RESEARCH PAPER

ASSESSMENT OF TEMPORAL VARIABILITY IN THE LEVEL OF POPULATION VULNERABILITY TO NATURAL AND MAN-MADE HAZARDS (THE CASE OF MOSCOW DISTRICTS)

Roman A. Babkin[1], Svetlana V. Badina[1,2*], Alexander N. Bereznyatsky[1,3]
[1]Plekhanov Russian University of Economics, Stremyanny lane, 36, 117997, Moscow, Russia
[2]Lomonosov Moscow State University, Faculty of Geography, GSP-1, Leninskie Gory, 1, 119991, Moscow, Russia
[3]Central Economics and Mathematics Institute of the Russian Academy of Sciences, Nakhimovsky avenue, 47, 117418, Moscow, Russia
*Corresponding author: bad412@yandex.ru
Received: July 20th, 2022 / Accepted: November 11th, 2022 / Published: December 31st, 2022
https://DOI-10.24057/2071-9388-2022-116

ABSTRACT. The relevance of the study lies in the need for a scientific search for the possibilities of using new types of Big data in studies of the population vulnerability to solve practical problems of improving the safety of urban spaces from natural and man-made hazards. The object of the study is the administrative districts of Moscow; the subject is the temporal patterns of vulnerability of their population to potential natural and man-made hazards. The research question of the study is to develop a typology of Moscow districts and further assess this sustainability in terms of the population vulnerability to natural and man-made hazards. To achieve this research question, a set of tasks was solved: 1. Processing of the mobile operators' data array and further construction of a continuous graph of the Moscow population dynamics in 2019 (with a time cycle of 30 minutes, over 36 million measurements in more than 7 thousand time slices); 2. Empirical justification of natural temporal boundaries of daily, weekly, seasonal cycles of population dynamics in Moscow districts; 3. Justification of key factors and parameters of urban population vulnerability; 4. Development and approbation of the dynamic clustering method of Moscow districts using selected variables and periods. The study is based on the impersonal mobile operators' data on the locations of subscribers for 2019, provided by the Department of Information Technologies of the Moscow city. The method of dynamic cluster analysis is used. Four particular clusterings were obtained that characterize the "behavior" of the settlement system in the main intervals of social time (weekdays and weekends of the cold and warm seasons). Cluster stability matrix allows to identify which of the districts retain their properties during the period under review, and which are characterized by instability of considered indicators of population vulnerability. Depending on the stability of the position of the districts in a particular cluster, "stable", "conditionally stable" and "nomadic" types of districts were identified. The study showed that the first two types include spatial-settlement structures that are stable in time with approximately the same level of population vulnerability during the year, while the third type requires a special differentiated approach to the development of measures to protect the population from natural and man-made emergencies. Calculations have shown that "nomadic" type of districts concentrate on average from 2.2 million people in the summer season to 3 million people in the winter season, that is, a very significant share of the entire population of the capital.

KEYWORDS: mobile operators' data, vulnerability of the urban population, dynamic clustering, typology of urban districts, Moscow, intracity population mobility, social time, time-geography

CITATION: Babkin R. A., Badina S. V., Bereznyatsky A. N. (2022). Assessment Of Temporal Variability In The Level Of Population Vulnerability To Natural And Man-Made Hazards (The Case Of Moscow Districts). Geography, Environment, Sustainability, 4(15), 90-101
https://DOI-10.24057/2071-9388-2022-116

ACKNOWLEDGEMENTS: The research was funded by RFBR and Moscow city Government according to the project 21-35-70004.

Conflict of interests: The authors reported no potential conflict of interest.

INTRODUCTION

One of the key issues in field of monitoring and managing natural and man-made risks is the problem of a reliable population estimates at different time intervals and in different parts of the cities. For instance, in case of a major emergency in the affected area, there may be significantly more people than expected, based on official statistics. This can seriously complicate evacuation and rescue efforts, lead to an increase the number of victims and injured.

Modern Big Data technologies (in our case, mobile operators' data) make it possible to assess the location of people with high accuracy, including in the poly-time slices. The speed of public life and citizens mobility, which have greatly increased in recent decades, lead to significant fluctuations in the population size and a high degree of uncertainty in the state of urban settlement systems at a certain point in time. However, the movement of the population is subject to cyclic patterns: daily, weekly, and seasonal cycles (Makhrova et al 2022).

In this regard, in this study, it was carried out an attempt to structure a time series of indicators characterizing the present population of Moscow districts, to identify the natural boundaries of different time cycles. The key task of the study is to develop a typology of Moscow districts according to the degree of sustainability of their main population vulnerability characteristics (population density and mobility) in weekly and seasonal cycles. The least sustainable city districts require increased attention, flexible approaches in terms of developing preventive measures to protect the population from potential emergencies.

The selection of key elements of the temporal structure requires consideration of theories that study the cyclical nature of socio-economic processes. Initially, the theory of cycles appeared in economic science and was an attempt to explain the recurring changes in market conditions. The works of many outstanding economists are devoted to the study of multi-temporal market cycles: W. Sombart, N.D. Kondratiev, J. Schumpeter, K. Juglar, S. Kuznets, Yu.V. Yakovets et al (Kondratiev 2003). The issue of cyclicity came to economic geography through the economy, supplemented by social and spatial components. In particular, one can note numerous works on the identification of the urbanization stages by D. Gibbs, L. Klaassen, G. Scimeny, H. Geyer and T. Kontuli (Gibbs 1963; Klaassen and Scimeni 1981; Geyer and Kontuly 1993). One of the modern economic geographers who studies socio-economic cycles and integrates cycles theories with the ideas of T. Hegerstrand is V.L. Baburin (Baburin 2011).

Another direction in the research of cyclicity is the study of the settlement systems dynamics. Thus, pendulum labor migrations and daily population pulsations are the subjects of researches by modern Russian scientists – A.G. Makhrova, P.L. Kirillov, Yu.Yu. Shitova, A.N. Bochkarev et al. (Makhrova et al 2016; Makhrova and Babkin 2018).

Another important research area in the field of population dynamics is related to the study of seasonal changes under the influence of dacha-recreational and rotational migrations: A.G. Makhrova, L.B. Karachurina, P.L. Kirillov and D.Yu. Zemlyansky (Zemlyansky 2011; Makhrova and Kirillov 2015; Karachurina and Ivanova 2017). As an example of short cycles, one can mention weekly cycles, considered by T.G. Nefedova as a special case of "otkhodnichestvo" – "half- otkhodnichestvo-half-pendulum". This type of cycles is widespread in the Moscow oblast and neighboring regions (Nefedova 2015).

Natural and man-made emergencies are also subject to cyclic patterns. The superimposition of the ascending phases of some natural and socio-economic cycles can leads to an increase in damage scale. For instance, the researchers (Zhongrui et al 2003; Kaniewski, et al 2016; Knaub and Ignateva 2022) analyze the relationship between solar activity and the frequency and magnitude of various natural disasters. Studies on the relationship between climate cycles and natural disasters are singled out as a special group (Zhang et al 2010; Luque-Espinar et al 2017, Froude M.J. and Petley 2018). The study (Baida 2019) analyzes the influence of heliophysical and space cycles on hazardous man-made phenomena and processes.

It is important to note that the above works on the cyclicity of population movement are mainly based on imperfect official statistics data. On the contrary, in this study, the use of mobile operators' data made it possible to construct a continuous time series and move to a very large scale – to the level of urban districts, and, accordingly, to obtain the most reliable results.

Turning to the objectives of this study, it is necessary to dwell in more detail on the concept of "social time" and the problem of year periods stratification. Social time is time within the boundaries of social functions, different from standard physical time (Sorokin and Merton 1937). T. Hegerstrand associates it with pacemakers and defines it as time expressed in events, things or conditions (Hägerstrand 1973). The complexity and multicomponent nature of spatial population dynamics requires a systematic consideration of its structure (Fig.1).

In general, spatial dynamics can be divided into two groups: cyclic and non-cyclic. Cyclic dynamics is associated with the natural processes of the settlement system functioning and is subject to certain temporal rhythms. The shortest temporal type of cyclic rhythm is daily dynamics, which is mainly due to the pendulum labor and educational migrations. The longest type is seasonal dynamics, depending on the work-recreation cycle and the seasons change (natural-climatic factor). Between these cycles, there is an intermediate type – weekly dynamics, which is associated with the weekday-weekend cycle of life.

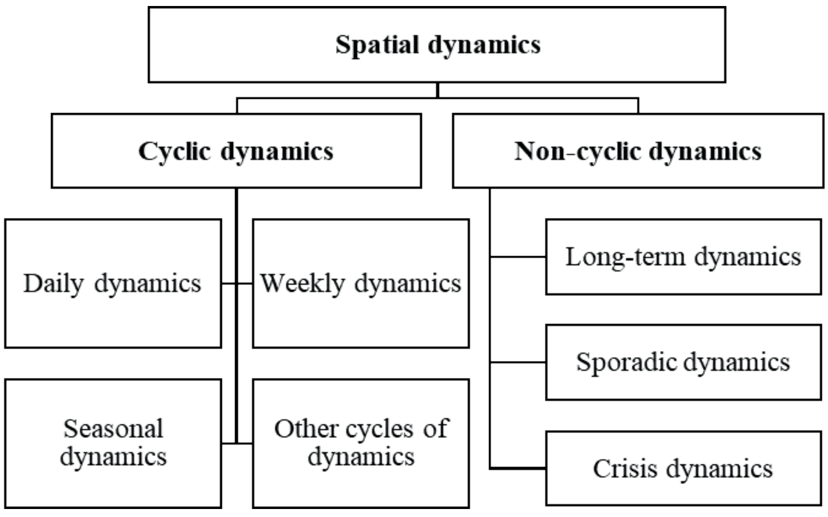

Fig. 1. Types of spatial population dynamics

Source: compiled by the authors

It is convenient to analyze all three cycles using the mobile operators' data, while they are correlated with the main attraction areas for people, which also provides convenience for spatial analysis. A simplified correlation of the pastime (and the corresponding functional zones of urban space) and social time intervals is shown in Table 1.

Thus, the easiest way to determine the presence of citizens at work (study) and at home, since the vast majority of citizens work (study) on a weekday in the cold season, and are at home on a weekday night in the cold season. Recreational activity is most typical for the weekends of the warm season. Finally, temporally distribution of leisure activities is wider, but more typical for weekends. In general, the cyclical movement of people within these four spheres of human activity forms the basis of the settlement spatial dynamics. Disparity in the location of residence places, centers of labor, leisure and recreational attraction is the main factor stimulating population migration and causing regular population fluctuations.

Expanding the spatio-temporal analysis, one can additionally single out places of concentration of dachas or second houses, the main centers of attraction during the various cultural and sports events, the peculiarities of people movement in emergencies, etc. Thus, each type of pulsation is determined by different types of population mobility, which, in turn, have different areas of attraction for commuters. These types can be associated with certain areas of human activity, which takes place in relevant intervals of social time.

The main idea of chronogeography is that the study of various types of people movements must be carried out with close integration of the spatial and temporal characteristics of the data. In this context, the chronogeographic concept and modern possibilities of "big data" open up wide opportunities for the active use of closely related pacemakers and spacemakers[1] in modern economic geography (Table 1).

In this regard, the empirical justification of the time boundaries of different day periods is the most important methodological task. These day periods, on the one hand, will be characterized by a certain structural stability at the selected time interval, and, on the other hand, will differ in different parts of the city (Ahas et al 2015). The typology of urban areas based on the cyclical features of the population distribution will make it possible to identify areas and periods of peak population concentration and, along with this, on the contrary, territories with reduced load.

Thus, the problem of optimizing the territorial structure of settlement can be solved in order to reduce the population vulnerability through specific measures. These include measures to deconcentrate the population, redistribute human flows by locating new places of work, housing, leisure and recreational infrastructure, public transport developing, etc. in areas with potential density increase in certain periods.

Table 1. Correlation between social and physical time

№	Social time element (pacemaker)	Approximate boundaries in terms of physical time	Spacemaker	Clarification
Daily level (daily cycles)				
1	Morning	06:00 a.m. - 12:00 p.m.	Transit from residence place to work place	The time of the beginning of the mass commuters movement from residence places towards work places
2	Day	12:00 p.m. - 06:00 p.m.	Work place	The time of maximum concentration of people in their work places
4	Evening	06:00 p.m. - 12:00 a.m.	Transit from work place to residence place, visits to "third places"	The time of the beginning of the mass commuters movement from work places towards residence places and visits to other places of leisure and consumption
3	Night	12:00 a.m. - 06:00 a.m.	Residence place	The time of maximum concentration of people in their homes
Weekly level (weekly cycles)				
5	Weekday	Monday – Friday	Residence place, work place	The period of the maximum volume of pendulum labor migrations
6	Weekend / holiday	Saturday –Sunday	Residence place, place of the second home / dacha	The period of the minimum volume of pendulum labor migrations
Yearly level (seasonal cycles)				
7	Cold / working / winter season	October – April	Residence place (main house)	The season characterized by the maximum people concentration in their main houses and least recreational mobility (dachas, holidays, etc.)
8	Warm / holiday / summer season	May – September	Place of the second home / dacha	The season characterized by the maximum people concentration in their second (suburban) houses and high recreational mobility (dachas, holidays, etc.)

Source: Orange Smile illustrated by authors, (2022)

[1]By analogy with "pacemakers", which are key time intervals, "spacemakers" are points or areas on which vital activity is attached in space (Petrov 1986)

MATERIALS AND METHODS

The study is based on the impersonal mobile operators' data on the location of subscribers for 2019, provided by the Department of Information Technologies of the city of Moscow. The data represent information about the location of mobile subscribers during the day (with a time fraction of 30 minutes, aggregated in 500 square meters cells), obtained as a result of measuring the location of a mobile phone relative to three cellular stations. The total amount of data involved is 2.5 terabytes (over 36 million measurements in more than 7 thousand time slices during the period from January 2019 to January 2020). Using the set of keys, the cells were linked to the corresponding territories of Moscow and the Moscow Oblast in the context of selected time intervals, reflecting the temporal dynamics in the daily, weekly and seasonal cycles.

The primary task of the study is the empirical substantiation of the natural boundaries of the seasons and intraday cyclicity. The patterns revealed during the construction a continuous series of pulsations of Moscow population during a full year (Fig. 2), made it possible to proceed to a segmented consideration of the year seasons. The pulsation series of the actual Moscow population in January 2019 – January 2020 allowed to see many local extremes within the weekday-weekend cycle (occurring on weekdays, when Moscow's population is higher than on weekends). A noticeable decline in the total population is visible for the May – August period, that is, the dachas-vacation season. In addition, deeper extremes are typical for May holidays, as well as the entire period of New Year's festivities (January 1–7). Another notable distortion of the pulsation series under the influence of events is also Moscow City Day (September 7–8), when the "pit" characteristic of weekends is significantly smoothed out due to the influx of visitors from neighboring regions, as well as Muscovites who remained in the city.

Large cities and urban agglomerations are areas of increased danger first of all due to the high concentration of the population (United Nations… 2019). The territory of Moscow is characterized by an increased likelihood of a wide range of emergencies, both natural and man-made. Additionally, there are higher risks of terrorist attacks. The key natural hazards on the city territory include dangerous hydrometeorological phenomena (Akimov et al 2009), hazardous engineering and geological processes and phenomena (including flooding) (Osipov et al 2011), smoke pollution of vast areas of the city due to massive forest and peat fires in neighboring regions etc. There are some key man-made hazards which should be especially highlighted among the others in the context of Moscow. They include man-made fires, accidents at electric power facilities, accidents at railway and road transport with the release of hazardous substances and the emergence of vast areas of fire, collapse of structural elements of buildings and structures of transport communications, etc.), the emergence of floods due to the potential destruction of water-limiting devices on Moskva river and adjacent water reservoirs. Particular attention should be paid to the dangers associated with potentially hazardous industrial facilities (explosive, chemical, radiation and fire hazardous), institutions working with pathogens of high pathogenicity (Badina et al 2022b).

Therefore, based on the scientific experience in the field of assessing the vulnerability of the urban population to natural and man-made hazards (for instance, (Cutter et al 2003; De Oliveira Mendes 2009; Flanagan et al 2011; Nelson et al 2015; Aksha et al. 2019; Spielman et al 2020; Siagian et al 2014; Ward and Shively 2017), as well as an analysis of the consequences of major natural disasters in Russia and in the world, it was determined that the potentially most vulnerable areas of urban space, other things being equal, are those where at the same time:

1. The population density is higher, because a high population concentration in big cities with their characteristic high building density and infrastructure limitations is a key factor in increasing the risk (Badina 2020; Baburin and Baldina 2021).

2. Variation from Rosstat data is higher, because in Russian practice, the organization of preventive measures to protect the

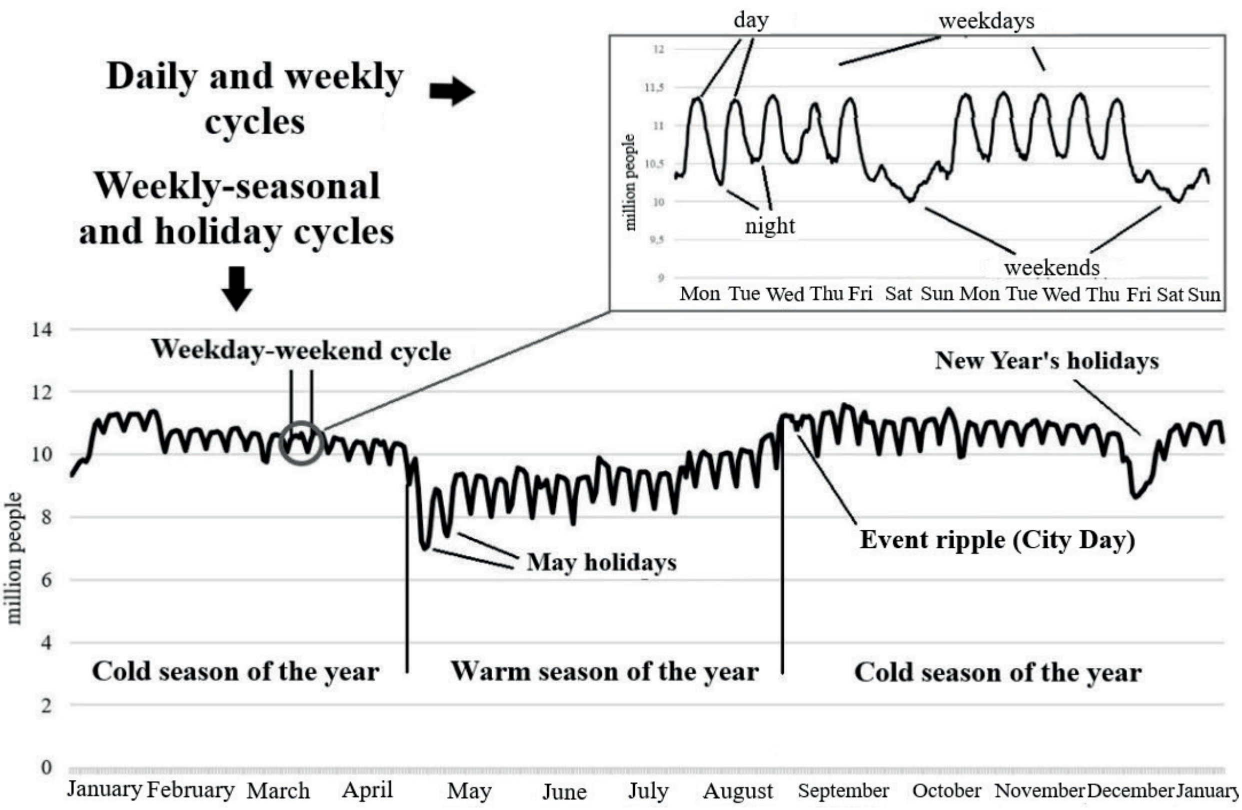

Fig. 2. The pulsation series of the present population of Moscow in January 2019 – January 2020

Source: compiled by the authors based on mobile operators' data population from emergencies and measures to eliminate the consequences (including population evacuation) are carried out based on official statistics, which, as shown by our previous studies (Badina and Babkin 2021), significantly differ from reality.

3. Dynamic component is higher, since the intensive population movement in the daily cycle on the urban territory increases the uncertainty.

In order to select parameters that could best numerically describe the above characteristics of population vulnerability, about 20 different indicators were calculated, as well as the correlations between them. As a result, for the purposes of Moscow districts typology, according to the degree of present population vulnerability, the following parameters were chosen:

1. Median present population density according to mobile operators' data (persons per sq. km).

2. The ratio of the population size of the district according to Rosstat to the median daily population size according to mobile operators' data (%);

3. General daily gradient (the ratio of the maximum present population size according to the mobile operators' data to the minimum (%)).

The cluster analysis method was used as a typology tool. A detailed description of the methodology and results of cluster analysis carried out on the selected key slice is shown in the previous authors work (Badina et al 2022a). In addition, in this study, an important indicator of the transit flows intensity was considered separately (it was not included directly in the cluster analysis, since it is related to the indicator "Median present population density").

Dynamic clustering will make it possible to identify the typological stability of Moscow districts: how stable is their position within a particular cluster in different phases of the weekly-seasonal cycle. It has great pragmatic importance, since the least sustainable city districts require increased attention, flexible approaches in terms of developing preventive measures to protect the population from potential emergencies.

Dynamic clustering is an iterative cluster analysis based on the three above variables and on four different time periods, each of which characterizes a certain segment of the weekly-seasonal cycles: weekdays of the cold season, weekends of the cold season, weekdays of the warm season and weekends of the warm season. As a result, four particular clusterings are obtained that characterize the "behavior" of the settlement system in the main intervals of social time. After that, a cluster stability matrix is compiled, which allows to identify which of the districts retain their properties, and which are characterized by instability of three considered indicators.

At the same time, the selection of "natural types" of districts is carried out. Depending on how strongly the connection with the "neighbors" is saved according to the initial classification, the stability of the districts with respect to temporal displacements is calculated. The more surviving pairs in each new clustering, the more stable the result.

RESULTS

Static clustering

Based on the study of the pulsation series, it was decided to consider the transitions of districts from group to group, depending on one or another phase of the weekly-seasonal cycle. Consideration of various clustering options is necessary due to the fact that three indicators included in the cluster model are changeable throughout the year and can contribute to the "drift" of the district from one cluster to another.

The most complex (in terms of the number of influencing factors) indicator is the ratio of population density according to Rosstat to the density according to mobile operators' data. In general, the least deviations are typical for the districts of the central business core of Moscow, and the highest deviations – for residential districts, and especially for districts of accelerated housing construction. At the same time, for the vast majority of districts, the maximum deviations are observed on weekends of the warm season, when many Muscovites go to their suburban homes and vacations.

The highest median population density is characteristic of both attractor districts (primarily the Central Administrative District, as well as such subcenter districts as Begovoy, Dorogomilovo, etc.), and some small residential districts. For Moscow districts, this parameter is almost everywhere higher on weekdays of the cold season. The most significant deviations of daily population density gradients are observed in the most attractive districts for business and daytime recreation. The most significant values of daily gradients (2 times or more) are observed in weekdays of both cold (to a greater extent) and warm (to a lesser extent) seasons due to a significant increase in the number of people in the daytime. These values are significantly lower for residential districts, as well as dacha-recreational districts, which, with a certain degree of conventionality, include some districts of New Moscow. The multi-temporal pattern of changes is reflected in various combinations of districts in clusters and, as a result, in the previously mentioned four clustering variants.

The "season" in terms of this study is the time when the pulsation regime and the general characteristics of present population change due to natural seasonality and the prevailing social cycles (Fig. 2). At the previous stage of the study, based on *static clustering* for the general statistical data set (for the whole year), a typology of Moscow districts was created, which reflects the main features of the population spatial dynamics in the context of its vulnerability (Badina et al 2022a). Characteristic names that most fully reflect the essence of each group were given to five selected clusters (Table 2).

Table 2. Characteristics of clusters

Cluster (type of municipalities)	Population density	Intensity of transit flows	Intraday population gradients	Level of official statistics' distortion
Center	very high	very high	very high	low at night, high during the daytime
Transit residential	high	high	average	low
High-density residential	high	average	average	low
Low-density residential	average	average	average	low
Low-density peripherals	low	low	low	high

Source: (Badina et al 2022a)

Dynamic clustering

The most potentially vulnerable districts located in clusters with the maximum values of all four considered indicators. Therefore, these include clusters "Center" and "Transit residential". *Dynamic clustering* made it possible to reveal that each considered time interval is characterized by its own pool of clusters. Therefore, analysis shows six clusters for the weekdays of the cold season: "center", "transit residential", "low-density peripherals", "low-density residential" and two clusters with the characteristics of "high-density residential" (Fig. 3a). For the weekends of the cold season, same as for weekdays, 6 clusters are also identified: "center", "transit residential", "low-density peripherals", "low-density residential" and two clusters with the characteristics of "high-density residential" (Fig. 3b).

Clusters of "Transit residential", "High-density residential" and "Low-density residential" correspond to residential areas of the city, which are characterized by a strong daily outflow of population. In addition, for these clusters official statistics somewhat exaggerate the size of the population. The key difference between the clusters are the population density and the position on the main flows of movement of citizens: the population density reaches the highest values in the clusters "Transit residential", "High-density residential", to which homogeneous arrays of residential buildings are confined. On the territory of most of the municipalities of the "Low-density residential" cluster large areas are occupied by non-residential zones – the territories of small enterprises (primarily communal ones), large parks and urban forests, objects of railway transport infrastructure. For these three clusters the real population density is almost always lower than the official one, therefore, the problem of population vulnerability is the least acute for them.

The cluster "Center", consisting of a group of districts forming the business core of Moscow and concentrating the largest number of transport hubs, are characterized by high values of all considered indicators. They are distinguished by the highest density of the daily population and accordingly the highest intraday gradient of change in the daily population density (in the cluster "Center" these values are higher). Huge flows of people in the morning, afternoon and evening hours greatly increase the potential vulnerability of these territories and require especially close attention. In addition, there are still a number of potentially dangerous industrial enterprises on the territory of these clusters, as well as a number of potentially dangerous research institutes.

A separate category is represented by the areas included in the cluster "Low-density peripherals". This cluster has the lowest intraday population density and the lowest density gradient. This cluster includes many municipalities on the territory of which a large area is occupied by forests and other undeveloped territories – in particular, the municipalities of New Moscow. These are areas of new development, characterized by a low population density (due to the large areas of the districts). However, despite the small overall density, the population concentration here in some areas is very high. In addition, these areas are characterized by the greatest underestimation of real population density and population density by official statistics (2-3 times)[1].

A larger number (8) of clusters is formed in the case of weekdays during the warm season: "transit residential", "low-density peripherals", two clusters each with the characteristics of "center", "low-density residential", and "high-density residential" (Fig. 4a). On the contrary, for the weekends of the warm season, clustering showed only four groups: a highly compressed "center", "low-density peripherals", "low-density residential" and "high-density residential". This period is characterized by low transit, so the cluster of "transit residential" was not formed (Fig. 4b). In the warm season citywide mobility decreases which leads to the "migration" of districts from the most mobile to the more inert clusters (from the cluster "Center (var. 1)" to "Center (var. 2)" ("Subcenter" type) from "Transit residential" to "High-density residential", etc.).

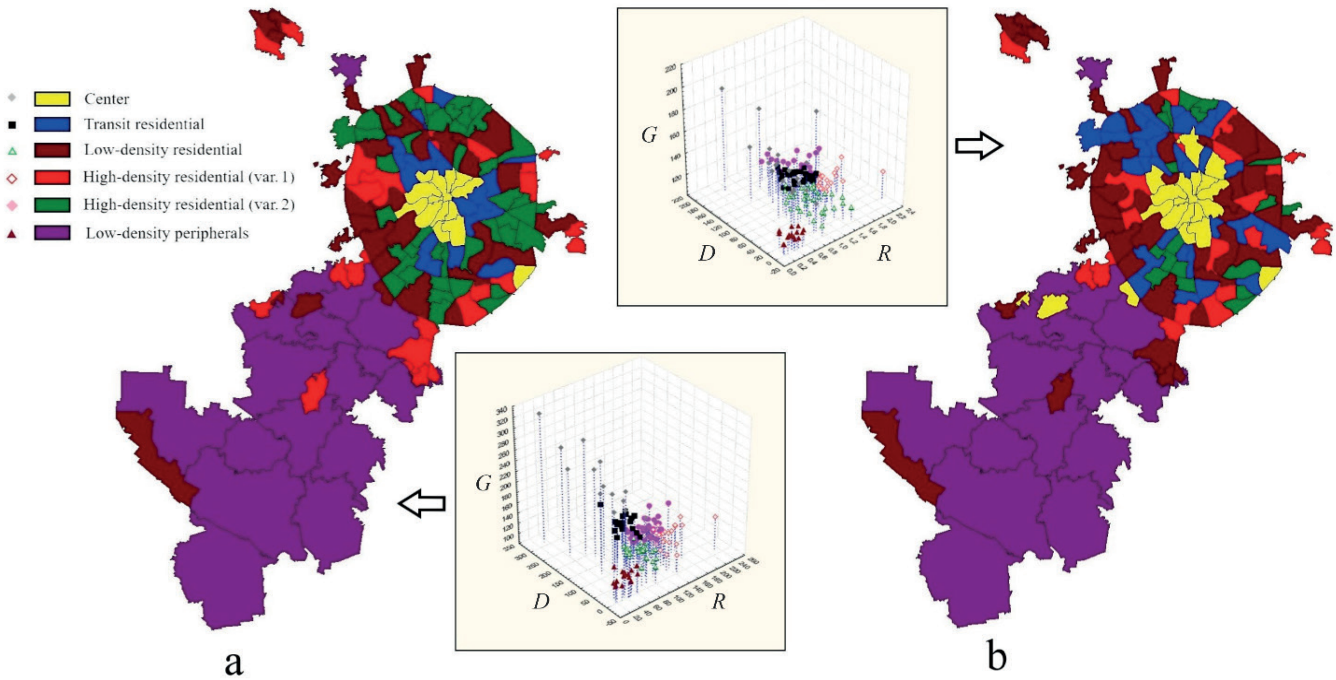

Fig. 3. Clustering for the cold season (a – weekdays, b – weekends). G – total daily gradient, %; D – median population density, people per sq. km; R – the ratio of Rosstat to the median, %

Source: compiled by the authors based on mobile operators' data

[1] As a result of active housing construction and rapid population growth, Rosstat does not have time to track real population changes of these territories providing information with a significant time lag.

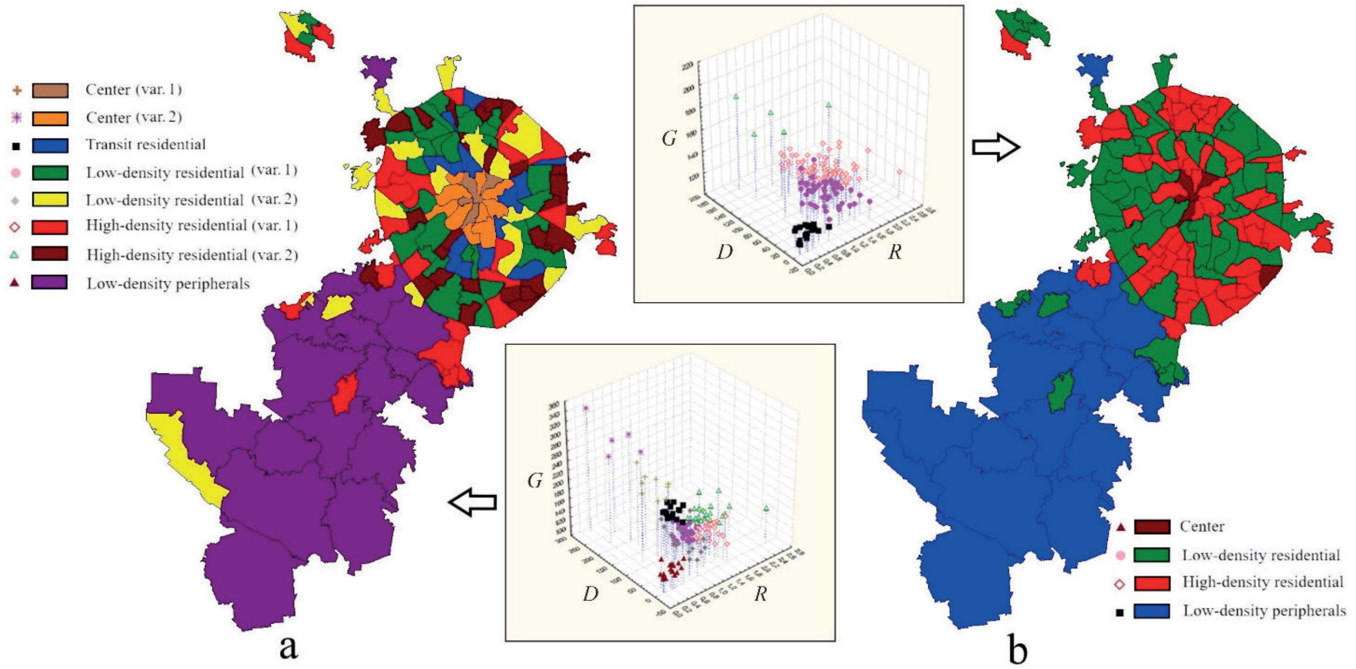

Fig. 4. Clustering for the warm season (a – weekdays, b – weekends). G – total daily gradient, %; D – median population density, people per sq. km; R – the ratio of Rosstat to the median, %

Source: compiled by the authors based on mobile operators' data

Thus, in the territorial aspect, the group of central districts and districts of New Moscow is especially pronounced. The rest of the districts more "wander" between clusters and, accordingly, they are less typologically stable.

The resulting four classifications clearly demonstrate the transformations of the Moscow settlement system in the weekly-seasonal cycle of social time. Daily cycles are also embedded in the clustering parameters.

According to the results of particular clussification, information about the affiliation of city districts to a particular cluster in different time intervals was processed and a cluster stability matrix D was compiled (Fig. 5). Matrix D is used to analyze the stability of clusters for various time intervals.

For each classification k=1...4, $D_k=[d_{ij}]$, where d_{ij}=1, if a pair of Moscow districts ij belongs to the same cluster, 0 – otherwise, if $i=j$ matrix value is missing (district is paired with itself). D_k matrices are aggregated into one:

$$D = \sum_{k=1}^{4} D_k$$

The maximum value of the matrix D elements is 4. It means that a pair of districts in all four classifications is

	A	B	C	D	E	F	G	H	I
1	Moscow district	Bogorodskoe	Veshnyaki	Vostochnoye Izmaylovo	Vostochny	Golyanovo	Ivanovskoe	Izmailovo	Kosino-Ukhtomsky
2	Bogorodskoe		1	3	3	1	1	0	0
3	Veshnyaki	1		0	0	4	2	2	2
4	Vostochnoye Izmaylovo	3	0		4	0	2	0	0
5	Vostochny	3	0	4		0	2	0	0
6	Golyanovo	1	4	0	0		2	2	2
7	Ivanovskoe	1	2	2	2	2		2	2
8	Izmailovo	0	2	0	0	2	2		3
9	Kosino-Ukhtomsky	0	2	0	0	2	2	3	
10	Novogireevo	1	1	2	2	1	1	0	0
11	Novokosino	1	1	2	2	1	1	0	0
12	Metrogorodok	0	2	0	0	2	2	3	4
13	Perovo	2	1	2	2	1	0	1	0
14	Severnoye Izmaylovo	1	0	1	1	0	0	0	0
15	Sokolinaya gora	0	2	0	0	2	2	2	2
16	Sokolniki	0	1	0	0	1	1	2	3
17	Preobrazhenskoe	1	1	2	2	1	1	0	0
18	Vnukovo	0	1	0	0	1	1	2	3
19	Dorogomilovo	0	1	0	0	1	1	1	1
20	Krylatskoe	2	3	1	1	3	3	2	2
21	Kuntsevo	0	2	0	0	2	2	3	4
22	Mozhaisky	1	3	0	0	3	2	3	3
23	Novo-Peredelkino	3	0	4	4	0	2	0	0
24	Ochakovo-Matveevskoe	0	2	0	0	2	2	4	3
25	Prospekt Vernadskogo	1	1	1	1	1	0	1	0

Fig. 5. Extract from the aggregate matrix D of pairwise connections

Source: compiled by the authors

in the same cluster. The minimum value is 0 (the pair of districts does not belong to the same cluster in any of the classifications).

If at each new time slice the districts keep their connection with their "neighbors" according to the initial[1] classification, then the result of clustering is considered stable regarding time shifts.

The more surviving pairs in each new clustering, the more stable the result. For each Moscow district, the number of all possible pairs with other districts that fall into one cluster in each classification is summed up. From the point of view of the matrix *D* elements, this operation is formalized in the form of counting the number of value matches (fours, triples, twos and ones) for each district – row. The ratio of counted pairs in one cluster at each time slice to the initial value (of the first clustering) forms a stability metric ρ, $0 \le \rho \le 1$. The higher this value for each district, the more stable its position in the cluster. Accordingly, if this value falls sharply with each new classification, then the district "migrates" between different clusters and the result is unstable. Below is a graphical demonstration of the calculated metrics (Fig. 6). For instance, for one of the districts at the initial classification, 12 pairs of districts were obtained that are in the same class with it. At the next stage, the number of districts pairs of 12 previously considered was reduced to 8. The value of the metric ρ in this case will be $8/12 \approx 0.7$. If the number of obtained pairs is 12, then we get the maximum value of the metric ρ equal to 1.

As can be seen from the graphs, at each new stage of clustering (for a different time slice), the number of surviving pairs decreases. At the same time, in all cases, a set of districts with maximum values of metrics close to one is clearly pronounced. This cluster is the most stable and includes the districts of New Moscow. Such a stable result obtained for New Moscow districts suggests that, despite being included in the administrative-territorial division of Moscow, these districts continue to function as part of the Moscow Oblast in terms of population movement. Thus, the space of Moscow breaks up, in fact, into two cities with different modes of operation.

Classification of districts according to the degree of stability of their position in clusters

Therefore, in order to understand which districts change or retain their affiliation with a particular cluster on weekly and seasonal rhythms, the transitions of districts from one cluster to another within four selected time ranges were analyzed. As a result, three types of districts were identified. Each type includes 11 subtypes (Fig. 7).

1. The first group of municipalities was formed by the "Stable Districts". They do not change their position in the four variants of clustering.

1.1. The subtype "Peripheral" represents the largest and most solid array of districts that are included in the "Low-Density Peripheral" cluster type. All these districts, with the exception of Molzhaninovsky, are located on the territory of New Moscow.

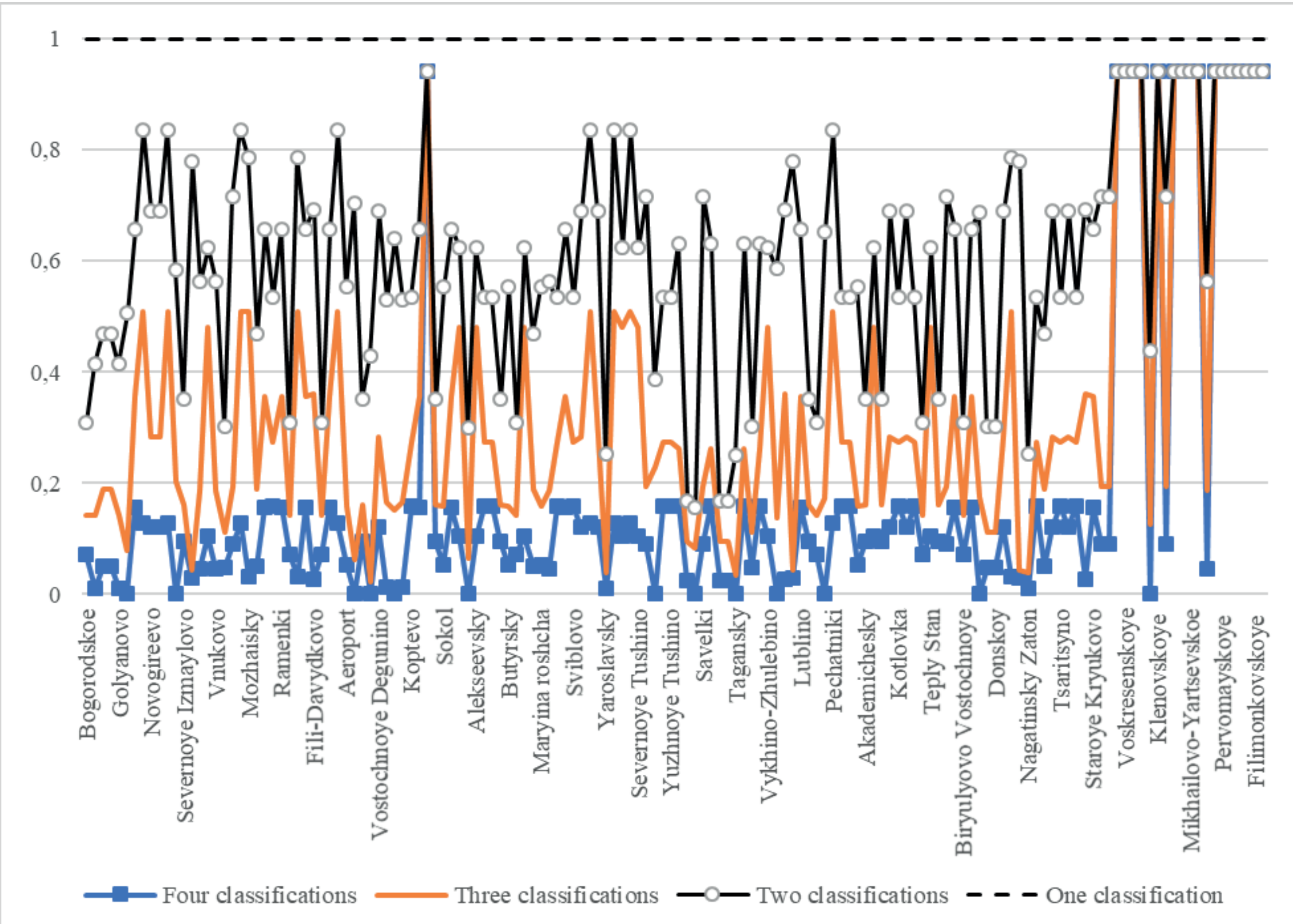

Fig. 6. The value of the stability metric for various clustering options (the case of Moscow districts)

Source: compiled by the authors

[1] "Initial" means the first classification that was made. For instance, firstly, we classify districts for weekdays cold season and it would be initial point for stability analysis. But the first classification could be for weekends warm season and so on. The stability analysis methodology does not depend on which classification comes first.

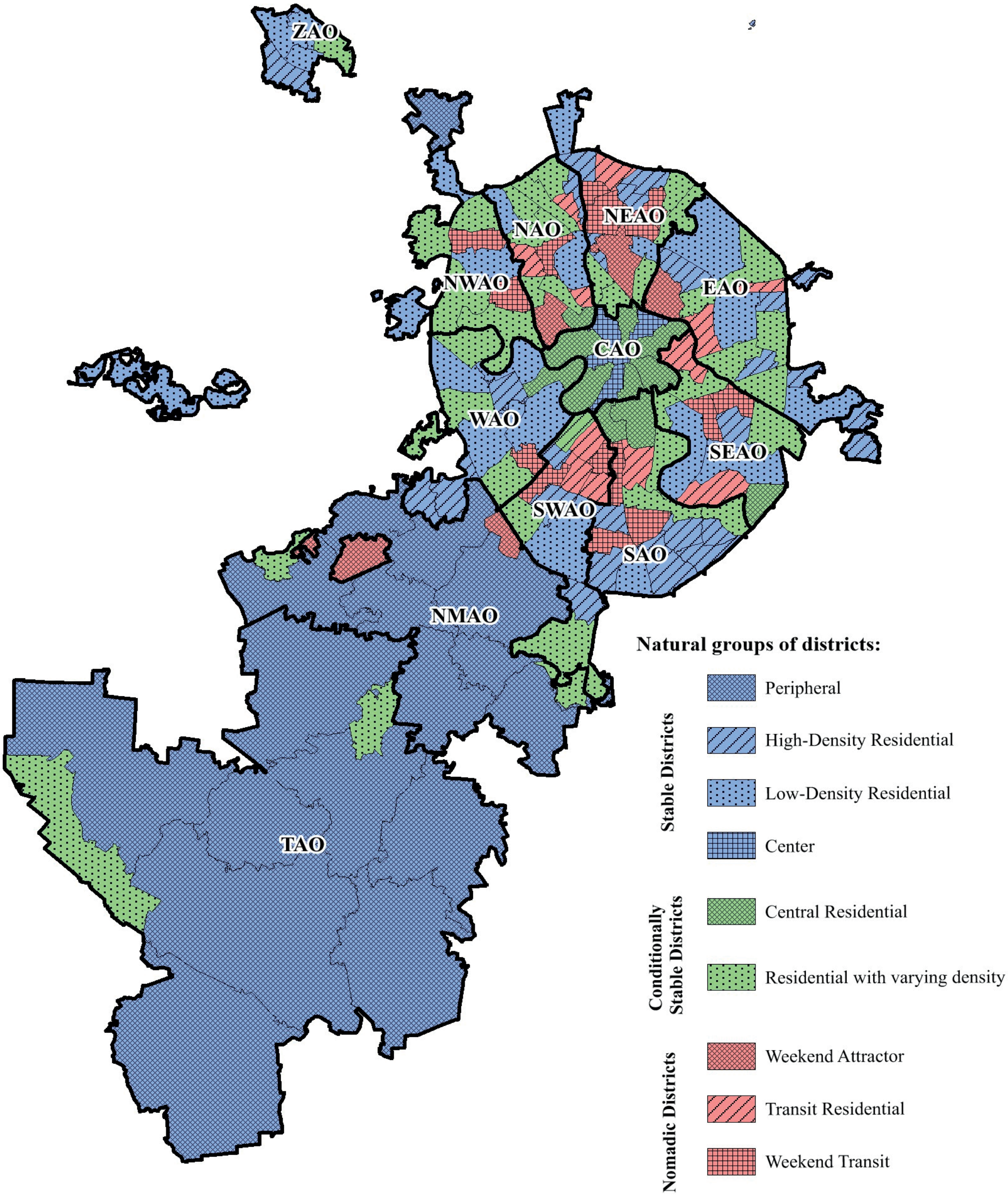

Fig. 7. Natural groupings of districts

Source: compiled by the authors

1.2 and 1.3. The subtypes "High-Density Residential" and "Low-Density Residential" includes scattered sleeping districts[1] of Moscow belonging to the eponymous cluster types.

1.4. The subtype "Center" includes four districts of the center (Arbat, Krasnoselsky, Tverskoy, Yakimanka) distinguished by a stable position in the "Center" cluster.

2. The second group of municipalities consists of "Conditionally Stable Districts", which can slightly change their position depending on the clustering time slice.

2.1. The subtype "Central Residential". This type includes several municipalities of the Moscow center, which, being powerful business attractors, also have a significant housing stock. As a result, in one of the time slices for such districts, the cluster type changes to the "sleeping" one. In most cases, this is the weekend of the warm season.

2.2. The subtype "Residential with varying density" include sleeping areas moving from "Low-Density Residential" to "High-Density Residential" within the week-seasonal cycles.

3. Finally, the third type, which requires special attention, is represented by "Nomadic Districts", which change their cluster type 2 or even 3 times depending on the time slice.

[1] "sleeping districts" or "commuter town" – a residential area of a city (usually in large metropolitan areas or their suburbs), whose residents daily commute to work in the business or industrial center and return home to spend the night

3.1. The subtype "Weekend Attractor" consist a group of districts located close to the city center. These districts moved to the "Center" cluster on the cold season weekends. Characteristic representatives of this type are the Sokolniki and Ostankinsky districts.

3.2. The subtype "Transit Residential" – sleeping districts on weekdays, becoming transit districts for commuting flows to / from the business center.

3.3. The subtype "Weekend Transit" is a group of sleeping districts on weekends moving into the "Transit Residential" cluster. First, these are districts with large transport hubs on their territory, for instance, Tsaritsyno or Shchukino.

The proposed method allows in two iterations (clusterization and identification of natural groups) to carry out a typology of urban districts in order to form approaches to the organization of preventive measures to protect the population from emergencies. The use of the cluster approach in four social time slices makes it possible to consider the stability of the spatial structure of settlement within the framework of weekly-seasonal cycles, and, accordingly, in terms of changes in their vulnerability. Most of the city's districts have a stable position at various time slices in the clustering. Some of them change slightly, for instance, they move from "Low-Density Residential" to "High-Density Residential" types. Finally, about 30 districts are distinguished by transitions between different types depending on the day of the week or the season. These most "unsustainable" or "nomadic" districts due to high uncertainty and the need to use different methods of regulating and controlling human flows will require local-targeted approaches to risk management. In subsequent works, the authors also plan to pay detailed attention to each type of districts, place them in the context of the likelihood of natural and man-made hazards.

DISCUSSION

The application of the dynamic clustering method and the subsequent typology of Moscow districts makes it possible to determine the rank of the vulnerability of various city parts to external shocks. At the same time, it should be noted that this approach, based on dynamic characteristics, does not take into account many other important components of the population vulnerability, such as age-sex composition, income differences, the proportion of youngest children and people with disabilities, people with limited mobility, etc.

Therefore, due to the objective limitations of the data used (problems of the non-personalized nature of data, underestimation of SIM cards of switched off devices, technical interference associated, for instance, with overlapping of signals from neighboring repeaters etc.), as well as the impossibility of taking into account the above significant characteristics of the population vulnerability, the author's approach cannot claim to be universal.

However, in the authors' opinion, despite all the weakness consideration of Moscow districts through the prism of the chronogeographic approach will allow the use of local-targeted approaches to minimizing the emergency consequences for present population. In this logic, the developed typology of Moscow districts in terms of the degree of stability of their main population vulnerability characteristics in weekly and seasonal cycles is the first step towards a more detailed study of natural and man-made risks.

This typology can be used for a wide range of practical tasks, as it well reflects the inequality of social time for different parts of the city. In particular, knowledge about the typological stability of Moscow districts in weekly and seasonal cycles makes it possible to apply appropriate mechanisms to each type in the field of protecting the population from natural and man-made hazards. Depending on the position of the district in the typology, it is proposed to use various methods of regulating and controlling human flows, focusing on individual districts, time slices and cycles that are important for a particular type.

The authors see a promising direction in the development and testing of methods that make it possible to analyze the connection between functional zones in urban space and social time using mobile operators' data. Thus, the temporal and spatial aspects will be best integrated and mutually supplemented, which will allow in the future to obtain the most reliable picture of reality, to identify key patterns.

CONCLUSIONS

The revolution of the last two decades in the field of production and processing of spatiotemporal information has led to a renaissance of chronogeography, which faced insurmountable technological challenges in data collection in the 1980s. Mobile operators' data on a new information and resource basis allow us to continue the traditions of spatio-temporal analysis, which was carrying out by the Institute of Geography of the Academy of Sciences more than 30 years ago.

As the current international and domestic experience shows, Big data and, in particular, mobile operators' data have a great importance for geographical research. This is a very promising and representative tool that can improve the quality of research in many areas. Overcoming technological barriers in obtaining and processing information about the population movement in "real time" mode using mobile operators' data allows in practice to carry out a detailed spatio-temporal analysis of the dynamic characteristics of large city population, which is clearly demonstrated in this article.

Of particular interest is the prospective use of mobile operators' data in the field of assessing and forecasting natural and man-made risks. In this article, to solve the applied problem of assessing the vulnerability of urban areas to potential threats, using the case of Moscow, the authors tried to synthesize three topical elements of modern geographical research – spatiotemporal analysis, Big data and emergency risk assessment. The broad interdisciplinary field of risk research can become a platform for a new era of integration of physical and socio-economic geography.

REFERENCES

Ahas R., Aasa A., Yuan Y., Raubal M., Smoreda Z., Liu Y., Ziemlicki C., Tiru M., Zook M. (2015). Everyday Space–Time Geographies: Using Mobile Phone-Based Sensor Data to Monitor Urban Activity in Harbin, Paris, and Tallinn. International Journal of Geographical Information Science, 29(11), 2017-2039.

Akimov V.A., Durnev R.A., Sokolov Y.I. (2009). Dangerous hydrometeorological phenomena on the territory of Russia. Moscow: FGU VNII GOChS (FC) (in Russian).

Aksha S.K., Juran L., Resler L.M., Zhang Y. (2019). An analysis of social vulnerability to natural hazards in Nepal using a modified social vulnerability index. International Journal of Disaster Risk Science, 10(1), 103-116.

Baburin V.L. (2011). Two-dimensional model of the territorial organization of society. Vestnik Moskovskogo Universiteta, Seriya 5: Geografiya, 1, 3-8 (in Russian).

Baburin V.L. and Baldina S.V. (2021). Forecasting of socio-economic damages from hazardous natural processes for the tourist cluster Resorts of the North Caucasus. Vestnik Moskovskogo Universiteta, Seriya 5: Geografiya, 2, 25-35 (in Russian).

Badina S.V. (2020). Prediction of socioeconomic risks in the cryolithic zone of the Russian Arctic in the context of upcoming climate changes. Studies on Russian Economic Development, 31(4), 396-403.

Badina S.V. and Babkin R.A. (2021). Assessment of Moscow population vulnerability to natural and technogenic hazards. InterCarto. InterGIS, 27(4), 184-201 (in Russian).

Badina S., Babkin R., Bereznyatsky A., Bobrovskiy R. (2022a). Spatial aspects of urban population vulnerability to natural and man-made hazards. City and Environment Interactions, 15, 100082.

Badina S., Babkin R., Mikhaylov A. (2022b). Approaches to assessing the vulnerability of large city population to natural and man-made hazards using mobile operators data (case study of moscow, russia). In: Wohlgemuth V., Naumann S., Behrens G., Arndt HK. (eds) Advances and New Trends in Environmental Informatics. ENVIROINFO 2021. Springer Cham, 171-186.

Baida S.E. (2019). Wave cycles of natural, human-made and social catastrophes. Civil Security Technology, vol. 16, No. 4 (62), 30–-36 (in Russian).

Cutter S.L., Boruff B.J., Shirley W.L. (2003). Social vulnerability to environmental hazards. Social science quarterly, 84(2), 242-261.

De Oliveira Mendes J.M. (2009). Social vulnerability indexes as planning tools: beyond the preparedness paradigm. Journal of Risk Research, 12(1), 43-58.

Flanagan B.E., Gregory E.W., Hallisey E.J., Heitgerd J.L., Lewis B. (2011). A social vulnerability index for disaster management. Journal of homeland security and emergency management, 8(1), article 3.

Froude M.J. and Petley D.N. (2018). Global fatal landslide occurrence from 2004 to 2016. Natural Hazards and Earth System Sciences, 18(8), 2161-2181.

Geyer H.S. and Kontuly T.A (1993). Theoretical foundation of the concept of differential urbanization. International Regional Science Review, 15(2), 157-177.

Gibbs J. (1963). The evolution of population concentration. Economic Geography, 2, 119-129.

Hägerstrand T. (1973). The domain of human geography. In: Chorley R.J. (ed.) Directions in Geography. London: Methuen.

Kaniewski D., Marriner N., Morhange C., Faivre S., Otto T., Van Campo E. (2016). Solar pacing of storm surges, coastal flooding and agricultural losses in the Central Mediterranean. Scientific reports, 6(1), 1-12.

Karachurina L.B. and Ivanova K.A. (2017). Migration of the elderly in Russia (according to the 2010 census). Regional studies, 3(57), 51-60 (in Russian).

Klaassen L.H. and Scimeni G. (1981). Theoretical issues in urban dynamics. In: L.H. Klaassen, W.T.M. Molle and J.H.P. Paelinck (ed.). Dynamics of Urban Development. Aldershot: Gower.

Knaub R.V., Ignateva A.V. (2022). The General Mechanism of the Origin of Natural Disasters in the Global Dimension. IOP Conference Series: Earth and Environmental Science, 988(2), 022068.

Kondratiev N.D. (2003). Large cycles of conjuncture and the theory of foreseeing. Selected Works. Voprosy Ekonomiki, 8, 153-154 (in Russian).

Luque-Espinar J.A., Mateos R.M., García-Moreno I., Pardo-Igúzquiza E., Herrera, G. (2017). Spectral analysis of climate cycles to predict rainfall induced landslides in the western Mediterranean (Majorca, Spain). Natural Hazards, 89(3), 985-1007.

Makhrova A.G. and Babkin R.A. (2018). Analysis of pulsations of the settlement system of the Moscow agglomeration with the use of cellular operator data. Regional studies, 2, (60), 68-78 (in Russian).

Makhrova A.G., Babkin R.A., Kirillov P.L., Starikova A.V., and Sheludkov A.V. (2022). Temporary mobility and population pulsations in space of post-Soviet Russia. Regional Research of Russia, 12(1), 36-60.

Makhrova A.G., Kirillov P.L. (2015). Seasonal pulsation of settlement in the Moscow agglomeration under the influence of dacha and labor pendulum migration: approaches to the study and assessment. Regional studies, 1(47), 117-125 (in Russian).

Makhrova A.G., Kirillov P.L., Bochkarev A.N. (2016). Pendulum labor migrations of the population in the Moscow agglomeration: experience of flow estimates using data from cellular operators. Regional studies, 3(53), 71-82 (in Russian).

Nefedova T.G. (2015). Seasonal work in the system migrations in post-Soviet Russia. Prerequisites. Demoscope Weekly, [online] Available at: http://demoscope.ru/weekly/2015/0641/demoscope641.pdf [Accessed 20 Apr. 2022] (in Russian).

Nelson K.S., Abkowitz M.D., Camp J.V. (2015). A method for creating high resolution maps of social vulnerability in the context of environmental hazards. Applied Geography, 63, 89-100.

Osipov V.I., Burova V.N., Zaikanov V.G. et al. (2011). Map of large-scale (detailed) engineeringgeological zoning of the territory of Moscow. Geoecology, 4, 306-318. (in Russian).

Petrov N.V. (1986). Spatial and temporal analysis in social geography: Main achievements and directions of research. Swedish. shk. [T. Hegerstrand]. Moscow: VINITI (in Russian).

Siagian T.H., Purhadi P., Suhartono S., Ritonga H. (2014). Social vulnerability to natural hazards in Indonesia: driving factors and policy implications. Natural hazards, 70(2), 1603-1617.

Sorokin P.A. and Merton R.K. (1937). Social Time: a methodological and functional analysis. The American Journal of Sociology, 42(5), 615-629.

Spielman S.E., Tuccillo J., Folch D.C., Schweikert A., Davies R., Wood N., Tate E. (2020). Evaluating social vulnerability indicators: criteria and their application to the Social Vulnerability Index. Natural Hazards, 100(1), 417-436.

United Nations, Department of Economic and Social Affairs, Population Division (2019). World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420). New York: United Nations.

Ward P.S. and Shively G.E. (2017). Disaster risk, social vulnerability, and economic development. Disasters, 41(2), 324-351.

Zemlyansky D.Y. (2011). An indicative approach to assessing the seasonal dynamics of population placement in Russia. Regional studies, 3, 83-92 (in Russian).

Zhang, Z., Tian, H., Cazelles, B., Kausrud, K. L., Bräuning, A., Guo, F., Stenseth, N. C. (2010). Periodic climate cooling enhanced natural disasters and wars in China during AD 10–1900. Proceedings of the Royal Society B: Biological Sciences, 277(1701), 3745-3753.

Zhongrui W., Feng S., Maocang T.A. (2003). Relationship between solar activity and frequency of natural disasters in China. Advances in Atmospheric Sciences, 20 (6), 934-939.