performed, and a similar conclusion was reached (Zeng et al. 2010). An analysis of particulate matter samples in Beijing and surrounding areas in August 2007 found that atmospheric particulate matter in Beijing gradually decreased from south to north (Zhao et al. 2009). From 2013 to 2014, the factors that caused changes in the concentration of particulate matter included high winds and biological particles in spring, humidity and rainfall in summer, temperature inversion and snowfall in autumn and winter, and other meteorological factors (Liu et al. 2016). In the 2014 Asia-Pacific Economic Cooperation (APEC) meeting and in the 2015 China Victory Day parade, to reduce man-made emissions, Beijing and its surrounding areas temporarily closed factories, construction sites and gas stations, banned the passage of vehicles on the road, and a 6-day statutory holiday was provided for state-owned enterprises and local government agencies. $PM_{2.5}$ decreased significantly (Xu et al. 2017; Wang et al. 2017; Xue et al. 2018; Li et al. 2016; Sun et al. 2016; Wang et al. 2016; Li et al. 2017; Huang et al. 2015). Since then, 'APEC Blue' and 'Parade Blue' have referred to good air quality. In Beijing, the daily concentration of $PM_{2.5}$ during the 'APEC Blue' period was 47.53 μg/m^3, and during the 'March Blue' period, it was 17.07 μg/m^3 (Lin et al. 2017). Regarding gas and particulate pollutants in Beijing and other regions, there are also many reports of temporal and spatial changes (Zhou et al. 2015; Guo et al. 2017; Chen et al. 2016; Wang et al. 2017). There is also the use of the community multiscale air quality modelling system (CMAQ) to calculate the reduction in the 'Air Pollution Prevention and Control Action Plan' (the Action Plan). It is estimated that from 2013 to 2017, the national population-weighted average $PM_{2.5}$ will drop from 61.8 μg/m^3 to 42.0 μg/m^3. Regionally, the largest decline in $PM_{2.5}$ will be in Beijing-Tianjin-Hebei with a simulated value of 38% (Zhang et al. 2019). Other authors have conducted similar studies in other regions (Cai et al. 2017; Jiang et al. 2015; Zheng et al. 2017; Xue et al. 2019). Recent reports using the CMAQ V5.0.1 model, concluded that the reduction of human activities during the COVID-19 outbreak still leads to serious air pollution incidents that cannot be avoided in Beijing because of meteorological factors (Wang et al. 2020).

To strengthen pollution control in Beijing, reduce the harm of air pollutants to human health and the environment, and improve people's living environment, research and work on monitoring, managing and improving environmental air quality has become the primary task of urban environmental protection. For this reason, in China, a series of national standards and governance measures have also been formulated, revised and promulgated. For example, the Ministry of Ecology and Environment promulgated the 'Ambient Air Quality Standards' (GB309S-2012) and 'Ambient Air Quality Index Technical Rules 2012' (HJ633-2012) on February 29, 2012. In the implementation of the 'Ambient Air Quality Standards', the Ministry of Ecology and Environment proposed that areas with good economic and technological foundations but prominent air pollution in the Beijing-Tianjin-Hebei region, the Yangtze River Delta and the Pearl River Delta must take the lead in implementing the new standards. On 10 September 2013, the Action Plan issued by the State Council further proposed that the overall air quality of the country should be improved within 5 years, requiring that by 2017, fine particulate matter PM2.5 in Beijing-Tianjin-Hebei, Yangtze River Delta and Pearl River Delta would be reduced by approximately 25%, 20% and 15%, respectively. The specific measures of the Action Plan can be divided into six main parts: strengthening industrial emission standards, upgrading industrial boilers, eliminating outdated industrial capabilities, promoting clean fuels in the residential sector, eliminating small polluting factories, and strengthening vehicle emission standards (State Council of the People's Republic of China 2013; Zhang et al. 2019). With the promulgation of the Action Plan, the Ministry of Ecology and Environment (MEE) has established a relatively complete network of comprehensive environmental monitoring stations covering the whole country. By 2015, a comprehensive monitoring network covering more than 1,600 sites in 366 cities was established. Each monitoring station records the mass concentration of atmospheric particulate matter $PM_{2.5}$ and other data once an hour. There are 36 monitoring stations in Beijing. Before 2012, it was difficult to obtain air quality data from ground monitoring stations. As a nationwide network of environmental monitoring stations has just been established, these local data are rarely used to study the impact of the Action Plan on Beijing's $PM_{2.5}$ and the temporal and spatial changes in Beijing's $PM_{2.5}$. This article uses hourly $PM_{2.5}$ data from 36 stations to study the temporal and spatial changes in atmospheric particulate matter $PM_{2.5}$ in Beijing from 2015 to 2020. With the gradual improvement of environmental monitoring stations, in recent years, some researchers have used them to study the temporal and spatial changes in pollutants. For example, according to data from 1,689 sites from 2015 to 2017, China's $PM_{2.5}$ and SO_2 showed a downward trend, O_3 showed an upward trend, and NO_2 showed little change (Silver et al. 2018). The temporal and spatial characteristics of air pollutants in China from 2015 to 2019 were studied, and except for O3, the mass concentration of $PM_{2.5}$ and other pollutants decreased (Guo et al. 2020). Other authors have performed similar studies (Guo et al. 2019; Fan et al. 2020). However, most of them take the whole country as the research object and there are relatively few specific studies on $PM_{2.5}$ in Beijing using the new monitoring stations. In addition, Beijing issued the 'Beijing Clean Air Action Plan 2013–2017' (Beijing Clean Air Action Plan, 2013), which requires the annual average concentration of $PM_{2.5}$ in Beijing to be reduced by more than 30% and controlled to approximately 60 μg/m^3. It also proposes 84 quantitative tasks and indicators based on pollution concerning automobile, industrial, coal and dust sources. The promotion of air pollution research is thus a current high priority. By studying the characteristics of Beijing's air pollution, analysing the level of pollutants and their temporal and spatial changes, air pollution research has important scientific significance for understanding Beijing's ambient air and controlling air pollution. Results can also provide references for decision makers to correctly formulate environmental policies.

MATERIALS AND METHODS

This article uses the data of 36 stations established by the Ministry of Ecology and Environment in Beijing. Each station records the mass concentration of $PM_{2.5}$ once an hour. The names and locations of these stations are given in Table 1 and Fig. 1. The data used in this article can be downloaded from http://beijingair.sinaapp.com/. Other researchers who used these data (Guo et al. 2020; Silver et al.2018; Guo et al. 2019; Fan et al.2020; Rohde and Muller 2015; Liang et al.2016; Leung et al. 2018).

From the time perspective, we statistically analysed the mass concentration of $PM_{2.5}$ per hour, month, quarter, and year in Beijing from 2015 to 2020. To understand and evaluate the air quality in Beijing, by the beginning of 2013, the Beijing Environmental Protection Monitoring Center had established a real-time monitoring network covering the city. The system includes a total of 36 automatic monitoring stations, which obtain continuous real-time monitoring of particulate matter $PM_{2.5}$ and are divided into the following categories according to their functions: 13 main urban environmental assessment points, 11 suburban assessment points, 1 control point, 6 district assessment points, and 5 traffic pollution monitoring points. The distribution of automatic monitoring sites, site names, site functions, and administrative area locations are shown in table 1 and figure 1. The monitoring site data are continuously sampled 24 hours per day with monitoring results reported as 1 h average values. The 36 monitoring points are located in Beijing's six areas of the main city and ten suburban counties, and their coverage can basically reflect the air quality of the entire Beijing area. The data in this article come from the Ministry of Ecology and Environment of China and the Beijing Ecological Environment Monitoring Center. The data of the Ministry of Ecology and Environment used in this article can be downloaded from http://beijingair.sinaapp.com/.

From a spatial perspective, we performed kriging interpolation on 36 stations in Beijing from 2015 to 2020 to obtain the spatial distribution of the Beijing $PM_{2.5}$ mass concentration. The kriging spatial interpolation method is based on the theoretical analysis of semivariograms and the method for unbiased optimal estimation of variable values within a region (Wang et al. 2015). Some scholars who study the spatial distribution of O_3 and PM have used this method for related research (Chih-Da Wu et al. 2018; James P. et al.1995).

To examine changes over time, we conducted a statistical analysis on the mass concentration of $PM_{2.5}$ in Beijing from 2015 to 2020 and calculated the relative changes in the mass concentration of $PM_{2.5}$ in months, seasons and years. Here, spring is from March to May, summer is from June to August, autumn is from September to November, and winter is from December to February.

The locations of the weather stations and their meteorological data come from the China Meteorological Science Data Sharing Service Network http://cdc.nmic.cn/home.do (China's ground climate data daily value dataset (V3.0) SURF_CLI_CHN_MUL_DAY_V3.0). This study uses data from three basic standard weather stations in Beijing, namely, Beijing, Yanqing and Miyun, and collects and organizes data for daily precipitation and daily averaged air pressure, temperature, wind speed, relative humidity, and sunshine hours. This study is based on monitoring data of the daily average $PM_{2.5}$ concentration in Beijing from 2015 to 2020 and comprehensively analyses the relationship between particulate matter and meteorological factors in terms of temporal resolution. The nonparametric correlation analysis method (Spearman rank correlation coefficient), which is more adaptable than traditional parameter analysis methods and has a wider application range, is used to study the correlation between the concentration of $PM_{2.5}$ and various meteorological factors in different seasons.

RESULTS AND DISCUSSION

Spatial distribution

We performed kriging interpolation on the annual average concentration of $PM_{2.5}$ at 36 sites in Beijing to obtain the spatial distribution of annual $PM_{2.5}$ from 2015 to 2020. From a geographical point of view, Beijing's $PM_{2.5}$ concentration is obviously high in the south and low in the north, with the highest concentration in the southeast. The concentration of $PM_{2.5}$ in the southwest is followed by the urban area and the northeast area, and the lowest concentration is in the northwest (Figure 1). In 2015, the difference between the regions with the highest and lowest concentrations of $PM_{2.5}$ reached 59 μg/m^3. This difference was reduced to 23 μg/m^3 by 2020. This spatial distribution

Table 1. Automatic monitoring site number, distribution, site name, site function and administrative area

Number	Longhude	Latitude	Place name	Function	Number	Longitude	Latitude	Place name	Function
1	116.43	39.95	Dongsi	Urban area	19	116.23	40.20	Changping Town	Suburbs
2	116.43	39.87	Temple ofHeaven	Urban area	20	116.11	39.94	Menlougou LongquanTown	Suburbs
3	116.36	39.94	Guanyuan	Urban area	21	117.10	40.14	PingguTown	Suburbs
4	116.37	39.87	Wanshou West Palace	Urban area	22	116.64	40.39	Huairou Town	Suburbs
5	116.41	40.00	Olympic Sports Center	Urban area	23	116.83	40.37	Miyun Town	Suburbs
6	116.47	39.97	Agricultural Exhibition HaD	Urban area	24	115.97	40.45	YanqingTown	Suburbs
7	116.32	39.99	Haidian Wanliu	Urban area	25	116.17	40.29	Dingling	Control poinl
8	116.17	40.09	Haidian North New District	Urban area	26	115.99	40.37	Badaling, Northwest Beijing	Distriet
9	116.21	40.00	Haidian Beijing Botanical Garden	Urban area	27	116.91	40.50	Miyun Reservoir in Northeast Beijing	District

10	116.28	39.86	Fengtai Garden	Urban area	28	117.12	40.10	Jingdong Donggao Village	Distriet
11	116.15	39.82	Fengtai Yungang	Urban area	29	116.78	39.71	Jingdongnan Yongle Store	District
12	116.47	39.96	U.S. Embassy	Urban area	30	116.30	39.52	Jingnan Yufa	District
13	116.23	39.93	Gucheng	Urban area	31	116.00	39.58	Soulhwestem Beijing Liuli River	District
14	116.14	39.74	Fangshan Liangxiang	Suburbs	32	116.40	39.90	Qianmen East Street	Traffic poinl
15	116.40	39.72	Daxing Huangcun Town	Suburbs	33	116.39	39.88	Yongdingmen Inner Street	Traffic poinl
16	116.51	39.80	Yrdiuang Development Zone	Suburbs	34	116.35	39.95	Xiühimen North Street	Traffic point
17	116.66	39.89	Tongzhou New City	Suburbs	35	116.37	39.86	South Third Ring Road West	Traffic point
18	116.72	40.14	Shunyi New City	Suburbs	36	116.48	39.94	East Fourth Ring Road	Traffic point

is related to Beijing's geomorphology and human activities. The northern part of Beijing is mostly mountainous areas, nature reserves and reservoirs, with few human activities, which is not conducive to the production of $PM_{2.5}$. The population and traffic in southern Beijing are both too high, which is conducive to the production of $PM_{2.5}$, especially under southerly winds. Particulates migrating from the south have the greatest impact on the southern part of Beijing and are more likely to form severe haze weather (Ma et al. 2017). Minor substances (NH^{4+}, SO_4^{2-} and NO^{3-}) are the main chemical components of aerosols; the trace material carried by the southerly wind is greater than that carried by the westerly wind, which, in turn, is larger than that carried by the northerly wind (Sun et al. 2006). Beijing's $PM_{2.5}$ has a good correlation with CO, NO_2 and SO_2 emissions in southern Hebei Province, and pollutant gas emissions in southern provinces have increased the burden of Beijing's $PM_{2.5}$ (Jiang et al. 2015). Long-distance transportation can even affect the aerosol boundary layer 1000 km away (Huang et al. 2020).

From the perspective of administrative regions, the mass concentration of $PM_{2.5}$ in urban areas is higher than that in suburbs, which is related to higher vehicle exhaust emissions in urban areas. Compared with previous studies on the source of $PM_{2.5}$, transportation is becoming increasingly important as a source of $PM_{2.5}$. In addition, there are other disadvantages caused by urbanization (Naděžda Zíková et al. 2016). The annual $PM_{2.5}$ concentration in traffic points and districts is higher than that in urban areas and suburbs. The higher $PM_{2.5}$ in the districts is related to the migration of particulate matter in the provinces and cities around Beijing. Except for individual months, the overall concentration in urban areas is higher than that in the suburbs, as shown in figure 2 and figure 4.

Changes over time

From 2015 to 2020, Beijing's PM2.5 concentration dropped with a linear trend of 13.98% $year^{-1}$. Although PM2.5 is declining year by year, the annual average mass

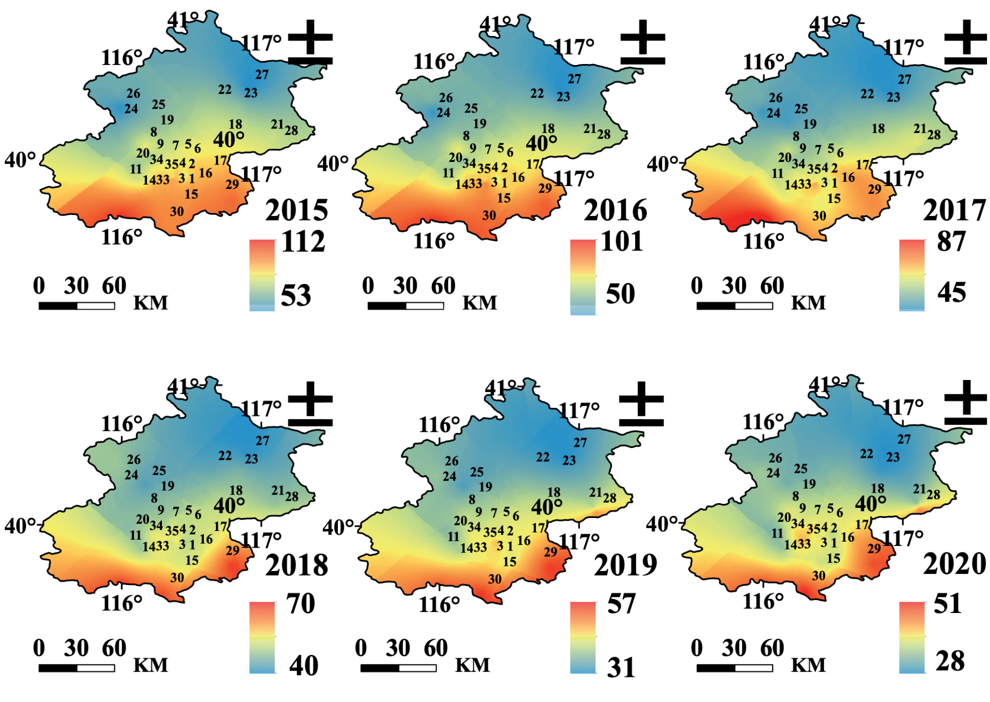

Fig. 1. The spatial distribution of PM2.5 (unit: μg/m³) in Beijing from 2015 to 2020 (1-36: site number)

concentration of $PM_{2.5}$ in 2020 is 37.99 μg/m³, which is still above the first level (35 μg/m³) of the latest 'ambient air quality standard' and some distance away from the World Health Organization's Air Quality Guidelines (10 μg/m³). From 2015 to 2020, the higher mass concentration of $PM_{2.5}$ in Beijing usually occurs in winter and spring and is related to local coal burning. According to the survey and research in the Beijing-Tianjin-Hebei region, residents' coal accounts for 46% of the monthly average $PM_{2.5}$, and Beijing, Tianjin and Hebei account for 3%, 3% and 40%, respectively. Since the Action Plan, Beijing has switched to natural gas and electricity instead of coal, but Hebei Province has had a significant impact on air pollution in Tianjin and Beijing (Zhang et al. 2017). In winter, more attention should be given to the prevention and control of $PM_{2.5}$. Lower $PM_{2.5}$ occurs in summer and autumn, which is related to increased precipitation or photochemical degradation in summer and autumn (Zhou et al. 2015). There are occasional low $PM_{2.5}$ mass concentrations in winter and spring, which may be related to snowfall in winter and spring, since snow plays an important role in the purification of $PM_{2.5}$ (Liu et al. 2016).

From 2015 to 2020, the $PM_{2.5}$ decreased the most in the fall of 2015, with a linear trend of 14.54% year^{-1}, followed by winter with a decrease of 12.70% year^{-1} and spring with a decrease of 11.88% year^{-1}. This is related to the Action Plan's emission reduction policy (Zhang et al. 2019). During summer, the decrease is approximately 8.59% year^{-1} due to the low $PM_{2.5}$ concentration. In terms of months, December and October had the largest decreases in $PM_{2.5}$, with decreases of 23.92% year^{-1} and 14.07% year^{-1}, respectively. From 2015 to 2020, only in February and January did the annual average relative change (year^{-1}) show a nonsignificant upward trend (0.04% year^{-1} in February, 6.48% year^{-1} in January). The increase in $PM_{2.5}$ in January and February is related not only to coal burning but also to higher relative humidity in January and February, which will increase the man-made secondary inorganic matter and liquid water content in $PM_{2.5}$, and condensed water promotes the conversion of gaseous pollutants into particles and accelerates the formation of dense fog (Wu et al. 2018). The high air pressure in winter is also for a contributor to the high concentration of $PM_{2.5}$. The daily average air pressure in winter from 2015 to 2020 in Beijing was 1028.86 hPa, which was higher than that in other seasons. High pressure easily forms stable meteorological conditions, which reduce the diffusion of particulate matter. The greater drop in $PM_{2.5}$ concentration in June is related to the concentrated rainfall in summer. The daily average precipitation in summer from 2015 to 2020 in Beijing is 3.81 mm, which is much higher than that in other seasons. From the perspective of regional functions, the $PM_{2.5}$ of Beijing's main urban area has dropped by 13.62% year^{-1}, suburban areas have dropped by 14.99% year^{-1}, traffic points have dropped by 14.91% year-1, and districts have dropped by 12.25% year^{-1} from 2015 to 2020. The annual average relative changes in $PM_{2.5}$ at 36 stations in the main city, suburbs, traffic areas, and districts all showed a downward trend. Fengtai Yungang in the main city, Fangshan Liangxiang in the suburbs, East Fourth Ring

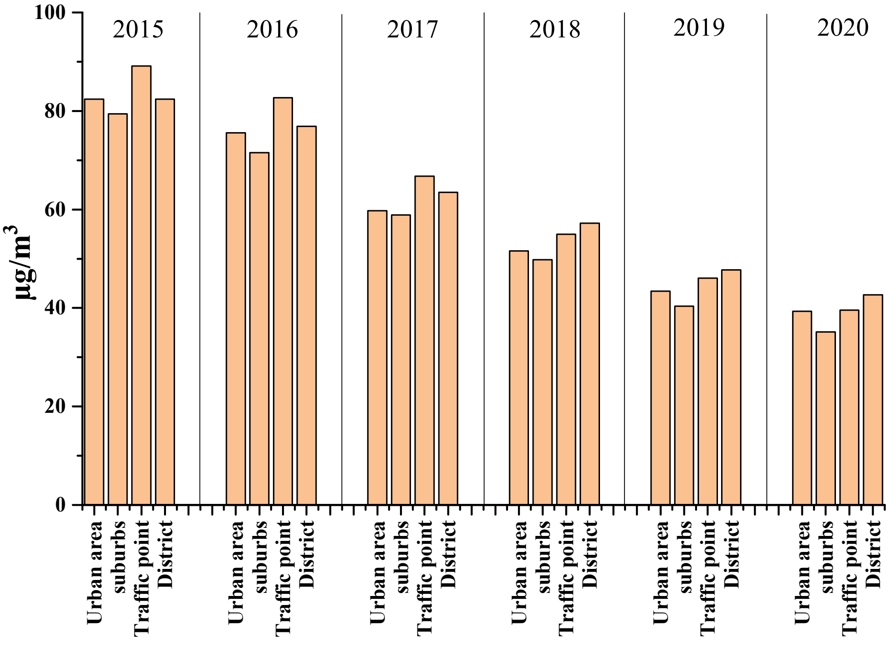

Fig. 2. The annual average mass concentration of $PM_{2.5}$ in each functional area from 2015 to 2020

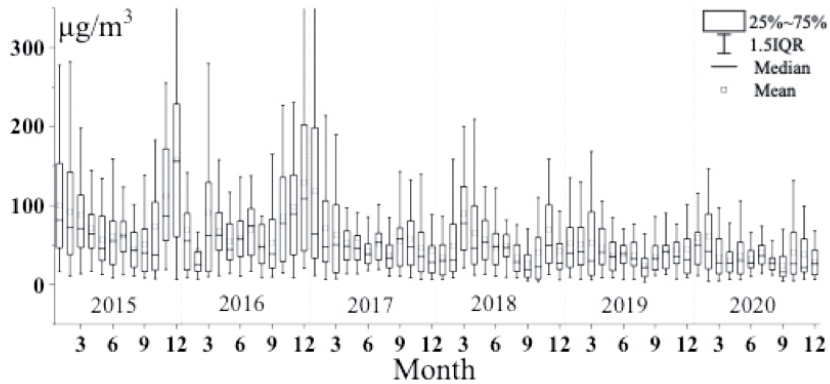

Fig. 3. Monthly change in $PM_{2.5}$ concentration in Beijing from 2015 to 2020

Road in the traffic areas, and Liuli River in the districts have the most decline, with a decrease of 15.59% year^{-1}, 16.50% year^{-1}, 16.12% year^{-1}, 15.64% year^{-1}, respectively. Haidian Botanical Garden in the main urban area, Yanqing Town in the suburbs, the Badaling Great Wall in the districts, the Xizhimen North Street in the traffic areas have the least decline with a decrease of 12.12% year^{-1}, 11.38% year^{-1}, 12.69% year^{-1}, 8.16% year^{-1}. The drop of the Great Wall's $PM_{2.5}$ is less due to its low concentration.

The hourly average concentration of $PM_{2.5}$ in different seasons from 2015 to 2020 did not show regularity. For example, the high concentration of $PM_{2.5}$ in the winter of 2015 appeared at 8 am, while in the winter of 2016 to 2020 at 8 am the average concentration is high or low, and the low concentration in the winter of 2020 appears at 8 am, which is the opposite of 2015, as shown in figure 5. As another example, the lowest average concentration of $PM_{2.5}$ in the winter of 2015 was at 1 am. The highest $PM_{2.5}$ concentration in the winter of 2018 was also at 1 am. Other seasons also showed similar phenomena, which are related to the variability of hourly meteorological factors.

As shown in Table 2, the daily mean $PM_{2.5}$ concentration in spring in Beijing has a significant negative correlation with wind speed and sunshine hours, while its relationship with relative humidity shows a significant positive correlation. With the increase in sunshine hours, the vertical diffusion capacity of the atmosphere is strengthened, which is conducive to the migration and diffusion of pollutants in the atmosphere and reduces the concentration of particulate matter at ground level (Li et al. 2009). The daily average value of $PM_{2.5}$ concentration in summer is significantly positively correlated with relative humidity. When the summer air humidity increases and the water vapour pressure increases, the particulate matter does

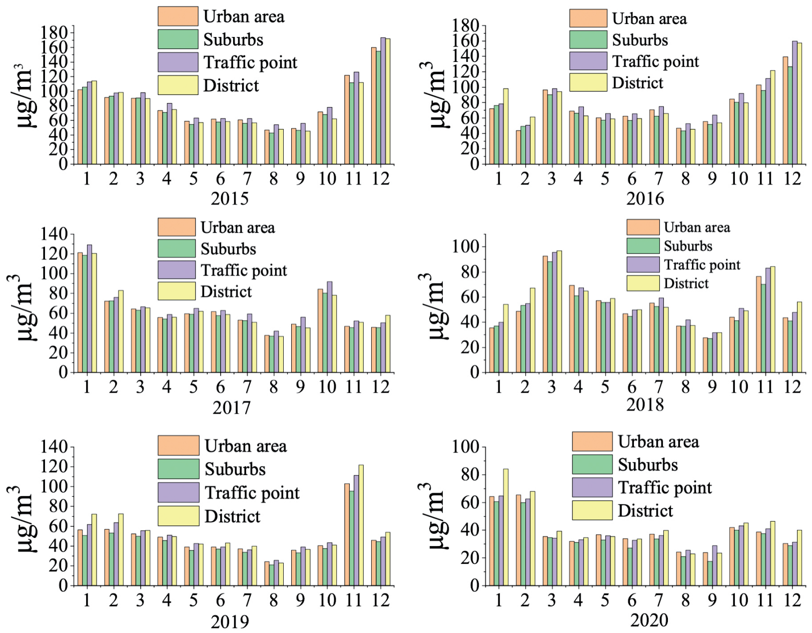

Fig. 4. Monthly mean $PM_{2.5}$ concentration in urban, suburbs traffic area, and district from 2015 to 2020

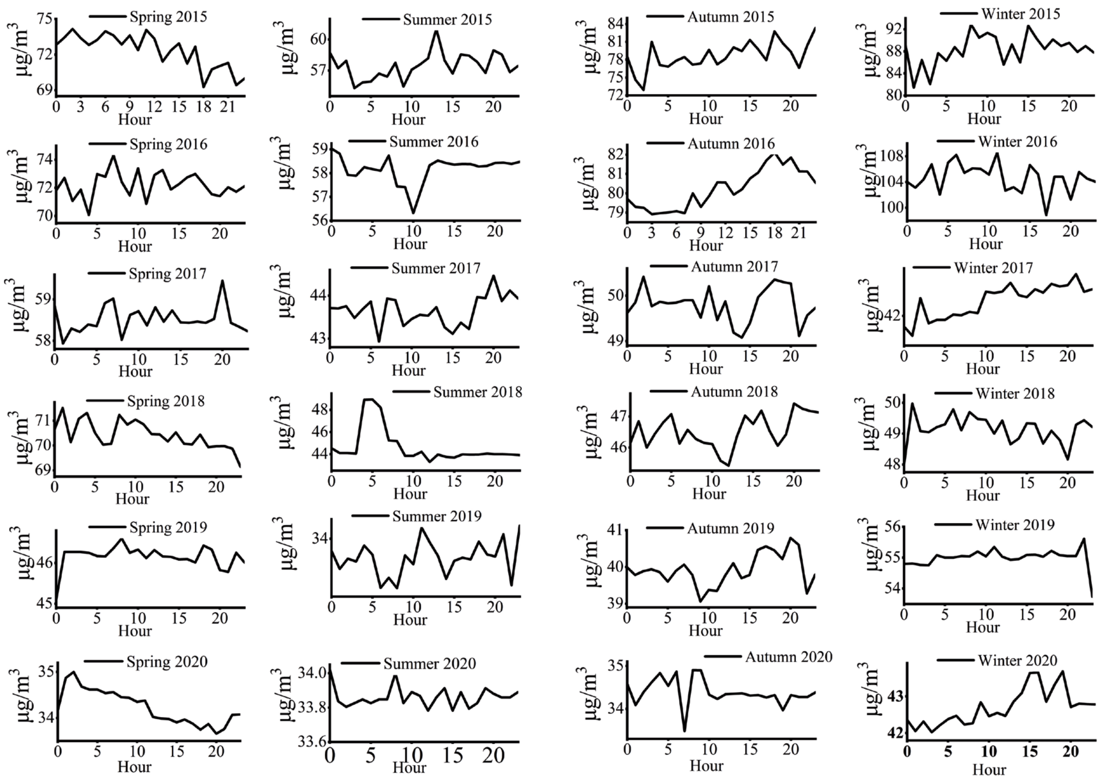

Fig. 5. Hourly average concentration of $PM_{2.5}$ in different seasons from 2015 to 2020

Table 2. The relationship between daily average $PM_{2.5}$ and daily average temperature, wind speed, humidity, precipitation, sunshine duration, and air pressure from 2015 to 2020. Yellow is the more significant correlation coefficient

		$PM_{2.5}$			
		Spring	Summer	Autumn	Winter
Temperature	Spearman	0.05	0.17	-0.08	0.13
	P value	0.20253	3.68E-05	0.06698	0.00563
Wind speed	Spearman	-0.21	-0.08	-0.22	-0.24
	P value	8.51E-07	0.06917	1.58E-07	6.30E-08
Humidity	Spearman	0.53	0.32	0.56	0.48
	P value	3.43E-41	1.53E-14	8.54E-46	3.03E-29
Precipitation	Spearman	0.04	0.01	0.08	0.08
	P value	0.36875	0.80717	0.08056	6.65E-02
Sunshine duration	Spearman	-0.42	-0.29	-0.47	-0.35
	P value	1.59E-25	4.23E-12	1.09E-31	6.64E-15
Air pressure	Spearman	-0.21	-0.07	-0.06	-0.18
	P value	5.90E-07	1.00E-01	0.14649	6.85E-05

not easily migrate and diffuse, and its concentration value increases. Precipitation factors have a significant effect on the deposition of atmospheric particulate matter (Hu et al. 2006). Summer is hot and rainy in Beijing, and the daily average precipitation in summer from 2015 to 2020 reaches 3.81 mm, which is twice the rainfall in other seasons. Although the correlation between the concentration of particulate matter and precipitation is not significant, it can be concluded from the daily average value of $PM_{2.5}$ concentration that its concentration is basically at a low level. Summer rainfall can effectively remove particulate matter in the atmosphere. Precipitation directly affects the value of water vapour pressure and relative humidity, which can better diffuse and settle atmospheric particulate matter in summer and achieve the least pollution. The daily average value of $PM_{2.5}$ in autumn in Beijing has a statistically significant negative correlation with average sunshine hours and wind speed and a positive correlation with relative humidity. In the autumn from 2015 to 2020, the wind speed in Beijing was the lowest in the four seasons, the daily average wind speed in autumn from 2015 to 2020 was only 1.76 m/s, the daily average relative humidity was high, the temperature inversion was prone to persist for many days, the weather system was stable, which was not conducive to the diffusion of $PM_{2.5}$, and pollutants easily continued to accumulate. The daily average value of $PM_{2.5}$ in winter is directly proportional to the daily average relative humidity and inversely proportional to the daily average sunshine duration and wind speed from 2015 to 2020.

CONCLUSION

Based on the $PM_{2.5}$ and meteorological data of various stations in Beijing, we studied the spatial distribution and temporal changes of $PM_{2.5}$ in Beijing from 2015 to 2020 and the correlation between $PM_{2.5}$ and temperature, air pressure, rainfall, relative humidity, and sunshine in different seasons. The concentration of $PM_{2.5}$ varies in different seasons. This is related to both human and meteorological factors. Until 2020, the annual average $PM_{2.5}$ in Beijing was 37.99 μg/m^3, which was 53.10% lower than the $PM_{2.5}$ in 2015, reflecting the effectiveness of the Action Plan. The annual PM2.5 concentration value is still higher than the World Health Organization 10 μg/m^3 standard value. Winter is the season of high incidence of $PM_{2.5}$. More attention should be given to the problem of $PM_{2.5}$ pollution in winter. The traffic area still has a high $PM_{2.5}$ concentration. To reduce $PM_{2.5}$ at traffic points, Beijing should continue to strengthen motor vehicle emission standards.

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RESEARCH PAPER

MICROPLASTIC ABUNDANCE IN VOLGA RIVER: RESULTS OF A PILOT STUDY IN SUMMER 2020

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ABSTRACT. In order to analyze the problem of microplastics pollution a comprehensive environmental survey was conducted along the entire Volga river in summer of 2020. The analysis of 34 water samples allowed us to determine the average concentration of microplastic (MP) in the surface water layer of the Volga river which accounted for 0.90 items/m^3 (0.21 mg/m^3). MP particles were found in all samples taken. The concentrations ranged from 0.16 to 4.10 items/m^3 (from 0.04 mg/m^3 to 1.29 mg/m^3). The maximum MP concentrations were recorded in large cities downstream of the sewage treatment plants. For Tver, Nizhny Novgorod, Kazan and Volgograd they reached 3.77, 1.91, 4.10 and 1.34 items/m^3 respectively. The key role of large settlements as sources of MP in the Volga water was revealed. The minimum MP concentrations were recorded upstream of the large cities showing relatively stable levels of 0.25 items/m^3 (0.05 mg/m^3). The lowest MP content (0.16 items/m^3) was revealed in the downstream area of the Cheboksary reservoir near Cheboksary. The results of weighing MP particles showed that their average concentration in the Volga water is 0.21 mg/m^3. In each of the investigated samples particles of three determined fractions – fragments, fibers and films – were found, however, their ratio was not constant. On average, the proportion of fragments and films in the Volga water was 41% and 37% respectively and share of fibers accounted for 22%.

KEYWORDS: Microplastics, river runoff, freshwater pollution, Volga river

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INTRODUCTION

Rivers are the main source of microplastics input into the oceans. The distinctive features of polymers, particularly their low density and resistance, make them a commonly used material, which, however, is becoming a dangerous pollutant nowadays. By themselves, polymer particles with a diameter of less than 5 mm (Cole et al. 2011; Hidalgo-Ruz 2012; Wright 2013) do not pose a threat to humans but their surface can adsorb toxic substances and bacteria, including pathogenic ones (McCormick et al. 2016).

In previous years, a lot of attention in the literature was given to the problem of pollution of the ocean by plastic waste, and a relatively small number of works considered the problem of river pollution, although 65-90% of plastics are carried into the ocean with river runoff (Hurley et al. 2018; He et al. 2019). Lebreton et al. (2017) and Schmidt et al. (2017) estimated that the input of plastics from rivers into the ocean ranges from 0.50 to 2.75 million tons per year. In recent years, studies are more often focusing on rivers as the main source of microplastics input to the ocean (Wijnen et al. 2019). Some of the first publications considering microplastics abundance in river waters (Moore et al. 2011; Klein et al. 2015; Dris et al. 2018; Horton et al. 2017; Liedermann et al. 2018) presented the data from rivers in California (2011) as well as the Rhine (2015), Seine (2015), Thames (2017) and Danube (2018) rivers. Depending on the shape, the following types of microplastic particles are distinguished: fragments, fibers, films, pellets, granules, foams (Dris et al. 2018). According to the origin, there are two types of microplastics – primary and secondary (Xu et al. 2019; Kapp et al. 2018; Horton et al. 2016).

The problem of microplastic pollution of freshwater bodies in Russia has not received sufficient attention. A comprehensive overview written by V.D. Kazmiruk (2020) contains more than 1000 references which include only 6 references to the studies performed in Russia. The research (Frank et al. 2021) is of importance. It contains the first results on the concentrations in the Surface Water of the Ob and Tom Rivers in Siberia.

The present field sampling provided the first estimation of microplastic abundance in the Volga river and can be considered as one of the first studies concerning this problem in Russia. The aim of the present research was to analyze data on microplastics in the water of the largest river draining the European part of Russia, the Volga river, from its source to the mouth.

The Volga river, the longest European river (3531 km), is of exceptional importance to Russia (Butorin et al. 1978). The Volga basin contains approximately 40% of the Russian population (about 60 million) and relates to 45% of the country's industrial and agricultural produce. The northern part of the Volga basin is in the taiga and mixed forest landscape zones, and the southern part is in forest–steppe zone, steppe zone, and the semidesert zone. The mean annual discharge at Volgograd (catchment = 1350000 km^2) is 8364 m/s. (Schletterer et al. 2019).

The objectives of the study included determination of the abundance, distribution and composition of microplastics in the Volga water. Water sampling, laboratory analysis and further processing of the obtained data were carried out by employees of the non-profit foundation "Clean Hands, Clean Rivers" and the scientists from the Faculty of Geography of Lomonosov Moscow State University.

RESEARCH METHODOLOGY

The main method of collecting surface water samples for the analysis of microplastic concentration involves sampling with a trawl net that allows to catch microplastic particles (Liedermann et al. 2018; Bruge et al. 2020; Collignon et al. 2012; Desforges et al. 2014). In general, either plankton nets (Campanale et al. 2019; McCormick et al. 2014; Eo et al. 2019) or MANTA nets designed for microplastic sampling are used (Yonkos et al. 2014, Mani et al. 2018). During sampling, a 2-meter-long net (Campanale et al. 2019) is towed behind a boat for a certain period of time. It is recommended to attach the net to the side of the towing boat in order to minimize the influence of waves generated by the movement of the vessel (Mani et al. 2018), as well as to avoid jets from the boat engine. The inlet of the net is half-submerged in order to reduce the force acting on the net from the flow and to take a sample only in the thin layer closest to the water surface. A spinner is installed in MANTA to calculate the volume of filtered water (Kapp et al. 2018). At the end of sampling, all unfiltered particles are transferred to a container for further laboratory analysis.

In the present study, we used LEI-MANTA300 set manufactured by EkoInstrument LLC with 300 µm bags for filtration (fig. 1). This device includes a net with a mesh size of 300 µm attached to the boat, which allowed to sample particles larger than 300 microns from the surface water. The inlet of the net with cross-section 30 x 15 cm is supplied with a current meter for determining the total volume of filtered water. During sampling, the LEI-MANTA300 net was towed behind the boat at a speed of about 5 km/h. Within this pilot study one sample was collected at each point. The towing duration was determined based on the expected microplastic abundance and ranged between 45 and 60 minutes. In case of a microplastic concentration of 0.1 particles/m^3, to detect only one particle it is necessary to filter at least 10 m^3 of water. For obtaining reproducible data, this volume must be increased. In the present study, the actual filtered volume ranged from 25 to 130 m^3.

After each sampling, the net was flushed so that the entire filtered sample was in the lower detachable beaker. The contents of the beaker were transferred to pass through a series of 5 mm (top) and 0.3 mm (bottom) sieves made of stainless steel. Coarse debris stopped by the upper sieve was removed after the adsorbed particles of microplastics had been washed off and collected. The particles stopped by the lower sieve, which included a mixture of microplastics and biological residues 0.3 – 0.5 mm in size, were transferred into a glass container and preserved in a 70% alcohol solution for subsequent laboratory analysis. The samples contained a significant amount of organic material that had to be removed prior to the analysis for microplastics. To do this, they were transferred into a 2-liter glass beaker mounted on a magnetic stirrer with a heating element, a 30% sodium hydroxide solution was added and heated to a temperature of 75-80°C. A 30% solution of hydrogen peroxide was added to the heated sample in small portions under constant stirring until its complete discoloration. The decomposition of a sample took from one to several hours, depending on the number of organic residues.

Unlike natural organic compounds, the majority of synthetic polymers are resistant to peroxide and little affected during the described process of organic material decomposition. The particles, which did not react with peroxide, were filtered off on a sieve with a mesh size of 100 µm. The mineral particles in the sample were separated

Fig. 1. Sampling for microplastics using the MANTA300 net (photo by M. Platonov)

from less dense polymer particles using a saturated saline solution and a funnel. The particles stopped on the sieve were examined using a stereo microscope with maximal 80x magnification for visual identification and counting of microplastic particles, which were then assigned to one of the six types: fragments, fibers, films, foams, pellets, granules. Visual identification avoids counting undecomposed organic or mineral particles. The counting of such nonpolymer particles is probably the reason for the tenfold difference with the microplastic concentration in the Ob River (Frank et al. 2021). This technique allows to quantify the distribution of different types of microplastic particles in different layers of river water and determine the total export of microplastics to the seas.

In most studies, types of polymers are determined using Fourier-transform infrared spectroscopy (Leslie et al. 2017; Mani et al. 2018; Kapp et al. 2018). The method of differential scanning calorimetry was applied by Castaceda et al. (2014). In the present study differential scanning calorimetry (DSC), which allows to record the phase transitions in polymeric materials, was used. Sample A combined the samples collected along the river section from Selizharovo to Tver (the Upper Volga), sample B –from the Ivankovskoye reservoir to Kostroma (the Upper Volga), sample C and sample D – the Middle Volga and the Lower Volga, respectively. The samples were dried at 60 °C, the images of the dried samples are presented in Table 2. Red marks identify the items that were selected for the analysis. When choosing individual particles for the analysis, two circumstances were taken into account: particles should be as diverse as possible and large enough to ensure accurate identification

The measurements were carried out on DSC 402 F1 Phoenix (Netzsch, Germany) at the Chemistry Department of Moscow State University. A weighed plastic item was placed in an aluminum crucible and heated in a range of temperatures from 25 to 200°C, with a rate of 10°C/min in an argon flow of 50 ml/min. As a reference sample, an empty aluminum crucible was used. Fig. 3 gives an example of the DSC thermograms obtained for the items in sample A. The peaks on the curves represent melting points, the inflections correspond to glass transition, the temperature of both was compared to literature data. The measurement results for all selected items are presented in Table 2.

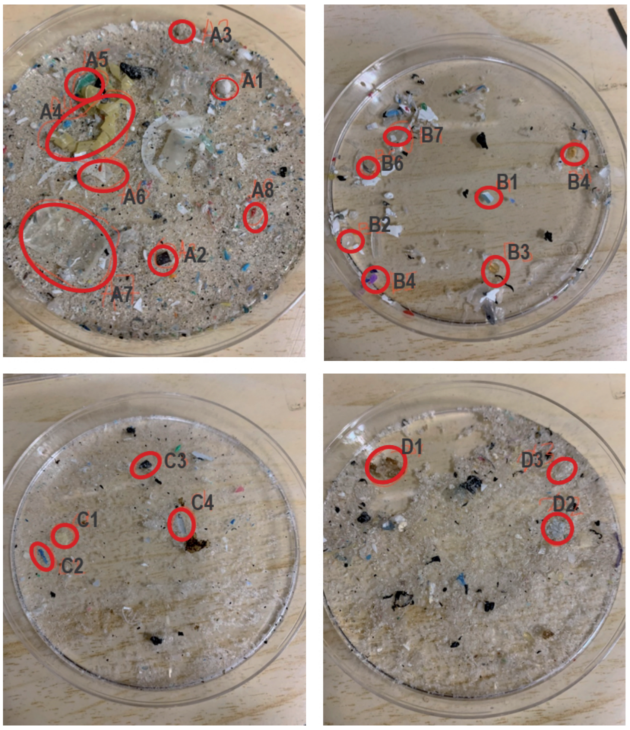

Fig. 2. Samples selected for the chemical analysis

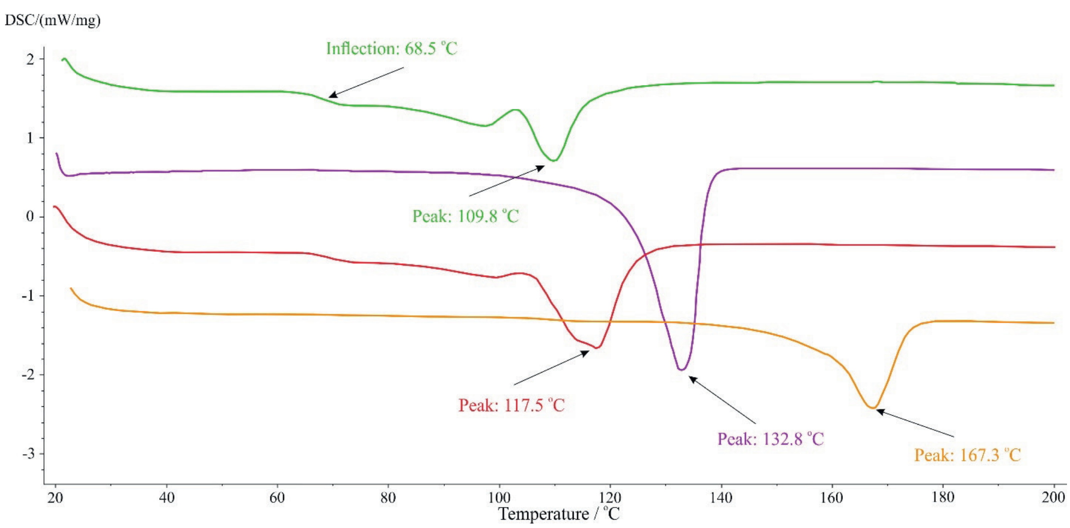

Fig. 3. DSC thermograms for plastic fragments in the sample A. The curves in the figure correspond to the fragments A2 (blue), A3 (olive), A5 (black), A7 (dark blue)

RESULTS

During the expedition, which took place in the summer and autumn of 2020, the sampling for microplastics was carried out at different locations along the entire course of the Volga river upstream and downstream of large cities (Table 1). The Upper Volga section, about 400 km long, was sampled from 12 to 18 July 2020 during the rain flood period (Fig. 4). During this period the sampling covered the area from the village Selizharovo to the village Gorodnya (both are located in Tver region) (Fig. 5).

Table 1. Microplastic abundance and distribution of particle types in water samples collected along the Volga river

No	Coordinates*	Site name	Number of item types	Volume, $м^{3**}$	Concentration	
	Latitude/ Longitude		Total [Fibers/Films/ Fragments]		items/m³	mg/m³
The Upper Volga (fig. 5)						
1	56.842/35.478	Selizharovo	17 [1/1/5]	50.4	0.337	0.029
2	56.750/33.688	Yeltsy	10 [6/1/3]	58.5	0.171	0.036
3	56.654/33.775	Downstream of Yeltsy	22 [2/8/12]	57.0	0.386	0.161
4	56.465/33.953	Upstream Rzhev (Sihka river, Dunka river, flooded sand quarry)	47 [13/5/29]	65.2	0.720	0.189
5	56.306/34.086	Rzhev	85 [17/15/53]	40.1	2.121	0.654
6	56.253/34.345	Staritsa	23 [15/3/5]	47.7	0.482	0.105
7	56.527/34.918	Downstrean of Staritsa (Ulyust river, Rzhavtsa river)	4 [1/2/1]	23.4	0.171	0.079
8	56.685/35.317	Bolshie Borki town	42 [6/0/36]	23.5	1.787	0.408
9	56.81/35.592	Upstream of Tver	17 [13/1/3]	24.3	0.700	0.115
10	56.85/35.793	Tver	13 [8/0/5]	26.4	0.493	0.078
11	56.857/35.935	Tver, city center	29 [15/1/13]	71.5	0.406	0.077
12	56.811/36.013	Tver, downstream of the wastewater treatment facilities	200 [30/20/150]	53.1	3.769	1.046
13	56.786/36.313	Tver, downstream	120 [30/15/75]	53.7	2.235	0.615
14	56.761/36.736	Upper Ivankovskoe reservoir	36 [15/11/10]	132.5	0.272	0.055
15	56.764/37.200	Dubna, downstream	49 [22/7/20]	65.2	0.751	0.106
16	57.556/38.302	Uglich, downstream	13 [8/3/2]	60.6	0.215	0.032
17	58.048/38.878	Rybinsk, downstream	42 [17/5/20]	107.6	0.390	0.054
18	57.556/40.079	Yaroslavl, downstream	26 [15/5/6]	95.0	0.274	0.039
19	57.678/40.996	Kostroma, downstream	43 [22/9/12]	65.2	0.660	0.103
The Middle Volga (fig. 6)						
20	56.357/43.907	Nizhny Novgorod, Sormovsky backwater	56 [27/20/9]	87.0	0.644	0.137
21	56.337/44.048	Nizhny Novgorod, city center	46 [15/18/13]	66.2	0.695	0.170
22	56.272/44.165	Nizhny Novgorod, downstream of the wastewater treatment facilities	118 [30/32/56]	61.9	1.907	0.404
23	56.166/47.243	Cheboksary, city center	10 [3/5/2]	64.3	0.156	0.044
24	56.119/47.563	Novocheboksarsk, downstream	17 [4/9/4]	25.9	0.655	0.200
25	55.791/48.932	Kazan, city center	15 [0/8/7]	77.6	0.193	0.065
26	55.682/49.005	Kazan, downstream of the wastewater treatment facilities	221 [7/106/108]	53.9	4.100	1.286

The Lower Volga (fig. 7)						
27	53.297/50.185	Samara, downstream Ptichi i.	102 [63/20/19]	81.1	1.258	0.174
28	53.161/49.969	Samara, downstream pr. Suhaya Samara	82 [35/15/32]	89.0	0.921	0.146
29	51.495/45.982	Saratov, Alekseevsky gully	49 [22/10/17]	69.0	0.710	0.116
30	48.780/44.652	Volgograd, downstream Volga HPP dam	12 [7/2/3]	65.2	0.184	0.024
31	48.604/44.626	Volgograd, downstream of the wastewater treatment facilities	94 [50/25/19]	70.0	1.344	0.234
32	46.390/48.060	Upstream of Astrakhan	47 [25/8/14]	98.7	0.476	0.067
33	46.360/48.033	Astrakhan, downstream of the wastewater treatment facilities	62 [35/10/17]	86.3	0.719	0.096
34	46.274/47.949	Astrakhan, downstream (Zolotoy backwater)	24 [11/6/7]	72.8	0.330	0.059

*the coordinates indicate the central point of the sampled river section, the length of which usually varied from 3 to 8 km. The boat moved predominantly downstream and followed the middle part of the river course

** the built-in current meter makes 3 readings per 1 m, the size of the MANTA inlet is 30x15cm, which, when half-submerged, provides a cross section of 0.3x0.075 = 0.0225 m^2

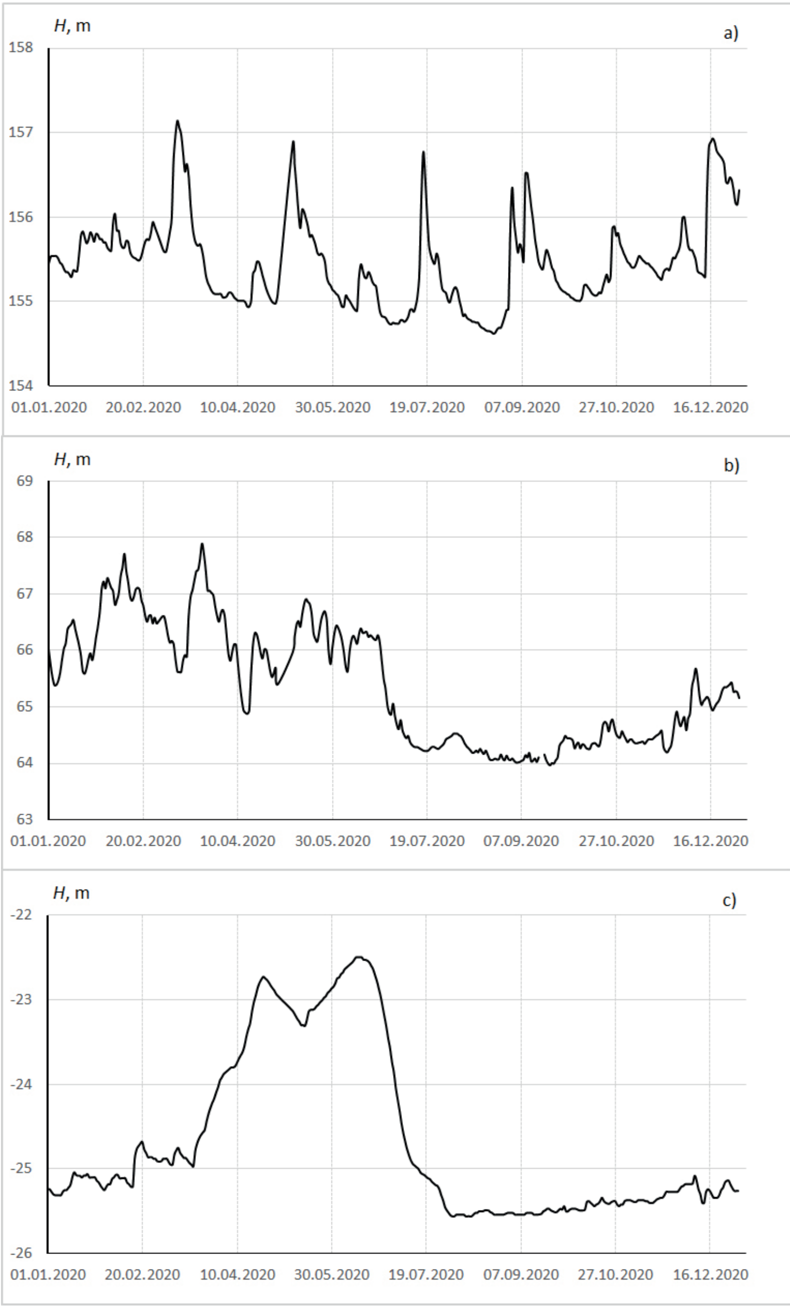

Fig. 4. Changes in the water level of the Volga river near Rzhev (a), Nizhny Novgorod (b) and Astrakhan (c) in 2020 (according to vodinfo.ru (2021))

According to the weather station in Staritsa (rp5.ru (2021)), the amount of precipitation in the period from 12 to 17 July was 123 mm. Due to heavy rainfall, the water levels in the considered section of the Volga river were increasing during the entire period of the expedition according to http://gis.vodinfo.ru/ (Fig. 4a). Such untypical hydrograph (fig. 4a) with the missing spring flood is likely related to the fact, that there was a "warm" winter with no ice on the river in 2019/20 – thus a lot of rain was falling in winter. Also, during the rest of the year there were heavy rainfalls, when the water levels reached the levels of the spring flood. Over that period (from 12 to 17 July), a total of 13 samples for microplastics were taken (Fig. 5). In the area of Selizharovo, the observed concentration was only 0.17 to 3.77 items/m^3 (from 0.036 mg/m^3 to 1.046 mg/m3), while near Rzhev these values increased to 2 items/m3, reaching about 4 items/m^3 at Tver. Largely due to heavy precipitation and the formed flood, the obtained values of the microplastics concentration turned out to be significantly higher than expected, characterizing the pollution of the Upper Volga as above average and, in some locations, as alarming. While in the upper section of the route the pollution consisted mostly of synthetic fibers, samples collected near Rzhev contained particles of different types of microplastics. The expected large amount of microplastics was found in the samples taken downstream of the wastewater treatment plant in Tver (up to 4 items/m^3 or up to 1 mg/m^3). At the same time, 10 km downstream of the wastewater treatment facilities of Tver the concentration almost halved, dropping down to 2.235 items/m3 (0.615 mg/m^3),. The high concentrations of about 2 items/m^3 (0.65 mg/m^3), were also obtained in areas outside large settlements, which was probably related to the washing off of the accumulated waste from the riverbanks that took place during the expedition. The average abundance of microplastics at the Selizharovo-Gorodnya section was about 1 items/m3 or 0.3 mg/m^3.

The section of the Upper Volga between the Ivankovskoye reservoir and Kostroma was surveyed later, from 28 to 31 October 2020, with the collection of 6 more samples. The average microplastics abundance within this section was less than 0.5 items/m^3 (0.07 mg/m^3), with a maximum of 0.75 items/m^3 (0.016 mg/m^3) (Dubna). The proportion of fibers in these samples reached 50%, while the share of fragments rose with the increase in the number of particles. Downstream of Dubna, the concentration increased several times – from 0.27 to 0.75 items/m3 (from 0.039 mg/m^3 to 0.106 mg/m^3), 40% of which was represented by fragments. The minimum concentration of microplastics was recorded at Uglich – 0.215 items/m^3 (0.032 mg/m^3), among which fragments accounted for only 15%.

Sampling along the second section was carried out from August 31 to September 3, which corresponds to the period of summer-autumn low water (Fig. 4b, Fig. 6). The samples were taken in Nizhny Novgorod, upstream, in the center and downstream of the city (at the wastewater treatment plant), in Cheboksary, upstream and downstream of the Cheboksary HPP dam, as well as upstream and downstream of Kazan (7 samples in total). All the samples contained a significant volume of organic substances that hindered the identification of microplastic particles, which required their additional preparation for the analysis. Microplastics were found at all the locations, while their amount and composition varied significantly. The analysis of the samples showed that the concentration of microplastics upstream of large cities was in the range from 0.156 to 0.695 items/m^3 (from 0.044 mg/m^3 to

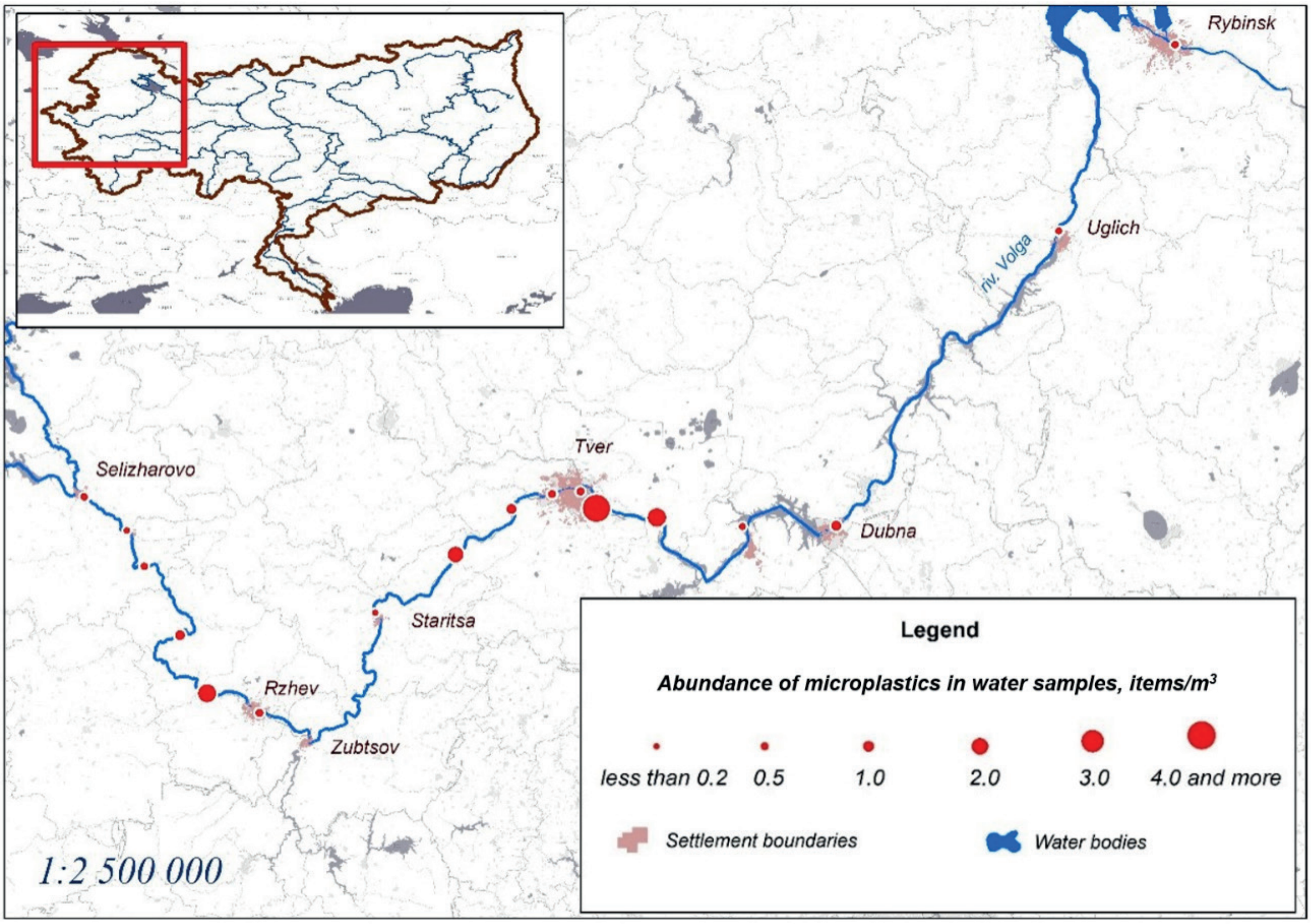

Fig. 5. Map of microplastics sampling locations and its abundance in the water samples (items/m^3) in the first section, from Selizharovo to Gorodnya

0.170 mg/m^3). The sample taken downstream of Nizhny Novgorod contained about 2 items/m^3 (0.4 mg/m^3), while downstream of Kazan the concentration reached 4 items/m3. The average microplastic concentration in this section was about 1.2 part/m^3 or 0.35 mg/m^3, which is 20% higher compared to the Upper Volga. This study once again confirm the significant contribution of wastewater treatment plants in large cities to the pollution of rivers with microplastics, which can be clearly seen in the example of Nizhny Novgorod and Kazan. At the same time, the negative effect of the Novocheboksarsk WWTP with approximately the same capacity was much lower. This can be related not only to their submerged water outlet but mainly to the technology of treated wastewater filtration, which was recently introduced at these treatment facilities and is applied before discharging water into the river. The worst conditions in terms of microplastics abundance were observed downstream of Kazan as the identified value of 4 items/m^3 is comparable to the level of pollution downstream of Tver.

The third part of the expedition was carried out in the lower reaches of the Volga river and took place from 12 to 19 October 2020 during the summer-autumn low water period (Fig. 4c). Eight samples were taken upstream and downstream of Samara, Volgograd and Astrakhan, all of which contained a significant amount of organic matter, making it difficult to identify microplastic particles. However, microplastics were still found in all the samples and their concentration averaged at 0.75 items/m^3 (0.12 mg/m^3) (Fig. 7), which was less than the average value for the Volga in general. The previously noted relationship between the microplastic abundance and the presence of large settlements was not found for this section of the river as the concentrations downstream of Samara and Astrakhan even slightly decreased. A significant rise in the number of microplastic particles (from 0.184 to 1.34 items/m^3) (from 0.024 mg/m^3 to 0.234 mg/m^3), was registered for Volgograd. This could be explained by a direct discharge of water from urban wastewater treatment plants into the main channel of the Volga, which occurs in Volgograd but not in Samara or Astrakhan. Volgograd is one of the most problematic cities in terms of adverse impact on the Volga and urgently requires modernization of existing wastewater and stormwater treatment facilities or installation of new ones. The situation in Astrakhan in terms of microplastics turned out to be better than in other cities. In the main channel of the Volga, the abundance of microplastics was about 0.5 items/m^3, but the situation in other branches might be much worse. In recent years, biologists have found microplastics in many dead organisms living in the Volga floodplain (Litvinov 2020), which indicates the need for a more detailed study of its abundance in the waters of this natural reserve.

An important aspect of this study was the analysis of the microplastics distribution between its different types (Fig. 8). The ratio of these types was different. It was found that with an increase in the total abundance of particles of all types, the share of fragments also increased. Thus, for samples with microplastics concentration exceeding 1 items/m^3, fragments on average accounted for 53% of all particles, while for concentrations of less than 1 items/m3 their share was around 32%. An increase in the proportion of fragments indicates the emergence of new pollution sources.

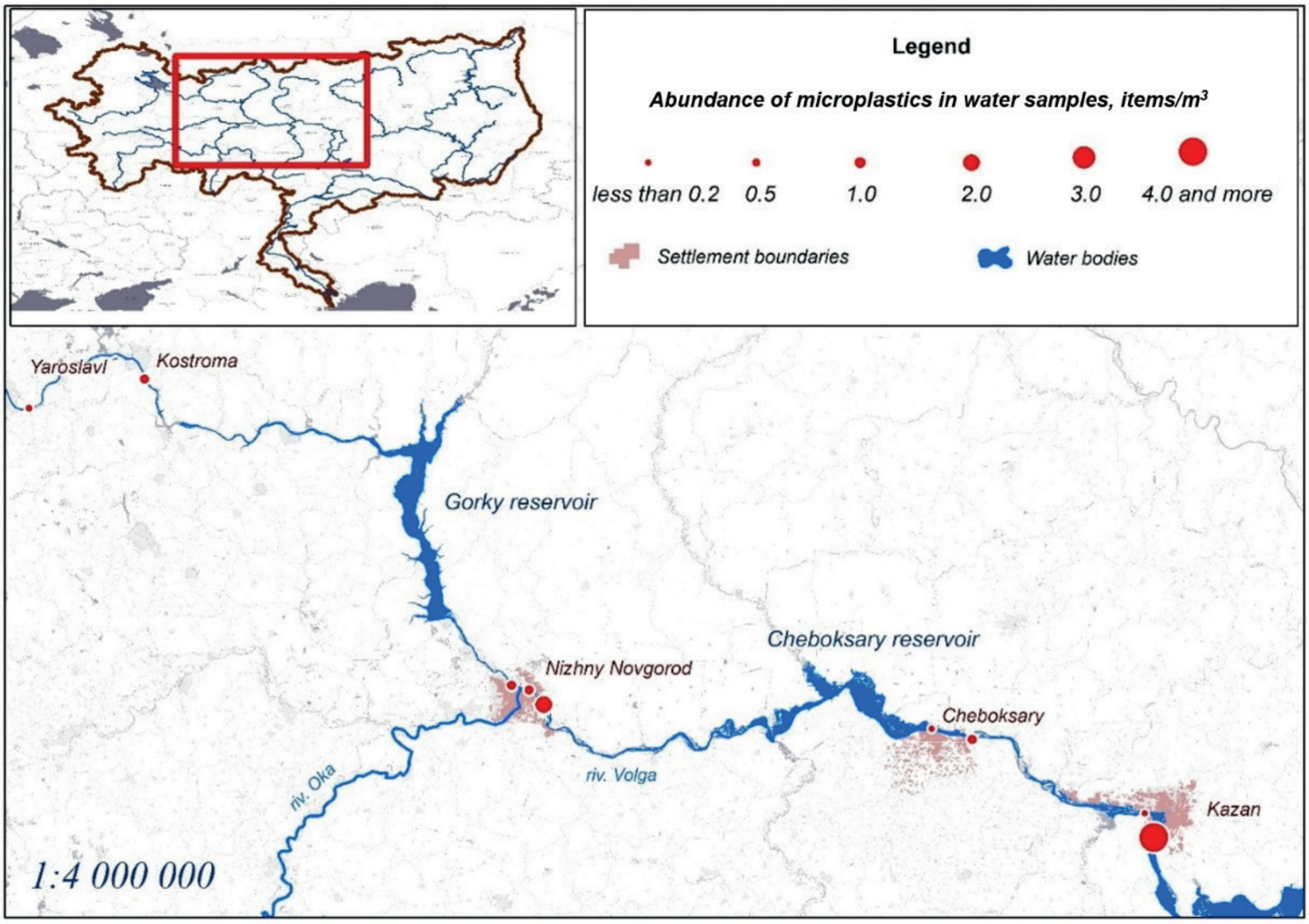

Fig. 6. Map of microplastics sampling locations and its abundance in the water samples (items/m^3) in the second section from Nizhny Novgorod to Kazan

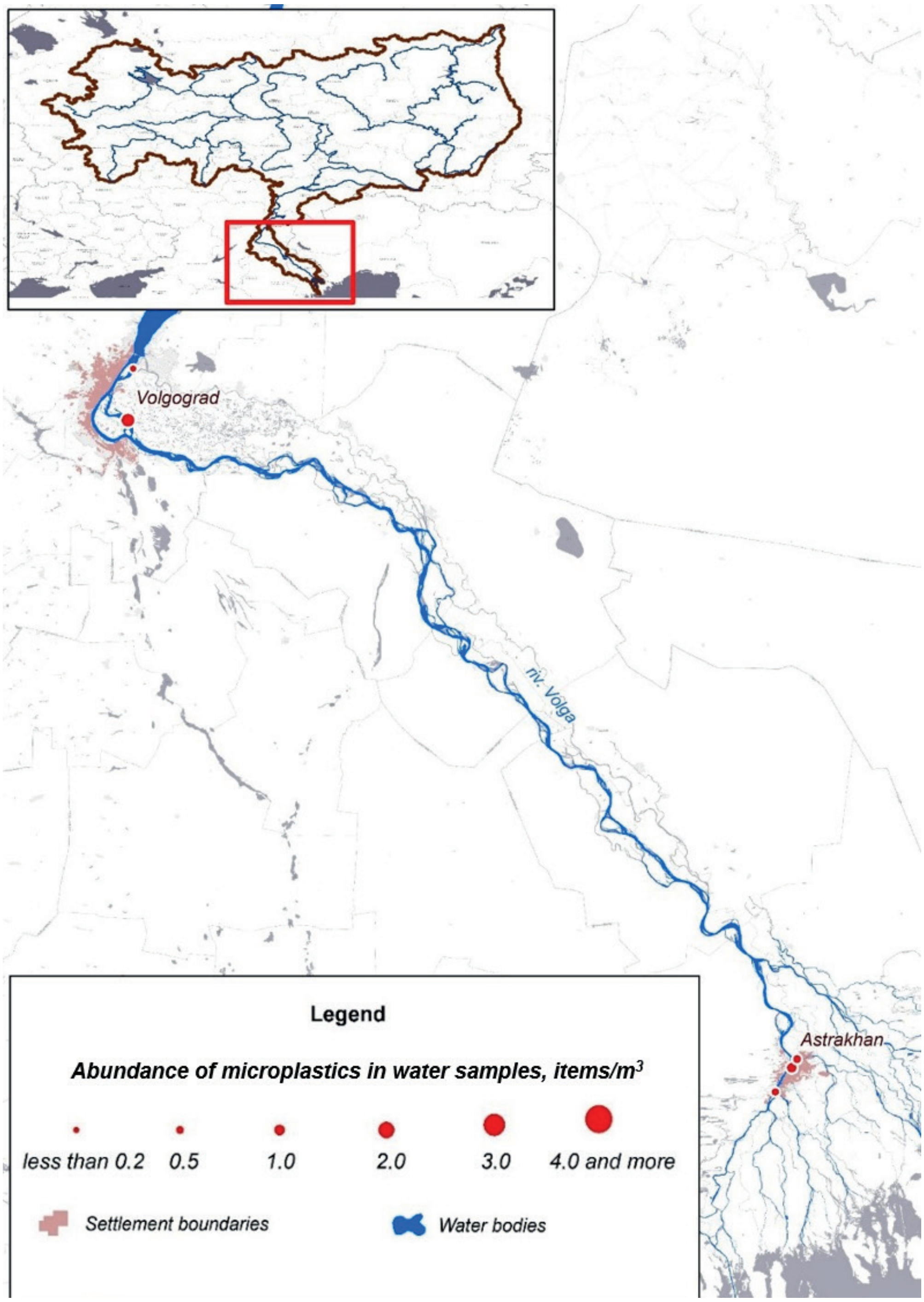

Fig. 7. Map of microplastics sampling locations and its abundance in the water samples (items/m^3) in the third section from Volgograd to Astrakhan

The DSC results (table 2) showed that polyethylene and polypropylene prevailed in all samples and represent items of various morphology and color, which indicates their different origin and confirms that household plastic waste is the main source of microplastics in the river. The samples also contained items that remained unchanged within the studied temperature range. These materials, which are likely characterized by transition temperatures outside this range, can include rubbers (whose transition temperature is below room temperature) or, on the contrary, more thermally stable polymers. Also, visible transitions may not occur in the case of so-called thermosetting polymers, which are three-dimensional crosslinked materials that do not change until the decomposition temperature is reached, for example, some polyurethanes, phenol-formaldehyde and epoxy resins. In addition, it should be noted that all samples were collected from a river and therefore predominantly contain fragments of materials with a density equal to or lower than that of water. These materials are mainly represented by polyethylene, polypropylene and polystyrene, while the likelihood of finding polyethylene terephthalate (PET) in a sample is quite small.

DISCUSSION

Microplastic particles were found in all the collected water samples (Fig. 2 – Fig. 7). Analysis of 34 water samples allowed us to determine the average concentration of microplastics in the Volga river, which was equal to 0.901 items/m^3 (0.212 mg/m^3) with the median value of 0.649 items/m^3 (0.106 mg/m^3) and a range of 0.156 to 4.100 items/m^3 (0.065 mg/m^3 to 1.286 mg/m^3).

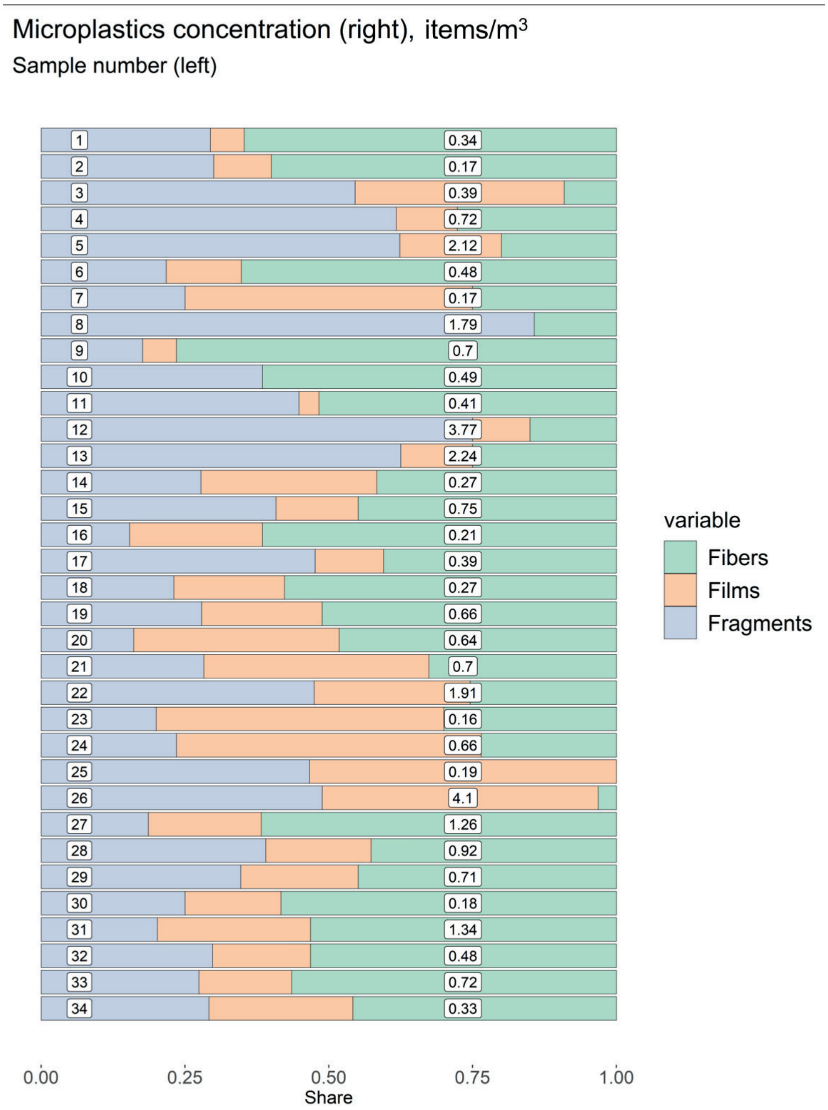

Fig. 7. Distribution of microplastics in samples by type

Table 2. The results of the differential scanning calorimetry analysis

Sample ID **	Temperature of phase transition*	The supposed nature of polymeric material
A1	T_g=107.7oC	Polystyrene
A2	T_g= 68 oC;T_m=109.8oC	Polyvinyl chloride
A3	T_m=117.5°C	Polyethylene
A4	T_m=131.7°C	Polyethylene
A5	T_m=167.3°C	Polypropylene
A6	T_m=125.7°C	Polyethylene
A7	T_m=107°C	Polyethylene
A8	T_m=132.8°C	Polyethylene
B1	T_m=165°C	Polypropylene
B2	T_m=159°C	Polypropylene
B3	T_m=110°C	Polyethylene
B4	T_m=108.1°C	Polyethylene
B5	T_m=167.2°C	Polypropylene
B6	T_m=130.7°C	Polyethylene

B7	T_m=164.6°C	Polypropylene
C2	T_m=107.8°C	Polyethylene
C4	T_m=124.6°C	Polyethylene
D2	T_m=124°C	Polyethylene
D3	T_m=112.2°C	Polyethylene

To assess the role of urban areas in the pollution of the Volga river by microplastics, their concentrations were measured upstream and downstream of several cities. Microplastics concentration downstream of Kazan compared to the upstream location increased more than 21 times, from 0.193 items/m^3 (sample 25) to 4.100 items/m^3 (sample 26) (from 0.024 mg/m^3 to 0.234 mg/m^3), the increase of more than 7 times (from 0.184 items/m^3 (sample 30) to 1.344 items/m^3 (sample 31) or from 0.044 mg/m^3 to 1.286 mg/m^3) was observed in Volgograd.

The maximum concentrations of microplastics were recorded downstream of the wastewater treatment facilities of large cities, particularly in Volgograd 1.344 items/m3 or 0.234 mg/m^3), Nizhny Novgorod (1.907 items/m^3 or 0.404 mg/m^3), Tver (3.769 items/m^3 or 1.046 mg/m^3) and Kazan (4.100 items/m^3 or 1.286 mg/m^3). The minimum concentrations were observed upstream of large cities and, in general, were around 0.25 items/m^3 (0. 054 mg/m^3). The lowest concentration of 0.156 items/m3 (0.044 mg/m^3) was observed downstream of the Cheboksary reservoir near Cheboksary. Unfortunately, water samples were taken in different phases of the Volga river hydrological regime: during a flood in the Upper Volga and in low-water conditions in the Middle and Lower Volga. Thus, the obtained results imply that urban wastewater treatment plants are one of the main sources of microplastics in the Volga river.

Our results provide a first indication of the microplastic pollution in the Volga river. The obtained values are significantly lower compared to the available data on the microplastics abundance in the water of other rivers worldwide. The most complete understanding of the microplastics runoff currently is available for the rivers of Northern and Western Europe and the USA. For example, in the Rhine, the microplastics concentration can reach 8.85 and 11.1 items/m^3 at Duisburg and Ries, respectively (Mani et al. 2018). Similar concentrations were observed in the Elbe where they varied from 0.88 to 13.2 items/m^3 (Scherer et al. 2020). For the Danube river, the analysis of the microplastics samples from the near-surface layer has shown an average concentration of 0.317 items/m^3 with a maximum of 14.2 items/m^3 (Dris et al. 2018), in Budapest, concentrations reached 50 items/m^3 (hu.wessling-group.com (2019)). A relatively high microplastics abundance was recorded in the Thames – within the area of the city it reached 24.8 items/m^3 (Rowley et al. 2020).

CONCLUSIONS

The results obtained in the present study provide a first indication of the microplastic contamination of the Volga river and can be used for comparison to other water bodies worldwide. The microplastic abundance in the Volga river turned out to be significantly lower than that in other large rivers. The obtained results, however, strongly depend on the sampling methods as well as on the location of the sampling site relative to large settlements, different systems of wastewater treatment facilities, phase of the hydrological regime, presence of reservoirs and other factors. Further estimation will require more detailed monitoring with multiple measurements. But in this study, we aimed to obtain the first results along the Volga river. In our pilot study we could only collect one sample per point, due to the fact that sampling takes from 45 minutes to an hour. Based on this, a more detailed monitoring with multiple measurements (parallel samples) is recommended. In order to draw more sound conclusions, data for the same hydrological conditions and phases of the water regime are required along with information on microplastics distribution over the water column and detailed consideration of urban impact, influence of reservoirs and other factors. An important aspect of future research would be addressing a number of methodological issues related to the collection and processing of water samples.

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RESEARCH PAPER

THE BELT AND ROAD INITIATIVE (BRI) IN NORTH EURASIA: CHANGING GEOGRAPHIES AND THE UNECE MULTILATERAL ENVIRONMENTAL AGREEMENTS

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ABSTRACT. The Belt and Road Initiative (BRI), launched by China in 2013 to increase economic and transport connectivity along the Eurasian continent and beyond, has posed unprecedented environmental and social risks, many of which are transboundary in nature. International legal tools contained in Multilateral Environmental Agreements (MEAs) can play an important role in mitigating such transboundary risks across space and time, as well as reduce the negative impacts of large infrastructure projects, such as are being developed under the auspices of the BRI. However, the adoption of MEA policy tools has been very uneven across the continent. Three conventions in particular, the 1991 Espoo Convention on Environmental Impact Assessment, the 1998 Aarhus Convention, and the 1992 Helsinki Water Convention (the UNECE MEAs) – have the least amount of ratifications by BRI countries. In this paper we discuss these three conventions and demonstrate their relevance in addressing the transboundary risks of large infrastructure projects which require complex coordination and long-term planning.

Extended ratification of these UNECE MEAs by nations along the BRI corridors should significantly assist in positively changing geographies by minimizing BRI environmental risks and threats on a transboundary and national dimension, but simultaneously (i) create a more unified approach towards sustainability across the BRI, (ii) raise involvement (and likely subsequent) support within communities for BRI projects, (iii) help to reduce related economic risks throughout Eurasia.

KEYWORDS: Belt and Road Initiative; Eurasia; UNECE; Multilateral Environmental Agreements; sustainable development; international environmental governance

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INTRODUCTION[1]

Since its launch in 2013 by China, the Belt and Road Initiative (BRI) has witnessed vast investments, which continue to significantly impact and change many geographical aspects of the Eurasian continent (see Kolosov et al 2017; Bird et al 2020). By mid 2018, the estimated investments figure rose to US$ 8 trillion (Flores 2018; World Bank 2019a) and is likely to be higher by 2021. Although the BRI promises to provide huge opportunities to alleviate poverty (World Bank 2019b), as it continues to develop at unprecedented scale and speed over space and time, this inevitably will result in equally unprecedented transformation, accompanied by associated, and also unprecedented, environmental risks.

The BRI focuses heavily on large-scale infrastructure development (E&Y 2015; Grimsditch 2015; IDI 2016; World Bank 2019a; and Teo et al 2019) and sharing industrial capacity (by 2018, China had concluded 25+ formal bilateral agreements aimed at moving industries from China to other BRI countries)[2], but its official objectives are far wider (Simonov & Withanage 2019). The BRI has been designed with economic and geopolitical objectives at its core and it will shape China's foreign policy and impact BRI countries, their socio-economic and geopolitical circumstances and environments, for decades to come. The largest BRI investments are in the energy and electric power sector, followed by transport and chemical engineering (World Bank 2019a; Bandiera & Tsiropoulos 2019; Teo et al 2019). The fast-paced growth of these large-scale (infrastructure) BRI projects makes the greening of the BRI one of the largest sustainable development challenges in Eurasia (and Africa) today.

With approximately 90 countries (plus the EU)[3] falling within the ambit of the BRI, the role of international environmental law and, in particular, specific MEAs in mitigating the BRI's environmental risks, enabling sustainable development and, thereby, positively impacting and changing geographies, is pivotal.

International law is a key tool to promote sustainable development as it not merely establishes internationally agreed (and consistent) regulatory structures, but also facilitates international cooperation and equity, and can positively influence domestic law and policy – as well as provide the basis for a paradigm shift within nations towards, for example, a 'low-carbon development strategy [which] is indispensable to sustainable development' (Halvorssen 2010; Schrijver & Weiss 2004; Boyle & Freestone 1999; Kim & Bosselman 2015; and Bosselmann 2017) and integrated biodiversity conservation strategies (Gillespie 2011; Bowman & Redgwell 1996; Bowman et al 2016; Morgera & Razzaque 2017; Robinson 2017; and Azizi et al 2019).

The concept and principle of sustainable development within international (environmental) law is well established (Sands 1993; Sands 1999, Schrijver & Weiss 2004; French 2005; and Schrijver 2007; Sands et al 2015; and Dupuy & Vinuales 2018) and provides a foundation for nations to balance environmental protection with economic growth on the transboundary, as well as national level.

Greening the BRI

Since the announcement of the BRI in 2013, the Chinese government has demonstrated many examples of its willingness to tackle the greening of the BRI and environmental risks associated with BRI projects, internationally and domestically, continuing to project the image of a new Green China it actively promotes (Li and Shapiro 2020).

Various key policy documents have been issued by China in connection with the BRI in 2015 (Vision and Actions on Jointly Building Silk Road Economic Belt and 21st-Century Maritime Silk Road, the '2015 BRI Vision') and April 2017 (Guidance on Promoting the Green Belt and Road, the '2017 Green BRI Guidance')[4] which set out the official scope, objectives and priorities of the BRI (see 2015 BRI Vision), a comprehensive list of policies and mechanisms to be applied in order to achieve sustainable development (see 2017 Green BRI Guidance), as well as mentioning the need for adherence to 'international norms' (see 2015 BRI Vision, section II).

In May 2017, China's Ministry of Environment issued the 2017 Belt and Road Ecological and Environmental Cooperation Plan (the '2017 BRI Green Plan')[5], which is one of its core BRI policy document and states that China will assist BRI countries «to fulfill [their] commitments under multilateral environmental agreements … such as Convention on Biological Diversity and Stockholm Convention on Persistent Organic Pollutants, by building up cooperation mechanisms for MEA implementation and enabling technological exchange and South-South cooperation.» (Part VII, Point (1), paragraph 5).

Although the 2017 Green BRI Plan mentions that 'guidance will be provided on environmental impact assessment' (Part IV(1), para 2) and refers to the need to facilitate environmental information, it does not specifically list the MEAs which are most relevant to addressing the risk of large transboundary infrastructure projects, such as the BRI projects, namely the following three MEAs (and their respective protocols) (collectively referred to as the UNECE MEAs):

• the 1991 UNECE Espoo Convention on Environmental Impact Assessment in a Transboundary Context (Espoo EIA Convention) and the 2003 Kyiv Protocol on Strategic Environmental Assessment (SEA Protocol);
• the 1998 UNECE Aarhus Convention on Access to Information, Public Participation in Decision-Making and Access to Justice in

[1]This paper follows on from a presentation by the authors, the abstract of which is published in the proceedings of the conference (see Shvarts et al, 2018).

[2]List of Deliverables of the Belt and Road Forum for International Cooperation, Xinhuanet, May 15, 2017, see http://news.xinhuanet.com/english/2017-05/15/c_136286376.htm, and State Council Information Office of the People's Republic of China (2017) China's industrial capacity cooperation aims to rebalance global economy, January 16, 2017, see http://www.scio.gov.cn/32618/Document/1540095/1540095.htm

[3]Wang, 2015 lists approximately 65 countries as BRI participating countries, whereas this paper refers to 90 countries as it includes the following additional countries (not listed in Wang, 2015): Members of the EU, countries within the European space and Kenya (although not in Eurasia, included due to its geographical location along the BRI maritime routes). As at 2020, China signed 200 cooperation agreements with 138 countries in Eurasia, Latin America, Africa, and with the Pacific nations (Tracy, 2021): Many of these countries are not located along the BRI corridors—some, for example, are in Latin America or in non-coastal parts of Africa. Whilst, some countries situated along the BRI corridors have not signed collaboration agreements with China (World Bank, 2019a).

[4]NDRC, 2017 Guidance on Promoting the Green Belt and Road, May 8, 2017, jointly issued by NDRC, MofCom, Foreign Ministry, and MEP, see <https://eng.yidaiyilu.gov.cn/zchj/qwfb/12479.htm>

[5]Ministry of Environmental Protection, Belt and Road Ecological and Environmental Cooperation Plan, published on May 14, 2017, see <https://eng.yidaiyilu.gov.cn/zchj/qwfb/13392.htm>

Environmental Matters (Aarhus Convention) and 2003 Kyiv Protocol on Pollutant Release and Transfer Registers (Kyiv Protocol); and

• the 1992 UNECE Helsinki Convention on the Protection and Use of Transboundary Watercourses and International Lakes (Water Convention) and its 2000 Protocol on Water and Health (Water and Health Protocol).

These UNECE MEAs, which were all concluded under the auspices of the United Nations Economic Commission for Europe (UNECE), are particularly important to enabling the further development of a green BRI on the following basis: They (a) provide for the putting in place of principles of international environmental law across the categories of environmental protection; and (b) provide key techniques to implement these principles, such as through environmental impact assessment (EIA), Strategic Environmental Assessment (SEA), access to environmental information (and environmental justice), and public participation (see Dupuy & Vinuales 2018), based upon internationally agreed standards. Consequently, these techniques are not just about environmental protection, but also about governance in general, government accountability, transparency and responsiveness. Indeed, it has been stated that «clear EIAs with international oversight and standards vastly improve the conservation in the [BRI] region» (Hughes 2019), whilst EIAs are known to promote sustainability and have been adopted worldwide (Morgan 2012; Aung & Fischer 2020).

An in-depth study of key MEAs relevant to the BRI projects (Cheremeteff & Broekhoven 2018; also see Appendix A hereto) demonstrates that these UNECE MEAs, while being most relevant to addressing the risks of large transboundary infrastructure projects, have the least amount of ratifications by, the BRI countries. It is beyond the scope of this paper to review the current political aspects and negotiations relating to the extension of the UNECE MEAs, as well as why and how states adopt MEAs, such as the UNECE MEAs, and present an interesting opportunity for further research in separate papers.

In order to address how international legal tools, such as provided under the UNECE MEAs, can positively affect and change geographies in Eurasia, in particular, by way of mitigating and preventing environmental risks posed by BRI projects, this paper will proceed in four steps. We will first elaborate the environmental and social risks arising from implementing the BRI, especially those risks posed by infrastructure projects transecting intact and sensitive ecosystems. Secondly, we will examine in more detail the UNECE MEAs designed to address the risks of large transboundary infrastructure projects. Thirdly, the environmental laws and policies currently applicable to BRI environmental risks will be discussed. Lastly, we will propose several considerations why the UNECE MEAs should be seen as forward-looking, comprehensive instruments that provide long-terms policy solutions to complex environmental and social problems – and, as a result, promise to positively affect and change the geographies along the BRI corridors in Eurasia.

THE BELT AND ROAD CHALLENGE: POLITICAL GEOGRAPHY AND ENVIRONMENTAL RISKS

The geographical reach of the BRI is over the territories of approximately 90 countries on the Eurasian continent. The initial design of the BRI (designed to resemble the ancient Silk Road) aimed for BRI projects to traverse Central Asia, Russia, India, Pakistan and Europe (terrestrial route) and to run along the coast of Asia, East Africa, the Arctic and Europe (maritime route) (see Fig. 1 below).

More than 20 United Nations agencies, funds and programmes are involved in the BRI[2]. In December 2016, UN Environment Programme (UNEP) and the China's Ministry of Ecology and Environment (MEE) signed a MoU according to which UNEP and MEE agree to work together to promote international cooperation for the sustainable development of the BRI[7]. The BRI International Green Development Coalition

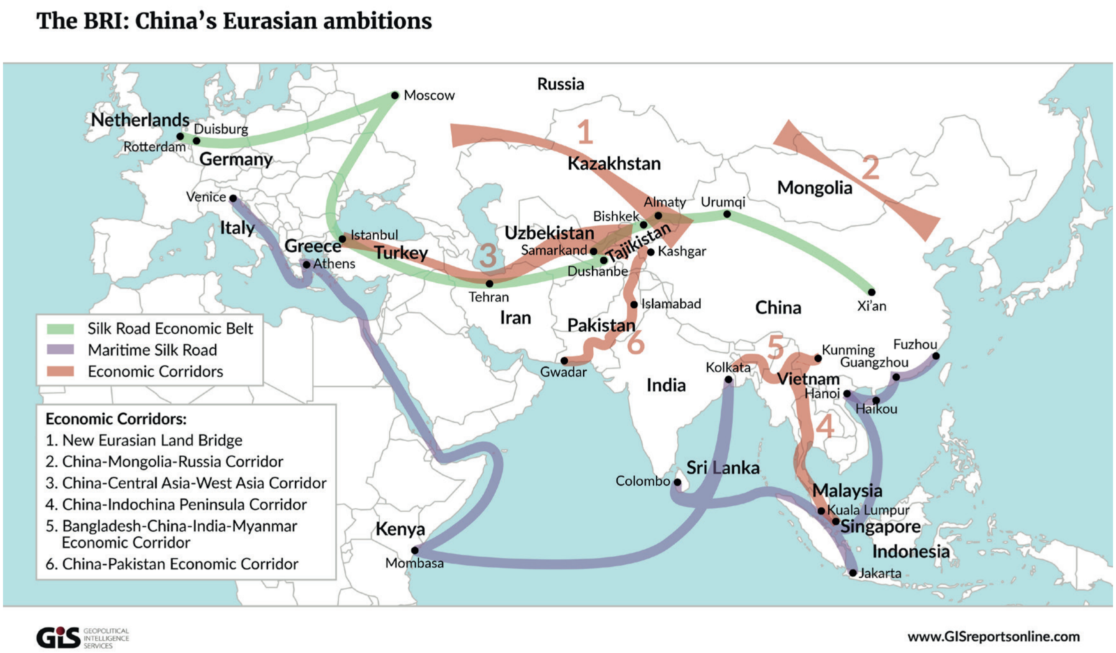

Fig. 1. BRI routes

(Source: www.GISreportsonline.com)[8]

[6]Remarks at the Plenary Session of the BRI International Green Development Coalition (BRIGC) by Mr. Nicholas Rosellini, UN Resident Coordinator, April 25, 2019, see <http://ww.un.org.cn/info/7/966.html>

[7]Memorandum of Understanding between the United Nations Environment Programme and Ministry of Environmental Protection of the People's Republic of China on Building a Green "Belt and Road", found at <https://wedocs.unep.org/bitstream/handle/20.500.11822/25336/MOU%20-%20Belt%20and%20Road%20Strategy%20-Dec%202016.pdf?sequence=20&isAllowed=y>

[8]From Chaudhuri, 2019 (this map is derived from third parties reflecting their views of national borders and do not represent any position or opinion of the authors or the GES editorial board).

(BRIGC), an international coalition working towards the sustainable development of the BRI, was established in 2017 and launched in April 2019, involves 134 partners, including the UNECE (status: 2019)[9] (Hardiman 2020).

Since 2015, the EU and China have been collaborating through the Connectivity Platform, which aims to explore opportunities for further cooperation in the area of transport, with a view to enhance synergies between the EU's approach to connectivity (including the Trans-European Transport Network, TEN-T) and the BRI[10]. In 2018, the European Commission launched an *EU Strategy on Connecting Europe and Asia* to strengthen the connectivity between Europe and Asia (including through interoperable transport, energy and digital networks) (Broer 2018), and China and the EU are cooperating in the development of a harmonised taxonomy of green economic activities (Albuquerque 2021). However, the EU does not appear to have a common position relating to the BRI and it has been proposed that China and the EU should set up a comprehensive international framework through which both the BRI and the EU-Asia Connectivity Strategy may be accomplished (Verhoeven 2020).

Unavoidably, such a large-scale developmental scheme, while promising the benefits of greater connectivity and reduced transportation and energy costs, carries significant environmental and social risks.

Environmental and Social Risks of the BRI

Due to the unprecedented scale and speed of BRI-related large infrastructure projects, such as pipelines, dams, highways, and ports, the associated environmental and social risks are particularly high (Shvarts, Simonov & Progunova 2012; Tracy et al 2017; Losos et al 2019; World Bank 2019a; Hardiman 2020; Hughes 2019; Hughes et al 2020)[11]. Many (including grandfathered) BRI projects will inevitably have significant, extensive, and irreversible environmental and social impacts, for example, relating to pollution, climate change, deforestation and environmental degradation, loss of wildlife, affecting habitats and biodiversity (by fragmenting and altering species' habitats and by preventing animal movement (World Bank 2019a; Hughes 2019), including tigers (Carter et al 2020; Ascensao et al 2018)), as already evidenced in projects such as the Amazar Pulp and Saw Mill in Russia's Eastern Siberian region (Simonov 2018), Primorsky 1 and 2 transportation corridors in the Russian Far East (ITE 2017), including some greenfield projects in the Arctic (FoE 2017). A 2019 World Bank policy paper (Losos et al 2019) identifies many direct and indirect environmental risks connected to BRI investments in transportation infrastructure and World Bank authors, furthermore, state that 'there have been serious concerns raised that the promotion of BRI fossil fuel investments (especially coal plants) could lock host countries into fossil fuel dependency for the coming decades and hamper them from reaching their nationally determined contribution carbon targets as established under the Paris Agreement on Climate Change' (Losos et al 2019).

The environmental risks are clearly demonstrated in a 2017 WWF spatial mapping exercise and analysis (WWF 2017) utilizing IUCN Red list data, relating to the BRI territorial corridors (see Fig. 2). WWF examined distribution data for all Critically Endangered, Endangered and Vulnerable terrestrial mammals, inland aquatic mammals, birds and reptiles on the IUCN Redlist of species (bird data are from Birdlife International). The BRI corridors overlap with many environmentally important areas such as Protected Areas, key landscapes, Global 200 Ecoregions, and biodiversity hotspots that cover the distribution range areas of 265 threatened species, including 39 critically endangered species and 81 endangered species (including the saiga antelopes, tigers, snow leopard, giant pandas, and river dolphins), as well as areas that are important for delivering ecosystem services that provide social and economic benefits to people. Furthermore, it was found that (i) BRI corridors overlap with 1,739 Important Bird Areas or Key Biodiversity Areas and 46 biodiversity hotspots or Global 200 Ecoregions; (ii) all protected areas in the BRI corridors were potentially impacted; and (iii) new activities (e.g., a road through previously remote, inaccessible frontier landscape areas) in areas with the greatest wilderness characteristics can cause more serious long-term impacts than an extra road in an accessible area.

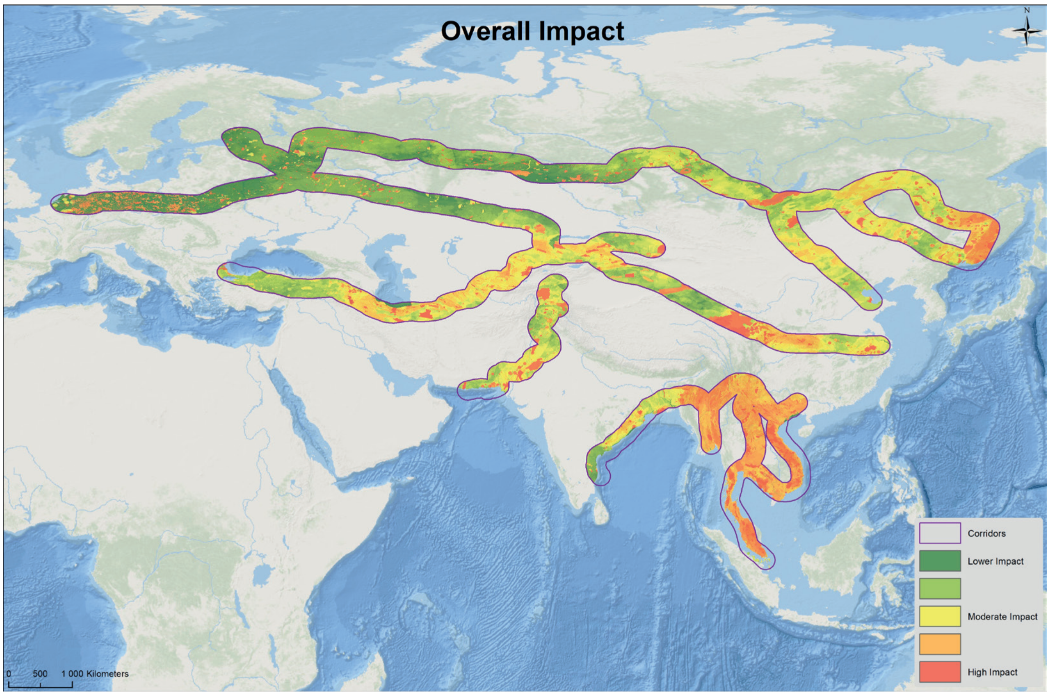

Fig. 2. Spatial analysis of BRI impact

Source: WWF, 2017

[9]UNEP (2020) The Belt and Road Initiative Green International Development Coalition, see <https://www.unenvironment.org/regions/asia-and-pacific/regional-initiatives/belt-and-road-initiative-international-green>

[10]The EU-China Connectivity Platform, EU Mobility and Transport, found at https://ec.europa.eu/transport/themes/international/eu-china-connectivity-platform_en

[11]And see Simonov, E., and Shvarts, E. (2015) "Pure growth vitamins", BRICS Business Magazine, 3 (11), see <http://bricsmagazine.com/en/articles/pure-growth-vitamins>

The 2019 World Bank Report mentions that BRI related topographical and hydrological damage results in related risks, such as landslides, flooding, soil erosion, sedimentation in rivers and interruptions of water courses (World Bank, 2019a). For example, Chinese-backed hydropower projects along the Mekong River pose risks with respect to change in river flow and blocking fish migration, loss of fauna and flora, deforestation, landslides and floods.

The lack of good governance, in particular in relation to transparency (World Bank 2019), stakeholder engagement and enforcement of environmental rules along the BRI are a concern: many BRI development schemes and projects may be planned or implemented with limited transparency and minimal public participation, within an inadequate environmental legal framework and with little respect for environmental rules, and rights of vulnerable local communities and indigenous peoples. It is argued that concerns about the BRI's environmental impacts are legitimate and threaten to thwart China's ambitions, especially since there is little precedent for analyzing and planning for environmental impacts of massive infrastructure development at the scale of the BRI (Teo et al 2019).

Furthermore, the concern that already established environmental policies and standards may decline in the territories between the EU and China is exacerbated by weak governance institutions and the need of BRI countries in Eurasia for infrastructure development and economic growth.

Mitigation of Infrastructure Project Risks

Much (but not all) damage incurred from large infrastructure projects can be mitigated or avoided in the early stages of project planning, with the tool of strategic environmental assessment (SEA) (Tracy 2021; and see Aung & Fischer 2020). It requires inter-sectoral assessment on a regional level, and the engagement of stakeholders and the public, and it considers alternative routes which do not overlap with key biodiversity areas, protected areas and intact ecosystems. Avoiding sensitive ecological areas is arguably the most effective strategy for reducing the negative impacts of transportation projects. SEAs are usually conducted at the regional or national level, or in the transboundary context involving several countries in mutual coordination, planning and project governance (Losos et al 2019).

However, complete avoidance of all key areas for biodiversity along the entire BRI routes will be difficult because of centres of biodiversity and endemism vary significantly across taxa and there are insufficient data for the prioritization of all key regions in advance (Hughes 2019). Thus, appropriate and adequate conservation provisions must be developed on a case-by-case basis but are possible only if comprehensive EIAs are conducted before planning is complete (Hughes 2019).

Therefore, EIAs and SEAs are potentially key tools for China and partner countries for integrating environmental information into decision-making (Aung et al 2020; Aung & Fischer 2020) – however, countries and funding agencies involved in the BRI have different environmental and EIA policies, making the application of consistent EIA standards across projects challenging (Aung & Fischer 2020). Aung & Fischer (2020) also state that, in some countries, authorities might decide to relax EIA requirements in order to attract BRI related investment, and institutional, political and financial constraints may limit the effectiveness of EIA to reduce and mitigate environmental impacts.

ENVIRONMENTAL LAWS AND POLICIES APPLICABLE TO BRI

The main environmental protection guards relating to BRI (infrastructure) projects are: (1) national environmental laws and policies (including provincial and local regulations) of BRI countries; (2) bilateral agreements between BRI countries; and (3) MEAs ratified by BRI countries.

This paper does not review all the applicable national environmental laws of all BRI countries, nor all the bi-lateral agreements, and international environmental laws, due to space constraints. However, it is noted that, although many of the BRI countries receiving investments have in place environmental legislation relating to EIAs, many are weak, and the extent and quality of assessment practices vary substantially between different countries: The results of a comparative evaluation (by Aung & Fischer 2020) indicate that there is great disparity between EIA systems in the 65 BRI countries that they reviewed. Countries with existing challenges, such as poverty, civil war and institutional instability tend to achieve lower EQI (EIA Quality Index) scores (Aung & Fischer 2020). It is noted that China's EIA system comes sixth within BRI countries and comes out on top in Asia, followed by Bhutan (Aung & Fischer 2020).

China has adopted domestic regulations mandating environmental assessment that have the elements of information disclosure and public participation (see Du 2009) in the *1989 Environmental Protection Law* (updated in 2014) (EPL) and *2003 Environmental Assessment Law* (EIA Law). In practice, however, the main tenets of SEA – long planning horizons, a careful consideration of alternatives, extensive public consultations and engagement of local/indigenous communities for their first, prior and informed consent (FPIC) – are not followed in China, and they are downplayed in China-led BRI infrastructure development abroad (Li and Shapiro 2020). There are no explicit Chinese (environmental) laws that would apply in an extraterritorial manner to BRI projects and investments outside China – although the Chinese BRI participants may be guided by the 2017 Green BRI Guidance and the 2017 BRI Green Plan, these policies are voluntary in nature, and all BRI participants are required to follow the project host country's legislation. Thus, the regulatory framework applicable to BRI projects (similar to any infrastructure project) largely depends upon the laws of the territory where such project is being implemented. This means that the strength of domestic environmental laws, as well as domestic monitoring and enforcement mechanisms, in the relevant country receiving BRI financing become very relevant.

Bilateral agreements for cooperation on environmental protection between China, Russia and Mongolia were concluded and the revival of such agreements could profoundly lessen negative impacts of the BRI on biodiversity (Zhang & Zhang 2017; Hughes 2019). Most of China's transboundary water-related treaties have been concluded with its four northern neighbours (Kazakhstan, Mongolia, North Korea and Russia), and cover few of the significant transboundary watercourses in the Southern parts of the country (which includes some of the world's most important basins, such as the Sinquan/Indus River (China, India, Pakistan), the Lancang/Mekong River (China, Myanmar, Thailand, Cambodia, Laos and Vietnam), and the Tsangpo/Brahmaputra River (China, Bangladesh, and India) (Wouters 2015). China's transboundary water-related treaties include a significant number that relate to border issues, with only a small number addressing user-allocation and ecosystem protection – most of the treaties are bilateral and contain general provisions aimed mostly at technical cooperation (Ibid).

Weak domestic regulatory frameworks in many Eurasian countries along the BRI corridors, as well as the array of bilateral agreements, puts international environmental law, including MEAs, into the spot light to address the BRI's environmental and social risks. The role of MEAs is particularly important as their very role is to protect the environment, but also to enable sustainable development across international borders (Sands et al 2015; and Sands 1994). Once ratified and implemented, MEAs can act as an important catalyst for signatory BRI countries to regulate, manage and potentially avoid the environmental and social risks posed by BRI projects, as well as potentially assist in preventing or reducing friction between BRI countries where given BRI projects cause environmental damage across borders.

Addressing Transboundary BRI Risks with International Legal Tools

As many BRI infrastructure projects mostly involve more than one country, MEAs become particularly relevant in addressing the transboundary risks arising from these projects. Amongst the BRI countries, many have ratified MEAs which are relevant to enabling sustainable practices along the BRI. The below Table 1 sets out the geographical distribution of ratifications by BRI countries of MEAs relevant to the BRI:

Table 1. Geographical distribution of ratifying BRI countries (MEAs relevant to BRI), Key (number of MEAs ratified): 1 = 5-12, 2 = 13-14, 3 = 15-21, 4 = 22-23

Country	Category number	Country	Category number	Country	Category number
Afghanistan	1	Iran	2	Palestine, State of	1
Albania	4	Iraq	1	Philippines	3
Andorra	1	Ireland	3	Poland	4
Armenia	3	Israel	1	Portugal	4
Austria	4	Italy	3	Qatar	2
Azerbaijan	3	Jordan	3	Republic of Korea	2
Bahrain	2	Kazakhstan	3	Romania	3
Bangladesh	1	Kenya	3	Russia	1
Belarus	3	Kuwait	2	San Marino	1
Belgium	4	Kyrgyzstan	2	Saudi Arabia	3
Bhutan	1	Laos	2	Serbia	3
Bosnia & Herzegovina	3	Latvia	4	Seychelles	2
Brunei	1	Lebanon	2	Singapore	1
Bulgaria	4	Liechtenstein	2	Slovakia	4
Cambodia	2	Lithuania	4	Slovenia	4
China	3	Luxembourg	4	Spain	4
Croatia	3	Macedonia, Rep of	3	Sri Lanka	3
Cyprus	3	Malaysia	2	Sweden	4
Czech Republic	4	Maldives	1	Switzerland	4
Denmark	4	Malta, Rep of	3	Syrian Arab Rep	3
Egypt	3	Moldova, Rep of	4	Tajikistan	1
Estonia	4	Monaco	2	Thailand	2
Finland	4	Mongolia	1	Turkey	1
France	4	Montenegro	3	Turkmenistan	1
Georgia	3	Myanmar	2	UAE	2
Germany	4	Nepal	1	UK	3
Greece	3	Netherlands	4	Ukraine	3
Hungary	4	Norway	4	Uzbekistan	1
India	3	Oman	2	Vietnam	2
Indonesia	3	Pakistan	3	Yemen	2

Source: Cheremeteff & Broekhoven 2018

Many MEAs are relevant to the BRI (see Cheremeteff & Broekhoven 2018, therein at *Appendix 1*) which can help establish enabling conditions for sustainable development and promote the greening of BRI projects in three ways (Cheremeteff & Broekhoven 2018): (1) Minimizing negative environmental impacts; (2) Promoting investment in 'positive' sustainable projects; (3) Pushing the development and adoption of newer, greener planning tools (e.g., EIAs/SEAs), investments mechanisms (e.g., sustainable finance), technologies and standards.

The UNECE MEAs are particularly important with respect to all of these three points. In particular, they can contribute to the greening of the BRI in core governance-related ways, including through techniques to implement international environmental law, such as EIAs and SEAs (Losos et al 2019; Lechner et al 2018 Zhang 2017; Aung & Fischer 2020), access to environmental information (and environmental justice) and public participation. The application of EIAs and, especially, SEAs will be vital to minimize negative environmental impacts and risks of BRI projects (Losos et al 2019, Hughes 2019), including early assessment of impacts at the feasibility stage rather than once investments have been made (Lechner et al 2018) – in addition, relevant financial support should be connected to such EIA requirement in order to create well-performing EIA systems (Aung & Fischer 2020).

Espoo EIA Convention and its SEA Protocol

The Espoo EIA Convention requires parties to assess the environmental impact of certain activities at an early stage of planning and to notify and consult each other on all major projects under consideration that are likely to have a significant adverse environmental impact across boundaries[12]. Parties are required to, either individually or jointly, take all appropriate and effective measure to prevent, reduce and control significant adverse transboundary environmental impact from proposed activities (Article 2). Further, the «party of origin» state is required to ensure that in accordance with the provisions of the Espoo EIA Convention, an EIA is undertaken prior to a decision to authorize or undertake a proposed activity listed in its Appendix I that is likely to cause a significant adverse transboundary impact (Article 2(3)). The assessment procedure must allow public participation in the preparation of documentation, ensure an opportunity to the public living in areas likely to be affected by (BRI) development to participate in procedures, and ensure that the opportunity provided to the public in the affected country is equivalent to that provided to the public of the party of origin (Articles 2(2) and (6)) (Sands et al 2015).

The SEA Protocol supplements the Espoo EIA Convention and requires parties to evaluate the environmental consequences of their official draft plans and programmes, including effects on human health (De Mulder 2011; Sands et al 2015). An SEA differs from a conventional EIA in that it takes place earlier in the decision-making process and has a much broader scope than the single project that is generally the subject of EIA (Sands et al 2015). The SEA Protocol requires parties to undertake a SEA for specified plans and programmes that are likely to have significant environmental, including health, effects (Article 4.1). It also makes provision for public participation in decision-making (Articles 8); consultations with environmental and health authorities and transboundary consultations (Articles 9 and 10); and monitoring (Article 12).

The Espoo EIA Convention and its SEA Protocol both have substantive rules which set out clear obligations and rights for the States parties (Koivurova 2007), and so are a vital tool through which environmental (and social) risks posed by large-scale BRI (infrastructure) projects can be minimized. As it is open to global ratification, the potential for it to become a global agreement on transboundary EIA is significant, despite acknowledged political challenges (Marsden & Brandon, 2015; Knox 2003; Koivurova 2012).

Aarhus Convention and Kyiv Protocol

The Aarhus Convention[13] and its Kyiv Protocol[14] are specifically dedicated to environmental democracy and put Principle 10 of the Rio Declaration into practice: the provisions empower people with the rights to easily access information, to participate effectively in decision-making in environmental matters and to seek justice if their rights are violated (Sands et al 2015)[15]. The Aarhus Convention requires each party to guarantee the rights of access to information, public participation in decision-making, and access to justice in environmental matters (Article 1). The main obligations are placed upon public authorities, which are, in response to a request, obliged to make available to the public 'environmental information' (Article 2(3)) (subject to certain exceptions), within one month of such request, without an interest having to be stated, generally in the form requested, and without an unreasonable charge being made (Article 4). The Aarhus Convention is not primarily focused on the private sector, but the parties are required to encourage 'operators' whose activities have a significant impact on the environment to inform the public regularly of the environmental impact of their activities and products, where appropriate within the framework of voluntary eco-labelling or eco-auditing schemes or by other means (Article 5(6)). Each party is also required to establish progressively a "coherent, nationwide system of pollution inventories or registers on a structured, computerized and publicly accessible database» (Article 5(9)).

The Kyiv Protocol expands upon this obligation and the nature of the pollutant release and transfer registers from industrial sites and other sources. Its objective is to enhance public access to information through the establishment of coherent, nationwide pollutant release and transfer registers (Article 1) (UNECE, 2020d).

As BRI projects will affect the environment and the communities within which they are developed and operated, the need for public participation, access to information and environmental justice will be key to BRI projects being sustainable, as well as more transparent, inclusive and socially responsible.

As former Secretary-General of the United Nations Kofi Annan stated, the Aarhus Convention is «the most ambitious venture in the area of environmental democracy so far undertaken under the auspices of the United Nation»[16]. Its ultimate aim is to increase the openness and democratic legitimacy of government policies on environmental

[12]UNECE, Espoo Convention, see <http://www.unece.org/environmental-policy/conventions/environmental-assessment/about-us/espoo-convention/enveiaeia/more.html>
[13]See <http://www.unece.org/env/pp/introduction.html>
[14]See <http://www.unece.org/env/pp/prtr.html>
[15]See also <http://www.unece.org/env/pp/welcome.html>
[16]United Nations Secretary General, see <https://www.unece.org/env/pp/statements.05.11.html>

protection, and to develop a sense of responsibility among citizens by giving them the means to obtain information, to assert their interests by participating in the decision-making process, to monitor the decisions of public bodies and to take legal action to protect the environment (Pallermaerts 2011). This, in itself, may be at odds with China's 'coercive environmentalism' (Li and Shapiro 2020) – indeed, combined with adaptive governance practices along Chinese-financed BRI railroad megaprojects (Carrai 2021), this may pose a current obstacle to some BRI countries signing the Aarhus Convention.

Water Convention and its Water and Health Protocol

The 1992 Water Convention (see Tanzi et al 2015) is a framework convention that was developed after the end of the Cold War, following the effects of 40 years of economic development characterized by a focus on heavy industry and on output maximization, rather than sustainability in both industry and agriculture (leading to numerous environmental initiatives in Eastern Europe and Central Asia) (De Chazournes et al 2015). It aims to protect and ensure the quantity, quality and sustainable use of transboundary water resources by facilitating cooperation[17] (Contartese 2017). It provides that parties take all appropriate measures to prevent, control and reduce any transboundary impact with respect to transboundary watercourses and international lakes (Articles 2.1 and 3), in particular (a) to prevent, control and reduce pollution of waters causing or likely to cause transboundary impact; (b) to ensure that transboundary waters are used with the aim of ecologically sound and rational water management, conservation of water resources and environmental protection; (c) to ensure that transboundary waters are used in a reasonable and equitable way, taking into particular account their transboundary character, in the case of activities which cause or are likely to cause transboundary impact; and (d) to ensure conservation and, where necessary, restoration of ecosystems (Article 2.2). It sets out that parties bordering the same transboundary waters have to cooperate by entering into specific agreements and establishing joint bodies (see Part II, and Article 9). As a framework agreement, the Water Convention does not replace bilateral and multilateral agreements for specific basins or aquifers; instead, it fosters their establishment and implementation, as well as further development[18]. There are further provisions for joint monitoring and assessment, common research and development, exchange of information, warning and alarm systems, mutual assistance, and public information.

The Water and Health Protocol aims to attain an adequate supply of safe drinking water and adequate sanitation for everyone, and protects water used as a source of drinking water (Article 6)[19]. It provides that appropriate measures are taken to prevent, control and reduce water-related disease within a framework of integrated water-management systems aimed at sustainable use of water resources, ambient water quality which does not endanger human health, and protection of water ecosystems (Article 4.1). In order to meet these goals, it strongly focuses on: governance, planning and accountability, requesting Parties to set targets throughout the water cycle and the nexus with health (Article 6); access to information and public participation (Article 10); and equity of access to water and sanitation (Article 5(l) amongst others).

As many of the BRI projects are infrastructure-related projects (including water dam projects, oil and gas pipeline constructions), it is likely that freshwater resources will be subject to significant (cross-border) pollution or that there will be impacts on quantity and environmental flows. Furthermore, shipping along rivers is likely to increase with growing trade along the BRI corridors, resulting in potential further freshwater pollution from ships and port activity.

The following five reasons are stated to make this treaty particularly applicable to Asian, as well as other states (Marsden 2015): (a) the presence of the largest amount of transboundary watercourses and international lakes (Marsden & Brandon 2015); (b) there is a need to ensure environmental protection, and equitable and reasonable use of them; (c) the potential for conflict based on sovereignty is high (this treaty is stated to be already well established in the UNECE region, and that it plays a 'major role in bringing states in the Caucasus, central, northern and eastern Asia together to resolve potential disagreements over water resources; other Asian states have also expressed an interest in joining', see Marsden 2013), and cooperation is therefore essential; (d) the Water Convention is the only international water treaty with detailed substantive environmental provisions, and with a primary focus on environmental protection (Wouters & Chen 2013; Marsden 2015); and (e) Asia has growing experience with both this treaty and other agreements for transboundary cooperation, with potential for increased membership. It is noted that the Parties to the Water Convention have extended to a number of African countries, i.e., Senegal (2018), Chad (2018), Ghana (2021) and Guinea Bissau (2021). The Water Convention is becoming increasingly global in its reach and provides encouragement for BRI countries to ratify it in order to assist with reducing and minimizing damage to and contamination of freshwater resources and international lakes by BRI projects. For example, China shares 40 major international waters with 14 neighbours (Wouters 2015; Devlaeminck 2018) and although China voted against the 1987 UN Convention on Non-Navigational Uses of International Watercourses, it is party to 50 treaties for the joint management of its water (Devlaeminck 2018; Wouters & Chen 2013). These are said, however, to be 'often vague and follow a «one-country, one treaty» approach' (Devlaeminck 2018). Thus, if more of these 15 countries were to ratify the Water Convention, it could have farreaching positive effects on their shared waters.

Rates of ratification of UNECE MEAs by BRI countries

The Espoo EIA Convention is ratified by approximately 48% of BRI countries (and one signed it); the Aarhus Convention by around 50% of the 90 BRI countries (and two have acceeded); while the Water Convention has been ratified by approximately 45% of all BRI countries (and one signed it) (Cheremeteff & Broekhoven 2018). In North Eurasia, the UNECE MEAs play a stronger role as can be seen in the below table:

Table 2 illustrates that the UNECE MEAs have been ratified by the majority of North Eurasian BRI countries (even when not taking into account that most EU countries have ratified these MEAs, too), as follows: Espoo EIA Convention (59%), Aarhus Convention (76%) and the Water Convention (65%).

[17]The Water Convention and the Protocol on Water and Health, see <http://www.unece.org/env/water.html>
[18]Introduction, About the UNECE Water Convention, see <http://www.unece.org/env/water/text/text.html>
[19] Introduction, About the Protocol on Water and Health, see <https://www.unece.org/env/water/pwh_text/text_protocol.html>

Table 2. Ratifications of UNECE MEAs by BRI countries in North Eurasia This table does not include EU countries, except for Estonia, Latvia and Lithuania

		Espoo EIA Convention	SEA Protocol	Aarhus Convention	Kiev Protocol	Aarhus Amendment	Water Convention
1	Armenia	Y	Y	Y	S	N	N
2	Azerbaijan	Y	N	Y	N	N	Y
3	Belarus	Y	N	Y	N	N	Y
4	China	N	N	N	N	N	N
5	Estonia	Y	Y	Y	Y	Y	Y
6	Georgia	N	S	Y	S	Y	N
7	Kazakhstan	Y	N	Y	N	N	Y
8	Kyrgyzstan	Y	N	Y	N	N	N
9	Latvia	Y	Y	Y	Y	Y	Y
10	Lithuania	Y	Y	Y	Y	Y	Y
11	Moldova	Y	S	Y	Y	Y	Y
12	Mongolia	N	N	N	N	N	N
13	Russia	S	N	N	N	N	Y
14	Tajikistan	N	N	Y	S	N	N
15	Turkmenistan	N	N	Y	N	N	Y
16	Ukraine	Y	Y	Y	Y	N	Y
17	Uzbekistan	N	N	N	N	N	Y
	Summary:						
	Yes:	**10 (59%)**	5 (29%)	**13 (76%)**	5 (29%)	5 (29%)	**11 (65%)**
	No:	**6 (35%)**	10 (59%)	**4 (24%)**	9 (53%)	12 (71%)	**6 (35%)**
	Signed:	**1 (6%)**	2 (12%)	**0**	3 (18%)	0	**0**

(Y = Yes; N = No; S = Signed, status as at January 2018, see also Appendix A hereto)

However, the formal adoption of the UNECE MEAs' policy tools by way of BRI countries ratifying the UNECE MEAs will not guarantee good environmental performance, nor have positive impacts on geographies along the BRI corridors in Eurasia, unless they are implemented (monitored and enforced) effectively at the national level. Furthermore, the effectiveness of EIA/SEA tools is contingent upon a particular governance process that includes meaningful public participations, stakeholder engagement, government accountability, transparency, and timely information disclosure. The factors related to information transparency and civil society engagement in decision-making are clearly correlated with the principles of democratic governance.

For example, although China has ratified over 50 MEAs and has signed many bi- and multi-lateral agreements with other nations addressing environmental issues (McBeath & Bo 2008), it and Mongolia have not signed or ratified any of the UNECE MEAs. Nevertheless, overall, China stands out as having signed and ratified many key MEAs relevant to the BRI (Cheremeteff & Broekhoven 2018). Indeed, China is seen as increasingly exhibiting a «notable shift from an un-cooperative and coercive veto power to a more constructive player in the multilateral environmental negotiations» (Wei & Lei 2018) and is «increasingly active in global environmental governance» (Yixian 2016). The question now is whether it is feasible to envision that more BRI countries in North Eurasia, such as China and Mongolia, will join, and whether countries such as Russia, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan will further ratify, and so extend the applicability of the UNECE MEAs regulatory framework.

CONCLUSION

The following reasons support why the UNECE MEAs should be seen as forward-looking, comprehensive instruments that provide long-term policy solutions to complex environmental and social challenges, and thus, enable positively (and sustainably) changing geographies in Eurasia:

Firstly, these conventions are governance related and create a framework for environmental (and social) impact assessment, strategic assessments, basin management and participatory mechanisms, based upon internationally agreed rules and standards. All this is central for any BRI activity to contribute to sustainable development within countries it touches.

Secondly, the BRI is already causing serious concerns with respect to the use of water resources and preservation of freshwater ecosystems. The terrestrial BRI corridors traverse the most arid areas of Eurasia, known for water-related catastrophes (e.g., the Aral Sea), conflict and rivalries. In 2017, China listed overseas projects that may affect cross-border water resource development on the *NDRC Catalogue of Sensitive Sectors for Outbound Investment*[20] and restricted their use by special verification and approval procedures (NDRC 2017). All of which indicate the imminent importance of the Water Convention to «de-risk» and smoothen the implementation of BRI project plans. Furthermore, with over 20 years of relatively successful transboundary water cooperation across Europe, the Water Convention offers an important and relevant reference point for China and Asia (including BRI countries) for various reasons (Wouters 2015): (i) it is open for universal endorsement, offering Asian riparian nations, including China, new opportunities for developing nascent transboundary water agreements and practice; (ii) as China 'declares war on pollution'[21], and takes steps to address environmental issues at the domestic level, how it manages this within a transboundary water context might find inspiration from the Water Convention; (iii) as China's engagement with Europe grows as a strategic partnership, a shared understanding and commitment to sharing best practice could help with China's water problems and the Water Convention provides and entry point for such an undertaking.

Thirdly, the BRI's motto and priority is «connectivity». The associated great environmental concern is that the BRI will disrupt and harm the natural connectivity between populations, ecosystems and natural processes. For example, and related to «connectivity» objectives, the 2017 Green BRI Plan explicitly calls for the development of «BRI biodiversity corridors» (at Point VII (1), para 2) and, in 2017, Russia and China declared their *Strategy for Development of Transboundary Protected Areas Network in Amur River Basin* as a model for other BRI regions (Simonov & Egidarev 2017). Spatial planning of the BRI biodiversity corridors should precede, and be harmonized with, the further development of «BRI economic corridors» – and transboundary SEA is the most potent tool for such harmonization (in alignment with the CBD and the CMS Convention provisions). Thus, the SEA Protocol is extremely relevant to the core «connectivity» tasks of the BRI.

Not only would further ratification of the UNECE MEAs be instrumental in supporting the implementation of MEAs already ratified by BRI countries, but also help to create a level playing field (Fulton & Wolfson 2015) across the BRI corridors, whereby a consistent set of internationally accepted rules and standards promoting good governance practices is established, which creates predictability of environmental rules and standards which apply to investments (and thereby facilitate the realization of greener infrastructure) along the BRI corridors.

The ratification of these conventions across Eurasia will be a necessary, but not the sole, condition towards developing a solid transboundary environmental protection framework. The next step, following ratification, is, of course, policy implementation and compliance with the UNECE MEAs. Although virtually all BRI countries have some elements of EIA or SEA policies and regulations (Losos et al 2019; Aung & Fischer 2020; Tracy 2021), the level of implementation of these remains inconsistent. Without proper safeguards in place, such as provided by the UNECE MEAs, the impact of new BRI infrastructure – including stretches of new roads, railways, and pipelines – will accelerate the intrusion of humans into currently still intact ecosystems, causing irreversible damage to and changes in ecosystem functions, and accelerate species loss throughout Eurasia.

The authors acknowledge that the likelihood of some BRI countries ratifying the EU-led UNECE MEAs, especially the Aarhus Convention, is currently diminishing. Although the window of opportunity on extending the UNECE MEAs (as existed in the early 2000-2010s) has been closing due to current geopolitical trends, it is likely that, in future, these UNECE MEAs become more palatable to BRI countries as they contain internationally agreed standards that can empower nations to create and enable sustainable development across and within their borders.

It is feasible that further North Eurasian countries will ratify the UNECE MEAs in future (and in the longer term, extend to the rest of Eurasia). The BRI is considered to be the largest infrastructure project of all time and this requires large-scale solutions, as can be provided by MEAs, especially the UNECE MEAs as they address the core planning and implementation stages of (infrastructure) projects. The time scale of extending membership of these conventions might be more drawn out, but the BRI itself is a long-term venture and the UNECE MEAs contain key instruments through which to address the immense environmental challenges posed by the large-scale BRI infrastructure projects.

Infrastructure development, especially trans-border infrastructure development for economic development of less developed countries, is one of the most important challenges of the first half of the 21st century. In June 2021, the G7 announced its «Build Back Better World» (B3W) plan, as a G7-led alternative to the Chinese-led BRI, in order to help build infrastructure in poorer nations in a 'values-driven, high-standard and transparent' partnership (TRT World 2021). It is stated to involve raising hundreds of billions in public and private money to help close a $40tn infrastructure gap in needy countries by 2035 (Wintour 2021). On this basis, it is feasible to expect a new potential wave of interest in the UNECE MEAs from many BRI countries, especially in Central Asia. Different economic and political competing alternatives require a common legal basis to be most effective. Thus, these competing trans-border infrastructure development projects will increase the international role, significance and importance of the UNECE MEAs, as is already starting to occur with the Water Convention expansion into Africa. The fact that the EU and China are now in constructive negotiations of a common «sustainable finance taxonomy», which is the key pillar of future international development efforts, demonstrates that the EU and China are starting to create and establish common rules for economic and geopolitical purposes.

Taking into account that China's efforts and ambitions to became a global environment and sustainability leader and the ongoing positive changes in China's positions on some challenging issues, including climate change, illegal timber and wildlife/ CITES imports issues during last 5 to 7 years, there exists some degree of optimism that the UNECE MEAs will potentially play a more important role in minimizing environmental and social risks, especially, for local populations and SMEs in different competing economical and geopolitical initiatives.

[20]China updates "Sensitive Sectors" for Outbound Investment', Xinhuanet, February 11, 2018, see <http://www.xinhuanet.com/english/2018-02/11/c_136967702.htm>

[21]Reuters (2014) 'China to 'declare war' on pollution', premier says', Reuters Environment, Beijing, March 5, 2014, see <https://www.reuters.com/article/us-china-parliament-pollution/china-to-declare-war-on-pollution-premier-says-idUSBREA2405W20140305>

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APPENDIX A:
Status of ratifications as at January 2018 (see Cheremeteff & Broekhoven, 2018).

	Espoo Convention*1	SEA Protocol to Espoo Convention	Aarhus Convention*2	2003 Kiev Protocol to Aarhus Convention	2005 Amendment to Aarhus Convention	Water Convention
Afghanistan	N	N	N	N	N	N
Albania	Y	Y	Y	Y	N	Y
Andorra	N	N	N	N	N	N
Armenia	Y	Y	Y	S	N	N
Austria	Y	Y	Y	Y	Y	Y
Azerbaijan	Y	N	Y	N	N	Y
Bahrain	N	N	N	N	N	N
Bangladesh	N	N	N	N	N	N
Belarus	Y	N	Y	N	N	Y
Belgium	Y	S	Y	Y	Y	Y
Bhutan	N	N	N	N	N	N
Bosnia & Herzegovina	Y	S	Y	S	N	Y
Brunei	N	N	N	N	N	N
Bulgaria	Y	Y	Y	Y	Y	Y
Cambodia	N	N	N	N	N	N
China	N	N	N	N	N	N
Croatia	Y	Y	Y	Y	N	Y
Cyprus	Y	Y	Y	Y	Y	N
Czech Republic	Y	Y	Y	Y	Y	Y
Denmark	Y	Y	Y	Y	Y	Y
Egypt	N	N	N	N	N	N
Estonia	Y	Y	Y	Y	Y	Y
European Union	Y	Y	Y	Y	Y	Y
Finland	Y	Y	Y	Y	Y	Y
France	Y	S	Y	Y	Y	Y
Georgia*3	N	S	Y	S	Y	N
Germany	Y	Y	Y	Y	Y	Y
Greece	Y	S	Y	S	N	Y
Hungary	Y	Y	Y	Y	Y	Y
India	N	N	N	N	N	N
Indonesia	N	N	N	N	N	N
Iran	N	N	N	N	N	N
Iraq	N	N	N	N	N	N
Ireland	Y	S	Y	Y	Y	N
Israel	N	N	N	Y	N	N

Italy	Y	Y	Y	S	Y	Y
Jordan	N	N	N	N	N	N
Kazakhstan	Y	N	Y	N	N	Y
Kenya	N	N	N	N	N	N
Kuwait	N	N	N	N	N	N
Kyrgyzstan	Y	N	Y	N	N	N
Laos	N	N	N	N	N	N
Latvia	Y	Y	Y	Y	Y	Y
Lebanon	N	N	N	N	N	N
Liechtenstein	Y	N	S	N	N	Y
Lithuania	Y	Y	Y	Y	Y	Y
Luxembourg	Y	Y	Y	Y	Y	Y
Macedonia	Y	Y	Y	Y	N	Y
Malaysia	N	N	N	N	N	N
Maldives	N	N	N	N	N	N
Malta	Y	Y	Y	Y	Y	N
Moldova, Rep of	Y	S	Y	Y	Y	Y
Monaco	N	N	S	N	N	N
Mongolia	N	N	N	N	N	N
Montenegro	Y	Y	Y	Y	N	Y
Myanmar	N	N	N	N	N	N
Nepal	N	N	N	N	N	N
Netherlands	Y	Y	Y	Y	Y	Y
Norway	Y	Y	Y	Y	Y	Y
Oman	N	N	N	N	N	N
Pakistan	N	N	N	N	N	N
Palestine, State of	N	N	N	N	N	N
Philippines	N	N	N	N	N	N
Poland	Y	Y	Y	Y	Y	Y
Portugal	Y	Y	Y	Y	Y	Y
Qatar	N	N	N	N	N	N
Republic of Korea	N	N	N	N	N	N
Romania	Y	Y	Y	Y	Y	Y
Russia	S	N	N	N	N	Y
San Marino	N	N	N	N	N	N
Saudi Arabia	N	N	N	N	N	N
Serbia	Y	Y	Y	Y	N	Y
Seychelles	N	N	N	N	N	N
Singapore	N	N	N	N	N	N

Slovakia	Y	Y	Y	Y	Y	Y
Slovenia	Y	Y	Y	Y	Y	Y
Spain	Y	Y	Y	Y	Y	Y
Sri Lanka	N	N	N	N	N	N
Sweden	Y	Y	Y	Y	Y	Y
Switzerland	Y	N	Y	Y	Y	Y
Syrian Arab Rep	N	N	N	N	N	N
Tajikistan	N	N	Y	S	N	N
Thailand	N	N	N	N	N	N
Turkey	N	N	N	N	N	N
Turkmenistan	N	N	Y	N	N	Y
UAE	N	N	N	N	N	N
UK	Y	S	Y	Y	Y	S
Ukraine	Y	Y	Y	Y	N	Y
Uzbekistan	N	N	N	N	N	Y
Vietnam	N	N	N	N	N	N
Yemen	N	N	N	N	N	N
Ratifications	44	31	46	36	31	41
Non Ratifications	46	52	43	49	60	49
Signatures	1	8	2	6	0	1
Abstentions	0	0	0	0	0	0
Total Ratifications including non BRI countries	45	31	47	36	31	41

*1 Not displaying 2001 Amendment and 2004 Amendment
*2 not displaying ratifications of 2005 Amendment to Aarhus
*3 Georgia has signed the SEA Protocol but is not a party to the Espoo EIA Convention
Y = Yes
N = No

RESEARCH PAPER

COASTAL EROSION AND TOURISM: THE CASE OF THE DISTRIBUTION OF TOURIST ACCOMMODATIONS AND THEIR DAILY RATES

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ABSTRACT. Beaches are key territories for tourist development but at risk of impacts of climate change—specifically with the consequent intensification of coastal erosion. This study examines the effects of coastal erosion on the distribution of lodging facilities and the value of daily rates practiced on the beaches of Tabuba and Cumbuco on the northeast coast of Brazil. The methodology comprises collecting information on the means of accommodation (distribution and daily rate), quantifying coastline variation and measuring the field to validate data. A total of 13.9 km of coastline were analyzed; erosion tendency was observed in 26.8% of the coast (9.0% erosion, 14.4% intense erosion, and 3.4% severe erosion). With the highest erosion rates, Tabuba's Beach has a low density in accommodation distribution and daily rates practiced in tourism. Cumbuco's Beach, conversely, has a lower risk of erosion, and the means of accommodation are concentrated. Coastal erosion has affected tourism development in Caucaia, influencing the choice of tourism accommodation entrepreneurs. the results indicate that there is a clear concentration of tourist accommodations in areas without notorious problems with coastal erosion, influencing in the distribution of tourist facilities and their daily rates. So, there is a direct connection does exist between local tourism system income and the beaches with problems with coastal erosion.

KEYWORDS: Beach erosion, sun-beach tourism, shoreline, coastal landscape, coastal management

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INTRODUCTION

The tourism industry is one of the economic activities that most emerge in the scenario of global economic growth. Some studies suggest that the growth of the economy and tourism activity are interdependent but not stable (Antonakakis et al. 2015; Dogru and Bulut 2018; Lakshmi and Shaji 2016; Seghir et al. 2015). The tourism industry is one of the sectors of the economy that produces the most indirect impacts, inducing the formation of human capital to meet its needs (Dogru and Sirakaya-Turk 2017).

In many territories, tourism is the main source of income generation, employment, and social development (Lee and Chang 2008). According to the World Tourism Organization (WTO), in 2018, there were 1.407 million international arrivals of tourists worldwide, generating revenue of US$ 1.462 billion. The WTO projects a growth of 3.3% per year until 2030; however, the values should be revised after the COVID-19 pandemic.

Indeed, understanding the causal relationship between tourism and economic growth is important in the implementation of public policies and strategies aimed at sustainable development (Burak et al. 2004; Phillips and Jones 2006). However, other causal relationships must be considered in the local development of this activity, such as coastal erosion. Sandy beaches, for example, occupy one-third of the coastlines and are environments that provide leisure, recreation, and tourism opportunities, which are important spaces for the social and economic benefits of residents and tourists (Luijendijk et al. 2018).

The beaches are landscapes in a constant process of metamorphosis by geological, oceanographic, hydroclimatic, and anthropogenic factors. In addition, sea-level rise induced by climate change can have a negative impact on coastal dynamics, driving the process of coastal erosion (Nicholls 2011; Stive et al. 2009; Zhang et al. 2004;). Vousdoukas et al. (2020) indicate that half of the world's sandy beaches could disappear by 2100 if the pessimistic scenario of rising sea levels materializes. This situation could hinder the development of global tourist activity. However, it is necessary to consider that this study does not consider the regional and local dynamic factors, and there may be an extrapolation in the results.

In this sense, the environmental quality of the beach is a determining factor in choosing the tourist destination, and visitors are concerned with the natural values of the beach and environmental degradation (Lima and Paula 2017; Roca et al. 2009; Semeoshenkova and Newton 2015). In this case, the challenge has been to reconcile environmental quality with the development of the tourism industry (Holden 2000). Roca et al. (2009) highlighted that the relationship between beach users and the environment is complex and, at times, confusing, as the satisfaction and pleasure of leisure and recreation activities are directly and indirectly affected by the environmental quality of the place. The environmental quality of the beaches and adjacent environmental systems has thus become a crucial factor of competitiveness among the numerous tourist destinations of the sun and beach modality (Mihalic 2000). Currently, several authors (Fuchs et al. 2014; Ladhari and Michaud 2015; Peña-Alonso et al. 2017) claim that the quality of infrastructure and services offered to users of coastal tourism is also a significant factor of attractiveness. Therefore, the environmental quality of the beaches must be accompanied by satisfactory levels of comfort and assistance for the development of leisure and recreation activities associated with beach tourism. In this process of valuing coastal areas in terms of tourist activity, there is a significant increase in demand for tourism products and services via online platforms, with numerous travelers who increasingly adhere to online channels (e.g., Booking.com) to conduct their research and define their itineraries and accommodation during their travel (Wu and Law 2019).

In Brazil, as in other parts of the world, beaches have become the main spaces for the development of tourism practice (Cruz 2003), with the need to protect them, something that may seem antagonistic today (Meulen et al. 2001). The erosion of sandy beaches represents a real threat to coastal economies (Alexandrakis et al. 2015; Phillips and Jones 2006). This is especially the case for those territories that derive their family income from tourist services, being a major factor for the socio-economic development of tourist communities, as is the case in most coastal cities in northeast Brazil.

This study is based on an approach that combines information about the state of the beaches (eroding, accreting, and stable) and the spatial distribution of the means of accommodation. In general, it is common for studies to address the cost of coastal erosion of sandy beaches from coastal protection measures that will be built. This study thus begins with an understanding of the general aspects of coastal erosion from the reflexes on the coastline and how these results influence the spatial distribution of the means of accommodation as a provider of tourist services. The hypothesis is that lodging facilities are installed in areas with better environmental quality, that is, coastal areas without signs of erosion.

TOURISM AND COASTAL EROSION IN CAUCAIA COAST (NORTHEAST BRAZIL)

Tourism in Ceará has emerged in Brazil, as pointed out in the Monthly Survey of Services (PMS) conducted by the IBGE, with an average growth rate of 4.8%, recorded in December 2019. The study also points out that this growth had a direct influence on the new flights implemented since the creation of the hub air in Fortaleza. As a reflex, the number of foreign passengers increased by 102% from May 2018 to April 2019. In 2019, the tourist indicators of Ceará indicate that there was a 5.5% growth in activity in relation to the previous year, with 3.7 million tourists and an impact of US$ 384,915.36 on the state economy (SETUR-CE 2020). This economic activity represented, in 2019, 12.6% of the Gross Domestic Product (GDP) of the State of Ceará. The coast as a tourist destination in Ceará concentrates 82% of the tourists who visit the state, 57% of the tourists who visit only the city of Fortaleza, 27% who visit Fortaleza and some other location, and 16% who visit exclusively, other Ceará destinations, with emphasis on Caucaia, Aquiraz, Aracati, and Beberibe (SETUR-CE 2020).

Tourism in Caucaia is a reflection of public policies adopted by the Government of the State of Ceará and the Federal Government, in which the tourism industry has been treated with strategic economic activity. Over the past 30 years, the state has invested more than US$ 185 million in tourism development projects and actions in Ceará through the Regional Tourism Development Program (Araujo and Pereira 2011; Silva and Lima 2015). Investments are initially concentrated in the road and air infrastructure, then in tourism products and the commercialization of destinations (e.g., Cumbuco, Jericoacoara, and Canoa Quebrada).

The coast of the municipality of Caucaia, located in the Metropolitan Region of Fortaleza-RMF (northeast Brazil), is less than 25 km from the city of Fortaleza (Metropolis) and the International Airport. According to records from the Brazilian Institute of Geography and Statistics (IBGE), as of 2019, Caucaia is the second-largest municipality in Ceará in terms of population (361,400 inhabitants), and GDP is US$ 1.086 million, occupying an area of 1,227.90 km^2 in the northeast portion of Ceará (IPECE 2017).

The Caucaia coast has approximately 45 km of sandy beaches, 75% of which consists of beaches with coastal erosion problems (Paula 2015). Currently, of the eight main beaches in the municipality, only Cumbuco Beach still does not show serious signs of coastal erosion. The study area is 14 km long and is located between the beaches of Tabuba and Cumbuco, on the west end of the Caucaia coast (Fig. 1). This spatial approach allows a comparative analysis of the geospatial behavior of the hotel sector on two neighbouring beaches to the detriment of the coastal erosion process in the region.

The chain of tourist service providers in Caucaia is quite diversified, with hospitality as the main branch. However, we also have to consider the contribution of other services—food, road passenger transport, local fish production (e.g., fish, shrimp, and lobster), sightseeing, and others. Considering public and private investments in the development of tourism in Ceará, Caucaia benefited in different investment phases, which allowed a rapid and concentrated expansion of tourism in the Cumbuco region, becoming the main tourist destination of Ceará visiting Fortaleza (SETUR-CE 2016). Caucaia has strong integration with Fortaleza, favoring spatial, social, and economic relations, streamlining the flow of people, capital, goods, and investments (Gonçalves 2011).

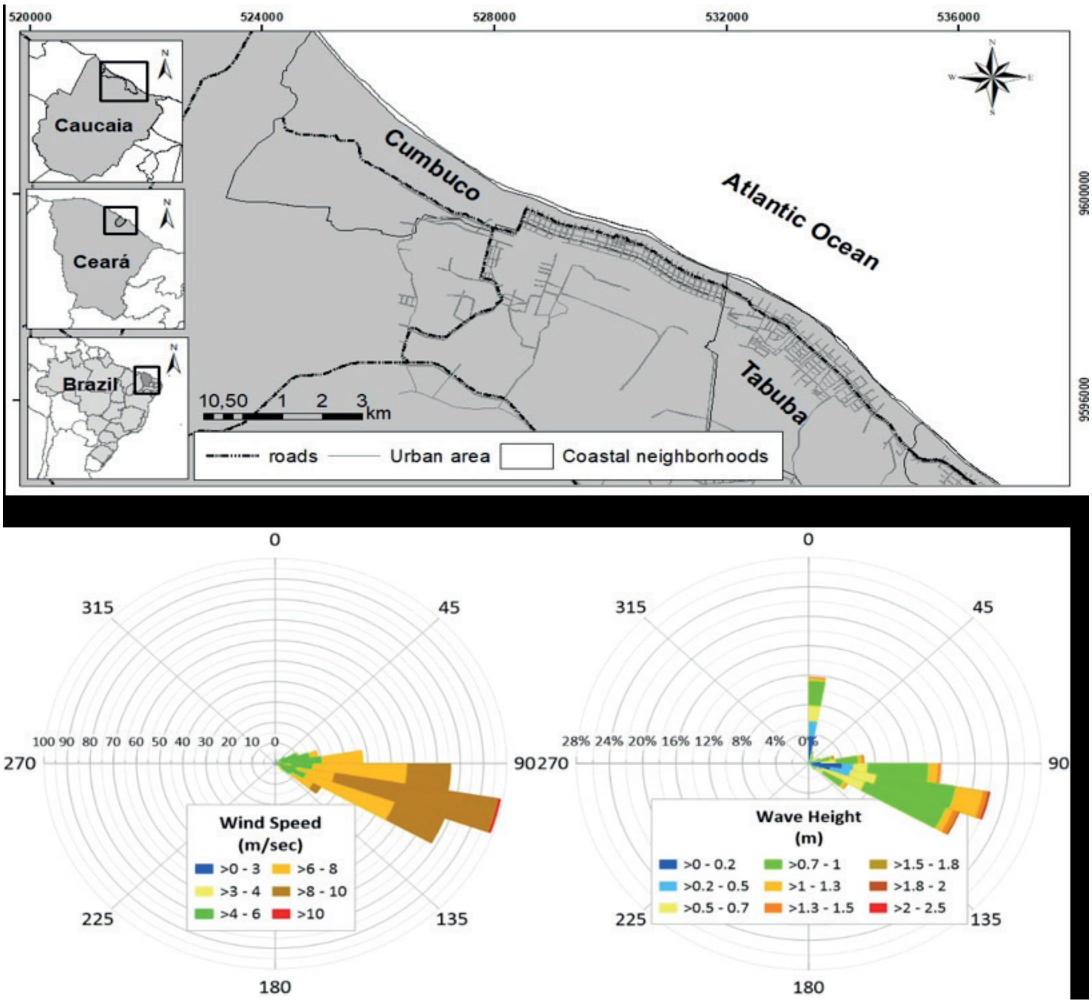

Fig. 1. Study area with indication of Tabuba and Cumbuco Beach in the Caucaia coast

Further, Caucaia has a strong paradigm in the recreational use of its coastline, directly reflected by the environmental stress caused by coastal erosion at Tabuba Beach (Fig. 2a) and the scenic splendor of Praia do Cumbuco (Fig. 2b). In the latter, the best environmental quality generated a massive appropriation of coastal spaces by social and economic actors, attracting major developers in the tourism industry, such as the Portuguese hotel group Vila Galé, which settled in the region in 2010.

According to the report of PRODETUR Nacional 2012, its latest version, entitled «Tourist hubs of Ceará: Tourism marketing plan,» Cumbuco Beach received an A rating for the product Nautical Sports (windsurf and kitesurf). This means that the destination and its characteristics are the main motivators of tourist flows. Tabuba Beach received a B rating. In this category, products that complement the offer of a class A destination are classified and considered strategic to extend the tourists' stay in the region.

Tabuba (4.4 km) and Cumbuco (9.6 km) are urban sandy beaches, with northwest alignment and the presence of dune strands of different generations. The width of the beach strip in Tabuba ranges from 0 m to 60 m, while that in Cumbuco ranges from 30 m to 105 m. These values depend on the level of erosion and the amplitude of the tide, which, in the region, can reach 3.3 m, according to the Directorate of Hydrography and Navigation (DHN) of the Brazilian Navy, configuring a mesotidal regime. Sea-type waves are more frequent and are associated with the direction and intensity of trade winds, with mean values of significant height (Hs) of 1.33 m, period (Ts) of 7 s, and Mean Direction (Dir.) from the E-SE. Breaking with the dominance of sea waves, swell-type waves occur less frequently, with an average Hs of 2.4 m, Ts of 14 s, and N-NE Dir.. E-SE winds direction are the most frequent, with an average intensity ranging from 5.1 m/s (Jan-Jun) to 9.4 m/s (Jul-Dec) (Silva et al. 2011).

Fig. 2. Coastline situation on the beaches of Tabuba (a) and Cumbuco (b) in February 2020

MATERIALS AND METHODS

Shoreline situation

The recent evolution of the coastline between the beaches of Tabuba and Cumbuco was assessed during 2004, 2011, and 2014 using satellite images with different scales and resolutions (Table 1). Orbital images from QuickBird and RapidEye multispectral satellites were used. Remote sensing techniques have been widely used in determining shoreline changes, contributing to accurate information for managing risks and natural disasters (Maglione et al. 2015; Tarmizi et al. 2014; Wikantika et al. 2007). The variation of the coastline due to erosion and sand deposition is a major concern for the management of the coastal zone and its economic activities, such as tourism (White and Asmar 1999).

All images were orthorectified and converted to the Geodetic Reference System adopted in Brazil, with Datum SIRGAS 2000, in the GeoTiff format, and projected using the Universal Transverse Mercator system (UTM, zone 24 South). Images were orthorectified using 30 non-collinear points from the initial image. The points were checked and georeferenced in the field using a GPS/GNSS to obtain the mooring coordinates in the orthorectification process. The selected points in the initial image were corners of rectangular objects (e.g., walls). Thus, the final image was adjusted by the parametric method and distortions eliminated.

Advancements in remote sensing techniques and refinement in the processing and interpretation of satellite images allow for a satisfactory degree, in most cases, to interpret changes in the position of the coastline with greater precision (Liu et al. 2013; Ryu et al. 2002). In recent years, several techniques, and tools (e.g., Digital Shoreline Analysis System [DSAS], Processing Algorithms, and Coastal Analysis via Satellite Imagery Engine [CASSIE]) have been developed to improve detection and accuracy in the extraction of the coastline (Liu et al. 2013; Liu and Jezek 2004).

In this study, the coastline was vectored in a GIS environment, with the aid of ArcGIS software. For the beaches of Tabuba and Cumbuco, the total sample of the coastline was 14 km, 46.5% of the Caucaia coastline. For this purpose, the indicator for the vectorization of the shoreline was the maximum range of the wave run-up (Crowell et al. 1991). After extracting the shoreline, the DSAS extension for ArcGIS, developed by the USGS (Thieler et al. 2005), was used to estimate changes in the coastline.

To determine the changes to the shoreline, the positions of the shoreline were incorporated, referenced with the baseline that was determined. The variation of the coastline is determined from the intersections of the transects oriented perpendicularly to the coastline (Kuleli et al. 2011). In this study, transects perpendicular to the coast were generated at 50 m intervals, with interceptions of 264 transverse transects 300 m long, perpendicular to the baseline (offshore). The scale adopted for mapping the coastline was 1:3,000 (Fig. 3). In DSAS, the rate of change of shoreline positions (erosion/accretion) was assessed using the end point rate (EPR) and linear regression (LRR) approaches (Thieler et al. 2005).

Erosion and accretion rates for the beaches of Tabuba and Cumbuco were categorized based on the behavior of the coastline identified with the use of DSAS and the application of the LRR parameter. Therefore, according to the indications of Esteves and Finkl (1998) and Luijendijk et al. (2018), the recent evolution of the coastline was grouped into six trend categories: accretion (> +0.5 m/yr), stable (between –0.5 and +0.5 m/

Table 1. General technical specifications of satellite images

Satellite images		
Source	Year	Resolution
QuickBird	2004	2.4m
RapidEye.	2011 and 2014	5 m

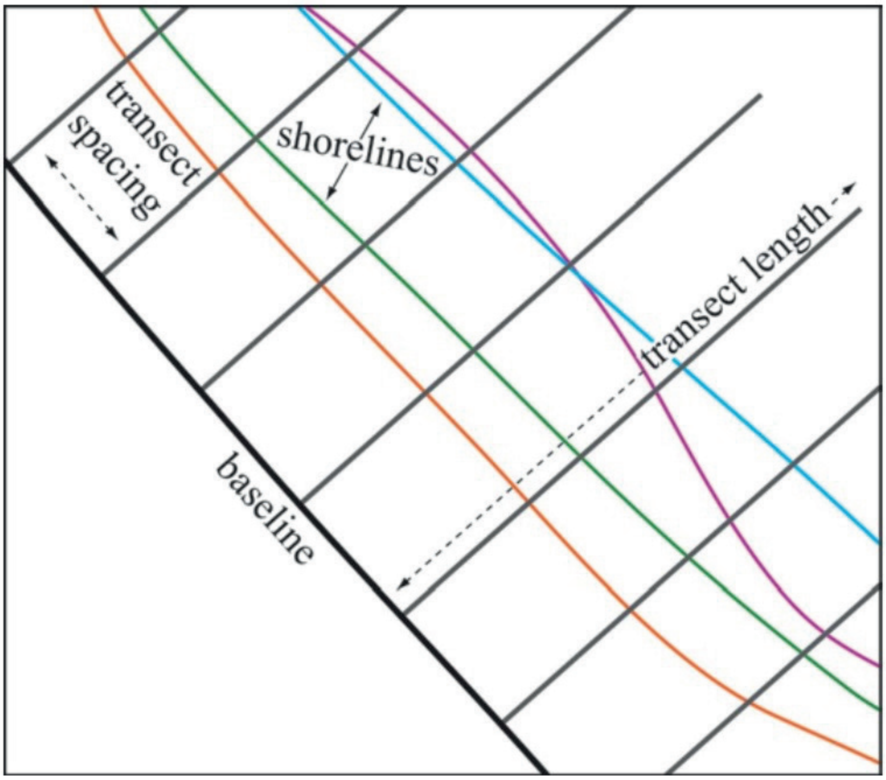

Fig. 3. Launching of transects from the baseline parallel to the shoreline vectors. Source: Thieler et al. (2017)

yr), erosion (between –1 and –0.5 m m/yr), intense erosion (between –3 and –1 m/yr), severe erosion (between –5 and –3 m/yr), and extreme erosion (<-5 m/yr). Finally, field campaigns were conducted between the years 2019 and 2020 to check the shoreline. In the field check, we sought to identify possible indicators of coastal erosion – the high-water mark, remains of building materials, coastal protection structures and rugged dunes. When identified, they were georeferenced with GPS/GNSS for crossing with the data obtained from the DSAS tool application.

Identification of accommodation facilities and tariffs

In recent years, the policy of reserving accommodation has undergone significant changes, especially with regard to the cancellation or alteration of reservations (Masieroa et al. 2020). In addition, finding the most suitable means of accommodation for travel plans has become easier and more attractive through digital platforms (e.g., Booking.com, Trivago, TripAdvisor, Hotels.com, Decolar.com, etc.). On these platforms, the tariff is dynamic, promotions are daily, policies are strict, and factors contribute to traveler safety (Masieroa et al. 2020; Mellinas et al. 2016). Further, it is possible to consult all available infrastructure (e.g., parking, swimming pools, internet, sports courts, and accessibility) at the place of accommodation and the opinion of other travelers about that means of accommodation.

The use of these online platforms has been increasingly influencing the decisions of different stakeholders, in which visitors stand out, especially with regard to the sharing of information and experiences on social media platforms, which can directly influence professionals of destination marketing and potential tourists (Tavakoli and Wijesinghe 2019). Thus, the correlation between the products/services offered, prices, locations, and shared traveler experiences are one of the main differentials for the use of online platforms.

The Booking.com platform was chosen as an environment for collecting data on the means of accommodation, as it has easily accessible information and availability for online consultation (Sparks et al. 2016). It is one of the largest digital platforms in the world to consult information on accommodation (Câmara 2013), including allowing a thorough study on the characteristics of the researched means of accommodation, such as the daily rate, types of accommodation, characteristics of accommodation, and others. The daily rates were converted to US dollars according to the quotation date on 08/10/2020 (R$ 1.00 = US$ 0.1854) provided by the Central Bank of Brazil. The booking platform is widely used for data collection and research development, reflecting its reliability and breadth (Ezzaouia and Bulchand-Gidumal 2020; Manes and Tchetchik 2018; Mellinas et al. 2016).

The means of accommodation (e.g., hotels, inns, flats, and hostels) and the daily rates on the beaches of Tabuba and Cumbuco were identified from the information available on Booking.com. It is important to highlight that the public control agencies do not have information on the average value of the individualized accommodation tariff or their location through geographic coordinates. The means of accommodation were identified from the cartographic base of Google Maps, available on the Booking.com platform itself, and later inserted and treated in the Quantum GIS (QGIS) software. After creating the attribute table with the location of the lodging establishments, an edition was made to incorporate the attribute daily rate. Finally, the attribute table was organized with the following variables: code of the means of accommodation (01-111), coordinates (latitude and longitude in SIRGAS 2000), name of the enterprise (alphanumeric code to maintain confidentiality), beach (Tabuba or Cumbuco), and price of the tariff (US$). Analysis of erosion rate and aspects associated with the means of accommodation was carried out by overlaying maps.

RESULTS AND DISCUSSION

Shoreline State in the Tabuba and Cumbuco Beaches

The coastline is an important coastal geomorphological feature in detecting the situation of a beach, especially the problems associated with coastal erosion. It is a dynamic system with rapid responses and evolution. Its tendency can be followed in mapping on different dates through data collection in the field or by satellite imaging (Diniz et al. 2020; Liu et al. 2013). At Tabuba Beach, 59% of its coastline is affected by erosion, while at Cumbuco Beach, only 11% of its extension is affected by coastal erosion (Fig. 4).

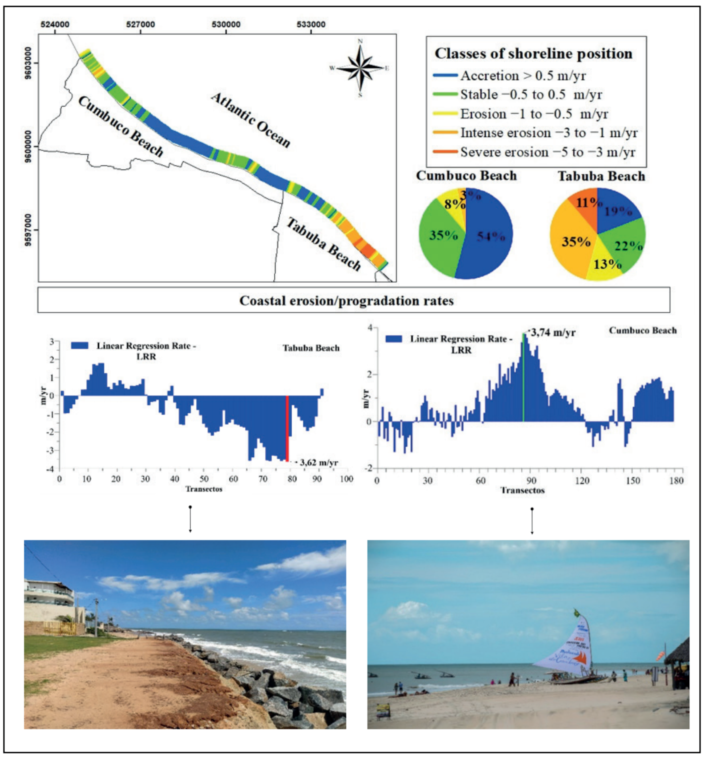

Fig. 4. Rates of shoreline position of the beaches of Tabuba and Cumbuco

Tabuba Beach is 4.5 km long and has 59% of its coastline in the erosion process, of which 35% are under intense erosion, 13% in erosion, and 11% in severe erosion, as proposed by Esteves and Finkl (1998) and Luijendijk et al. (2018). The remaining 41% are either stable or increasing. On this beach, maximum rates of coastal erosion of up to 3.62 m/yr were recorded. The eastern sector of this beach concentrates the highest erosion rates, experiencing an average retreat of the coastline on the order of 2.8 m m/yr. In the western sector, there are stretches with an average retreat of 1.5 m/yr and an average increase in beach range of 0.5 m/yr. Coastal erosion at Tabuba Beach follows the pattern of this coast, where coastal erosion has been moving from east to west from the municipality of Fortaleza to that of Caucaia. With the latter, the coastal erosion process has progressively affected all beaches east of Tabuba in the last 30 years, including Leblon Park, Iparana, Pacheco and Icaraí. This process is well evidenced by the numerous coastal protection infrastructures built between the cities of Fortaleza and Caucaia (Paula 2015).

Cumbuco Beach is the longest on the Caucaia coast, with approximately 9.6 km of sandy beaches in the presence of coastal dunes. Its situation in relation to coastal erosion is different from Praia da Tabuba, as 54% of its shoreline shows an accretion trend that is, there is an increase in the beach range, with a maximum record of 3.74 m/yr. Another 35% of the total length of the coastline is stable and has no apparent evidence of coastal erosion. Therefore, of 89% of the coastline of Cumbuco Beach, there is no evidence of coastal erosion, which is a significant situation for continuous coastal development based on sun, beach, and wind tourism. Finally, only 11% of this coastal stretch shows any indication of coastal erosion, reaching a maximum rate of 1.5 m/yr. This erosion rate is 58.5% lower than the rate recorded at Tabuba Beach, focusing mainly on the stretch below the boundary between the two beaches, which can mean continuity of the erosion process, which, in Caucaia, always goes toward the west, as is the case here.

Coastal erosion in this stretch of the Caucaia coast is well advanced along Praia da Tabuba, directly reaching the urbanized marine front, which is formed by summer residences and a few structures aimed at tourist development. This is the case for some inns and beach huts. The natural coastal landscape has been progressively modified due to the advance of the sea and the construction of coastal protection works. In total, seven rockfills are protecting 700 m of the urbanized marine front that were built between 2014 and 2019 (Fig. 5). The beach is mainly used for leisure as sunbathing and sea; however, the level of use of the beach is low, as the largest flow of visitors is directed Cumbuco Beach (IPETURIS 2011). Up to the time of this study, no coastal protection structure has been identified in Cumbuco Beach because, in the few places where the erosion problem manifests, there are no urban constructions. Therefore, there is no need to insert any defense apparatus from the coast.

Cumbuco is extremely popular throughout the year, as it has the best service equipment for the tourist sector. In addition, services for tourists are more diverse in the region, ranging from accommodation to windsurfing and kite surfing schools (IPETURIS 2011). The installation of tourist equipment such as Chico do Caranguejo beach hut and the Carmel Cumbuco Resort (Fig. 6) are highlighted, showing infrastructure development for tourists between the years 2004 and 2019.

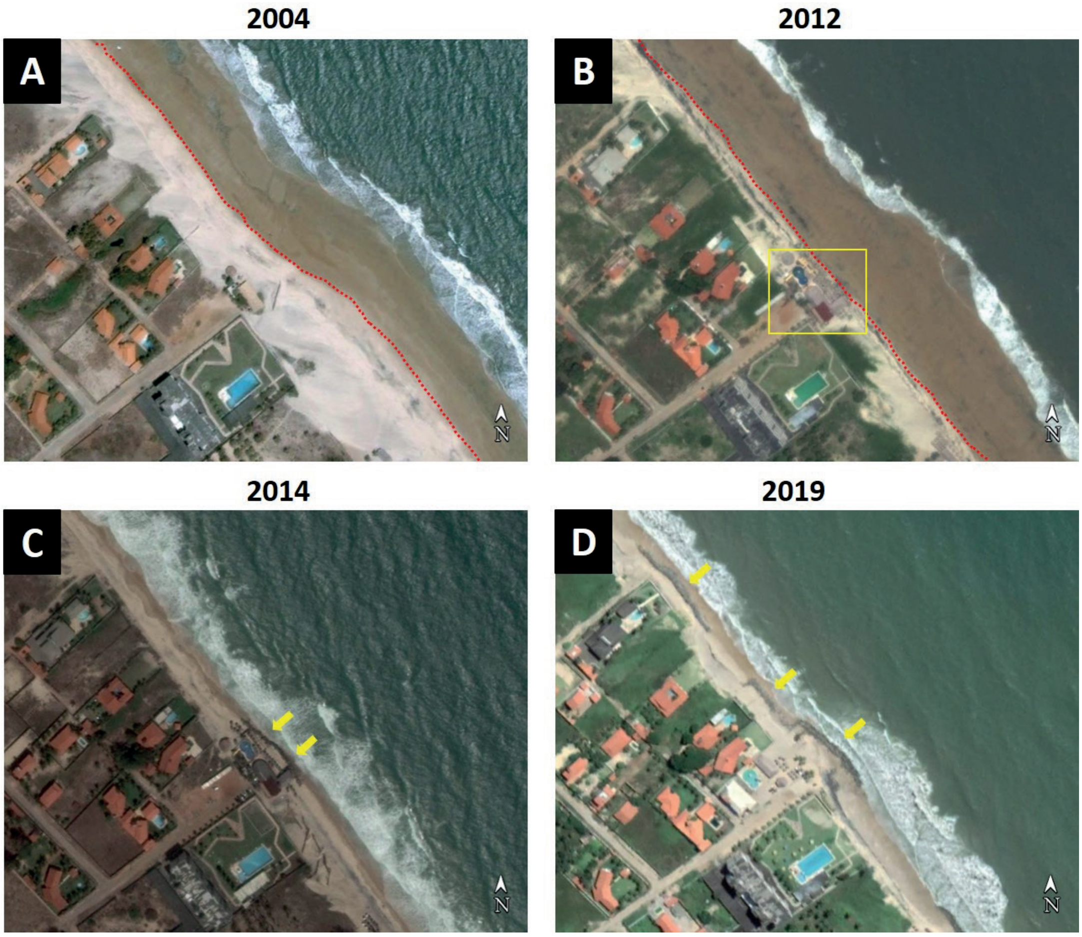

Fig. 5. A stretch of Tabuba Beach in different dates. A) in 2004, the edge between dry and wet sand (red striped line); B) in 2012, the yellow square indicate the place of a beach hut; C) and D) indicate the presence of rockfills (indicated by the yellow arrows) to contain the progress of erosive processes. Source: Google Earth

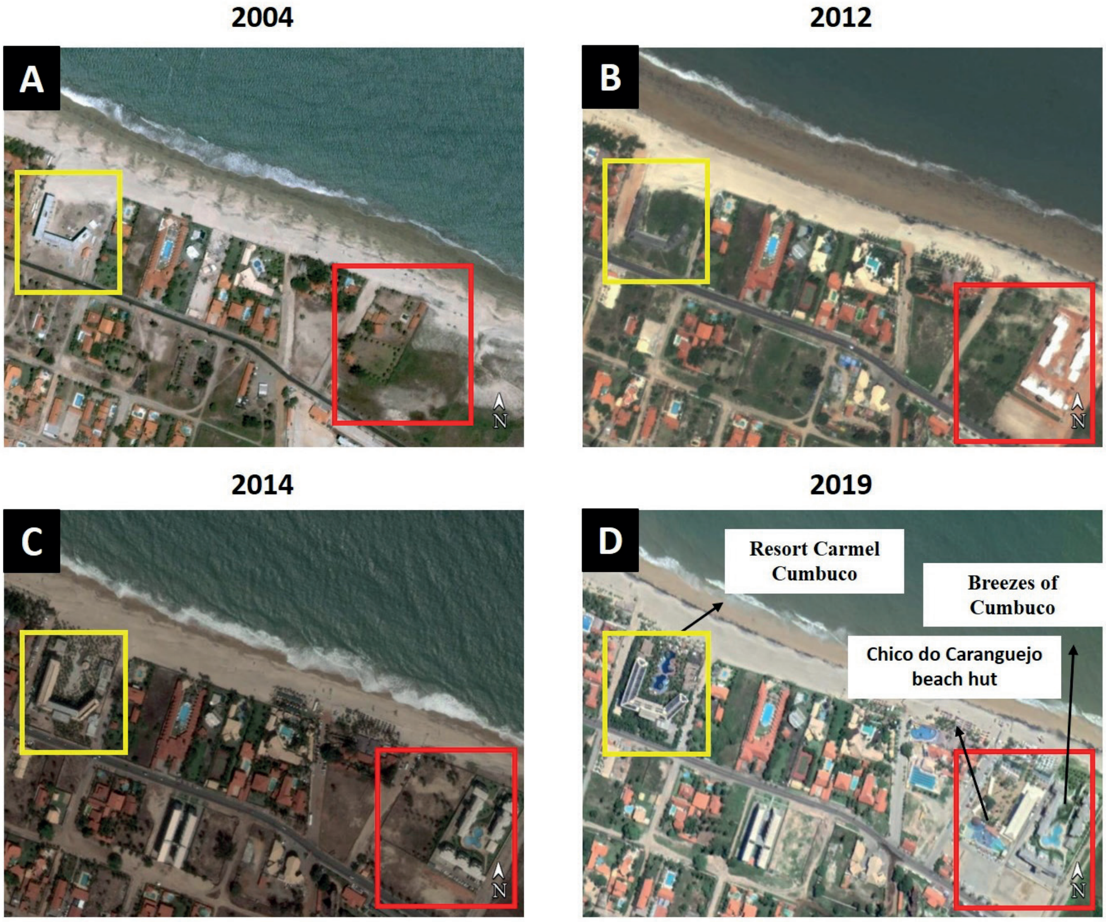

Fig. 6. A stretch of Cumbuco Beach. The yellow and orange rectangles highlight the spaces in which tourism equipment were built. Source: Google Earth

Distribution of Tourist Accommodation Facilities and daily rates in the Tabuba and Cumbuco Beaches

Considering the potential for attractiveness, the beaches of Tabuba and Cumbuco stand out as the main tourist destinations on the coast of Caucaia (Lopes 2015), the most visited in Ceará by tourists via the city of Fortaleza (SETUR 2020). Considering the tourist accommodation facilities, 111 means of accommodation were identified (e.g., apartments, resorts, hostels, houses, hotels, and inns), with only 11 of these (9.9%) being installed in Tabuba Beach, being in mostly small accommodation establishments. In contrast to the low attractiveness of Tabuba Beach to the installation of accommodation facilities, Cumbuco Beach concentrates more than 90% of all tourist accommodations. This reflects its better environmental quality compared to Tabuba Beach, which suffers from a severe coastal erosion (Fig. 7). This situation is reflected in the attractiveness of large tourist complexes, such as Vila Galé Cumbuco Resort and others installed in this region.

The advanced stage of erosive processes on the beach directly impacts coastal tourism, that is, the local economy that is directly linked to this activity. The reduced number of lodging facilities in Tabuba Beach shows the low economic dynamism of the location, especially in sectors with significant local economic impact – service and trade – especially when we consider that more than 60% of the GDP of the municipality of Caucaia comes from sector services (IPECE 2017).

The implementation of large tourist facilities, such as the resorts at Cumbuco Beach, takes place through foreign and national investments, configuring the location as a «tourist enclave» targeted by planned actions that focus on a group of national and international tourists, highlighting its hotel infrastructure software (Mesquita 2014). Cumbuco is thus a top tourist destination not only on the coast of Caucaia but also in the state of Ceará (Lopes 2015).

The high standard of consumption and the best environmental quality of the beaches can be seen from the value practiced in the hosting plan, such as the charge per night in the means of accommodation (Fig. 8). More specifically, in Caucaia, among the lodging facilities installed on the beaches of Tabuba and Cumbuco, the daily rate ranged from US$ 7.42 to US$ 278.86, a standard deviation of US$ 191.90, which shows a high degree of dispersion in the daily rates on the beaches in question. This is due to several factors, including the environmental quality of the place, the standard of facilities for tourist accommodations, and the diversity of services available to the visitor.

In Tabuba, the average daily rate recorded on Booking.com was US$ 56.01, with a minimum of US 7.42 and a maximum of US$ 278.86. At Praia do Cumbuco, the average value was US$ 50.57, with the same minimum and maximum variation recorded for Praia da Tabuba. This average daily rate in Cumbuco, below that recorded in Tabuba, is explained by the greater number of accommodations with an average price of US$ 7.42, generally associated with the offer of vacancies in hostels. However, in Cumbuco, almost all the enterprises with a daily value above US$ 87.15 are installed, a re-signified value by the existence of large hotel developments and luxury resorts (Fig. 9). Finally, between these two beaches, it is possible to observe a wide variety of prices practiced in the daily rate, in which the environmental situation and the size of the enterprise are important elements in the composition of the tariff of the means of accommodation.

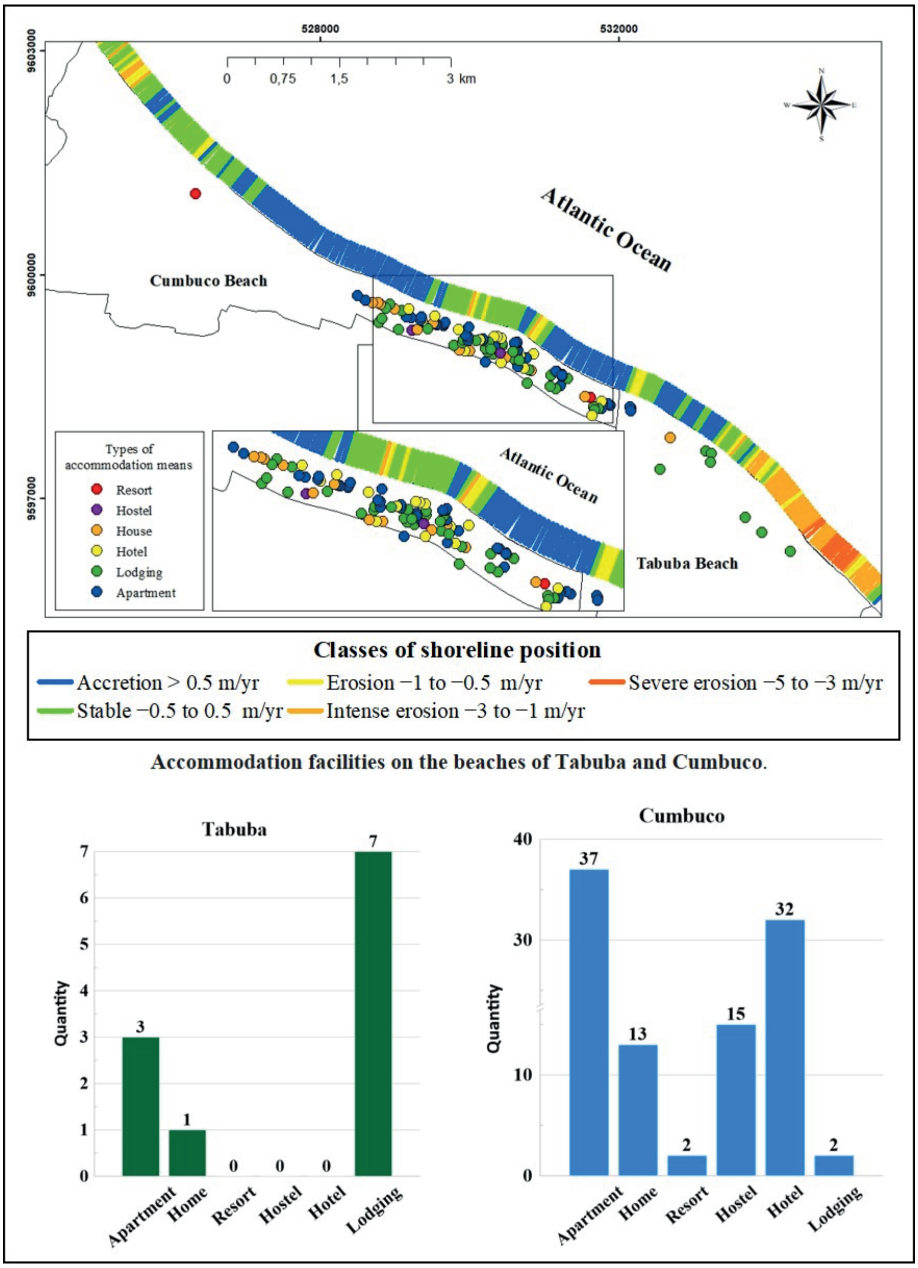

Fig. 7. Distribution of types of lodging in the beaches of Tabuba and Cumbuco

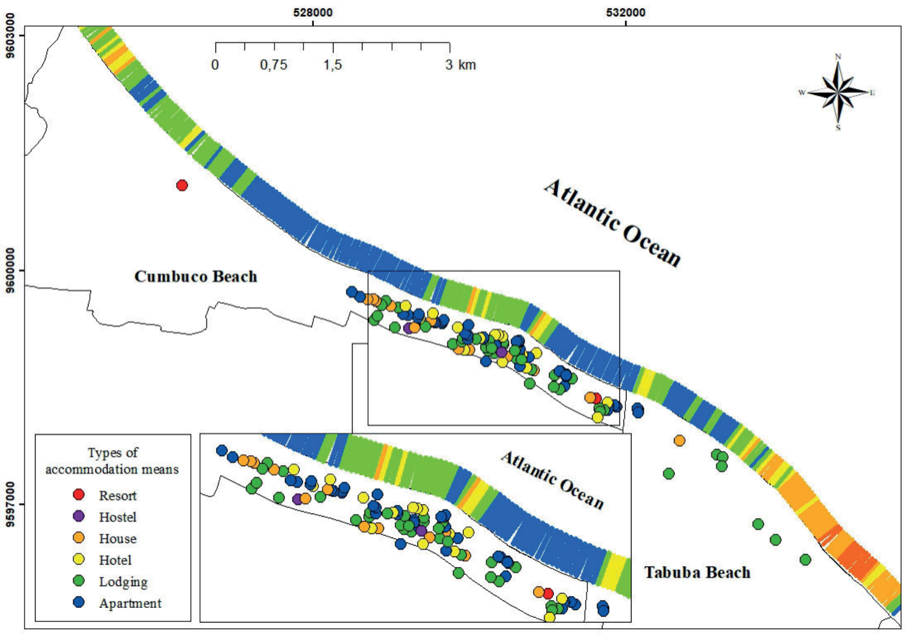

Fig. 8. Distribution of the daily rates (US$) of the lodging facilities on the beaches of Tabuba and Cumbuco

Fig. 9. Presence of luxury resorts in Praia do Cumbuco in the middle of the dune and coconut groves, registering the high standard of some accommodations in this sector of the Caucaia coast

Therefore, the large concentration of tourist infrastructure in the high-end hotel sector generates speculation in several other sectors of the economy, such as the food sector, service, commerce, industry, and civil construction, generating employment, investments, and revenue collection for the Caucaia municipality. Notably, the consolidation of the Cumbuco location as a «mandatory destination» for tourists is not only due to its hotel infrastructure but also because of the potential for the attractiveness of its beach, with several activities being offered for leisure and recreation, boosting the offer of various sectors of the economy. Allied to this, the better environmental quality of the beach and the fact that it is not affected by coastal erosion contributes to it being the main destination for tourists who enter Ceará via Fortaleza.

Coastal erosion is a factor that inhibits the instigation of new tourist accommodations at Tabuba Beach. Thus, one way to attract new tourist developments to Tabuba Beach would be to invest in coastal protection with environmental recovery. Currently, there are several seawalls installed along this beach, but they are ineffective in neutralizing the problem and in restoring the beach. In this case, government intervention would be important, as individual initiatives do not have the expected effect. In terms of recommendation, there could be an investment in actions with the conception building with nature (van den Hoek et al. 2012; de Vriend et al. 2015; Hoonhout and Vries 2017) – is a method, that to seek solutions that integrate environment and maritime infrastructure construction (e.g., Sand Motor Project).

CONCLUSIONS

The use of geoprocessing techniques is one of the main tools in environmental studies as well as necessary for territorial (re)ordering of coastal areas, especially in areas affected by the occurrence of erosion processes. The generation of data regarding the rates of erosion, stability, and progradation associated with the collection of information regarding the lodging facilities helped construct a framework that apprehended the performance of erosive processes on the hotel sector in Tabuba and Cumbuco.

The analysis conducted in this study indicates that the Caucaia coast has been progressively impacted by erosive processes in recent years. Of the 13.9 km of coastline analyzed—46.3% of the entire coastline—it was found that erosive trends are present in 26.8% of the coast of the analyzed coast; of these, 9% are erosion (–0.5 to -1 m/yr), 14.4% intense erosion (–3 to –1 m/yr), and 3.4% severe erosion (–5 to –3 m/yr).

The shoreline changes on the beaches of Tabuba and Cumbuco has produced antagonistic effects on coastal development, affecting beach businesses unevenly, as is the case with the hotel sector. The trends of progradation are verified mainly in Cumbuco Beach, presenting consequently better environmental quality in terms of area for conducting recreational activities.

The occurrence of erosion processes was more intense in Tabuba Beach, where the occurrence of coastal containment structures was identified to protect beach huts, evidencing the progress of erosion processes in the locality, generating direct impacts on the local economy. The spatial distribution of the lodging facilities indicates that Tabuba Beach do not constitute a location of interest aimed at mass tourism and, consequently, do not encourage the development of economic activities linked to this sector, in addition to the local devaluation due to erosive processes. In the locality of Cumbuco, where the beach is in a good state of conservation, there are several accommodation options, with the presence of resorts, generating commercial speculation that streamlines the local economy, expanding investments in trade, service, industry, and civil construction.

With that, it can be said that erosion processes tend to progress along Tabuba Beach, limiting the demand of this beach by investors in the accommodation sector. However, it is not evident in Cumbuco, where the real estate market is heated, and the demand for land construction of accommodation equipment is increasing, evidencing the best environmental quality of the place. Thus, it is necessary to apply measures aimed at the conservation and monitoring of coastal environments, which are essential for the municipality's economic development, especially for the tourist sector.

Finally, it is possible to confirm that coastal erosion directly affects the choice of location for installing a tourist accommodation. However, other variables of tourist attractiveness can also affect the location option for instituting a tourist accommodation. Thus, we suggest that other studies look at variables such as: distance of the coastal zone from the continental places of residence (cities) and urban infrastructure.

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