RESEARCH PAPER

SATELLITE IMAGES INTERPRETATION FOR HEALTH STUDIES OF URBAN AREAS

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ABSTRACT. Every year a variety of vector-borne infectious diseases claims the lives of millions of people worldwide. The study of the favorable conditions for their vectors and hosts is a particularly important task for understanding the patterns of the distribution with the focus on the urban environment, characterizing by a high population density and rapid transmission of the diseases. The existing methodology of Local Climate Zones (LCZ), which are areas with homogeneous land surface coverage, structure, and a specific nature of human activity was the first attempt to standardize urban environmental studies and has become an international standard for the analysis of urban morphology. The article provides an algorithm for adapting the methodology of identifying LCZ accounting vegetation and water areas for the tasks of medical geographical zoning and assessment of epidemiological risks and using the geographic information technology. The examples of the outbreaks of vivax malaria in the Moscow region in 1999–2003 and West Nile fever in the Volgograd region in 2010–2011 were used. As a result, a methodology of medical geographical zoning based on the idea of fragmenting the classification of LCZ using the normalized difference water index as indicator of the favorability for vector habitats was developed. The use of the methodology made it possible to reveal that the areas of various LCZs change after outbreaks, which may reflect changes in conditions and an increase in the favorability for vectors. Thus, LCZ can be used as indicators of changes in the natural and man-made environment that can provoke disease outbreaks.

KEYWORDS: satellite image interpretation, local climate zones, medical-geographical zoning, infectious diseases, medical geography, risk analysis, West Nile fever, malaria, geoinformation technologies

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INTRODUCTION

Infectious diseases have always played an important role in human health and society. Due to the observed climate change, the analysis of the distribution of vector-borne diseases is becoming increasingly relevant. These are diseases, the causative agents of which are transmitted through various arthropod vectors, thus, are directly dependent on climate conditions. Climate and weather conditions are direct abiotic factors affecting the ability of vectors to acquire, maintain, and transmit a pathogen. Geoinformation technologies (GIS) have greatly expanded the possibilities of medical geography in identifying the geographical factors of diseases, modeling their distribution, and predicting the development of epidemics. However, the distribution of vector-borne diseases outbreaks in urban settings have not been studied well (Eder et al. 2018).

Today, most of the world's population is concentrated in cities, and urban and suburban areas become the main object of study. Despite the great favorability of rural areas for the development of vectors, urban areas are particularly susceptible to outbreaks of vector-borne diseases today (Roehrig 2013; Misslin et al. 2016). Rapid urban growth, migration flows (often uncontrolled) and the formation of specific climate conditions lead to the emergence of vector-borne diseases. The example is the distribution of Dengue fever in American regions in 2019, when densely populated areas of large cities close to water bodies were at most risk (Dengue and severe dengue… 2022). While climate and weather conditions have well-documented effects on infectious diseases, urban environment could significantly enhance the influence.

The study of urban climate resulted in the concept of local climate zones (LCZ) (Stewart and Oke 2012), fundamentally different from each other on a number of parameters. They represent various types of buildings and of natural surface cover. The idea of the LCZ has become the international standard for the study of urban morphology and its impact on urban climate. However, a more thorough elaboration of the vegetation and water bodies in the allocated zones is required for the purposes of medical geography. The focus should be on vegetation cover and water areas which play a particularly important role as a favorable environment for the life cycle of the arthropod vectors.

A number of works that propose the use of LCZ theory to study the distribution of vector-borne diseases in cities have been published. All of them are based on a comprehensive analysis and identification of factors that influence the distribution of vectors. For example, studies on cities in sub-Saharan Africa (Brousse et al. 2019; Brousse et al. 2020) evaluated the possibility of using LCZ to determine the climate characteristics of urban areas and to study the risks of malaria. In (Tourre et al. 2008), the dependence of the normalized difference vegetation index (NDVI) on precipitation, temperature regime and its relation to the epidemiological situation was studied. Brousse et al. 2020 attempted to model the risks of adverse epidemiological conditions with the further possibility of applying such a model to any city in the world.

Thus, outbreaks of vector-borne diseases in cities necessitated clarifying the LCZ to assess the suitability of urban and suburban conditions for vectors. Previously, we conducted medical and geographic studies of two outbreaks of vector-borne diseases (malaria and West Nile fever) in Russia (Mironova et al. 2020; Shartova et al. 2022). During these studies, the problem of accounting the structure of the land cover of urban and suburban areas arose, which would satisfy the necessary requirements in detail and the set of indicators essential for the life cycle of vectors. This article presents a methodology for adapting the LCZ theory in the context of differentiation of vegetation and water areas under the tasks of medical geographical zoning using GIS on the example of temperate cities.

Study areas

The choice of regions for study was based on the sites of West Nile outbreaks in Volgograd region in 2010–2011 and vivax malaria in the Moscow region in 1999–2003 (Mironova et al. 2020; Shartova et al. 2022). The common feature of West Nile fever and malaria is transmission of pathogens to humans through mosquito bites (mainly, the genus Culex for West Nile virus and the genus *Anopheles* for the malaria pathogen *Plasmodium vivax*).

Outbreaks of West Nile fever in Russia are primarily confined to wetlands in the Volga Delta and floodplain areas (Adishcheva et al. 2016). A number of factors contribute to the focus on the Volgograd region. One of the reasons is the presence of a large ornithological node in the north of the region, since the hosts of the West Nile virus in nature are birds of the wetland complex. Another factor is a large number of small lakes, shallow channels, and wetlands in the floodplain of the Volga River, which are favorable for breeding of mosquitos. The warm southern climate also contributes to the life stages of vectors and replication of the virus in mosquitoes (Lvov et al. 2004).

The outbreak of vivax malaria in the Moscow region was largely contributed by the manifestation of urban heat island, which significantly increases the air temperature in the city, which, in turn, affects the intensification of development of the pathogen in mosquitoes (Mironova et al. 2019; Varentsov et al. 2019). The western part of the region was chosen, since in the previous study (Mironova et al. 2020) we found that the spatial distribution of infection was shifted to the west of the Moscow region. Fig. 1 shows the boundaries of the study areas.

Fig. 1. Study areas: western part of Moscow and its suburbs (northern red square); Volgograd and its suburbs (southern red square)

Local climate zones: the main provisions and allocation techniques

Urbanization over the past half century has not only changed the physical environment in cities but has also shaped local climate characteristics and features unique to urban areas. The LCZ system developed by Stewart and Oke (2012) interprets local climate zones as areas with a homogeneous coverage of the earth's surface and a special nature of human activity. The classification includes 17 types, 10 of which are built-up environments, and the remaining seven are "land cover types" (Samsonov et al. 2018).

There are a number of approaches to the allocation of LCZ. All of them use remote sensing data. In this article, the original WUDAPT technique based on pixel classification is used to determine LCZ of the study areas. The main goal of WUDAPT is to collect data on the cities of the world in order to create a database for a systematic study of the urban climate (World Urban Database – wudapt.org).
Within the framework of this study, to obtain LCZ, a set of reference areas was selected for each of the zone types based on visual interpretation of Landsat satellite images. The use of images from a single shooting system ensures the integrity of the study results. The main source were images from the Landsat-5 satellite, obtained using a seven-band scanning radiometer Thematic Mapper (TM). For later dates, images from the Landsat-8 satellite were used. We used the images dated 2010-07-14, 2011-07-08, 2001-07-05, 2020-07-25 for Volgograd and 2000-08-29, 2001-08-02, 1996-08-18, 2011-08-28 for Moscow. The time period was chosen to cover the outbreaks period and periods before and after the outbreaks.

The training sample was compiled based on height of buildings, density of their distribution, and nature of the underlying surface. For each zone a minimum of 10 test sites with a side length of at least 200 meters were taken, which is a WUDAPT recommendation. In total, 16 types of LCZ were clearly identified for each of the study areas.

Then, we performed an automated classification by the maximum likelihood method in ArcGIS10.5 software on the obtained reference sites. A majority filter was applied to the obtained decoding circuits in order to filter out small clusters of pixels creating image information noise. As a result, decoding circuits showing the distribution of LCZ over Volgograd and its surroundings, as well as over the western part of the Moscow region, were obtained.

It is especially important to correctly identify the essential object of research on images which is vegetation cover. Therefore, during the decoding we used multispectral images in four channels of optical range and synthesis in standard pseudocolors (near-infrared, red, and green).

Adapting the methodology of local climate zones to the task of medical geographical zoning

According to the WUDAPT methodology, the LCZs of vegetation are represented by four groups, which are insufficient for medical geographical studies. The principle of dividing all plant communities into dense and lightly wooded landscapes, shrubs, and low vegetation does not allow defining the most favorable areas for the development of mosquitos. This fact prompted a refinement of the classification, which takes into account not only the layering and density of vegetation, but also its moisture characteristics.

When assessing favorable environmental factors for mosquitoes, hydrographic objects also require special attention, since it is in water that the first three stages of their development take place. To estimate the moisture content, we referred to the normalized difference water index (NDWI). There are at least two indexes for which the abbreviation NDWI is used:

The McFeeters Index:

$$NDWI = \frac{\left(X_{NIR} - X_{SWIR}\right)}{\left(X_{NIR} + X_{SWIR}\right)} \quad (1)$$

and the Gao index (Ceccato et al. 2001):

$$NDWI = \frac{\left(X_{green} - X_{NIR}\right)}{\left(X_{green} + X_{NIR}\right)} \quad (2)$$

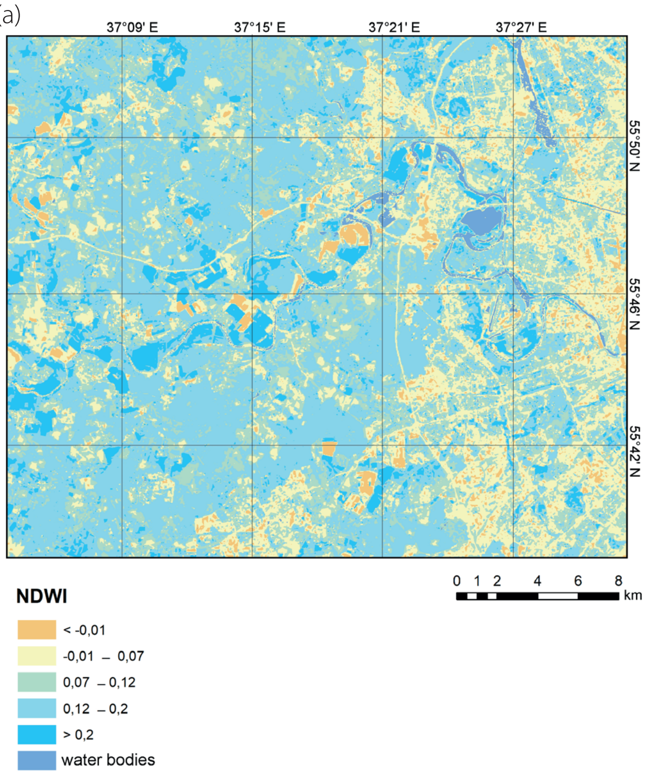
The indices themselves are fundamentally different from each other, since they refer to different spectral ranges. To classify vegetation, we use the Gao index, which uses the near infrared (NIR) and middle infrared (SWIR) ranges, as it reflects the water content in the leaves of plants. The McFeeters index was used to identify water bodies, based on the green and NIR channels.

To further divide LCZs into subzones, index images were created based on the presented formulas for the study periods, for which a suitable number of index value steps were then identified.

The optimal number of gradations was determined experimentally by gradually increasing the number of steps and a detailed visual analysis of the area. The division into seven gradations was the most suitable for the territory of Volgograd and its environment. For the territory of the Moscow region, the most suitable was the division into six gradations, which reflects all the main trends in the distribution of the index. Fig. 2 shows the resulting index images for study periods.

To select water bodies according to McFeeters index, a raster image with 2 ranges of values below and above 0 was created using raster calculator. This approach makes it possible to identify water bodies by spectral characteristics, not by visual decoding of images. Further,

(a)



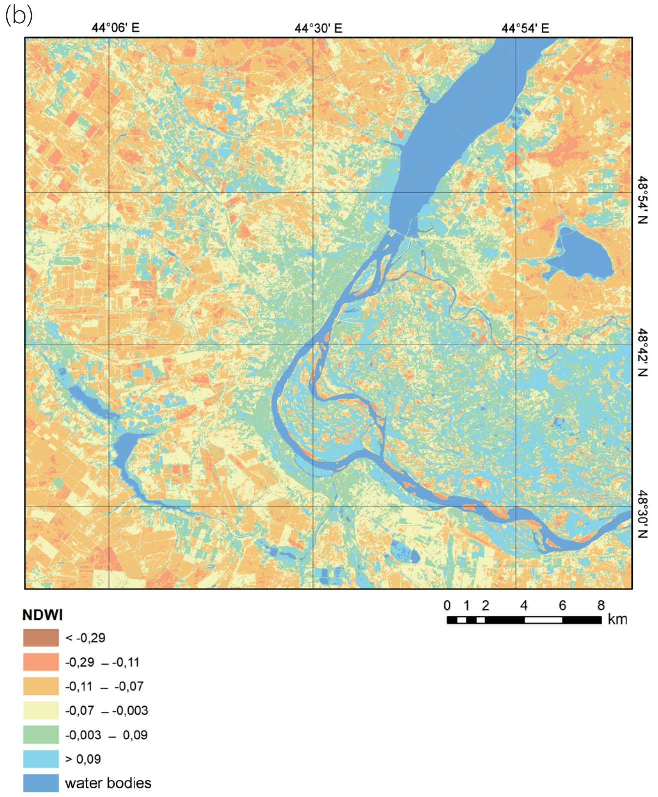


Fig. 2. Study areas index images with selected steps of the Gao NDWI index values: a) the western part of the Moscow region; b) Volgograd and the surrounding area

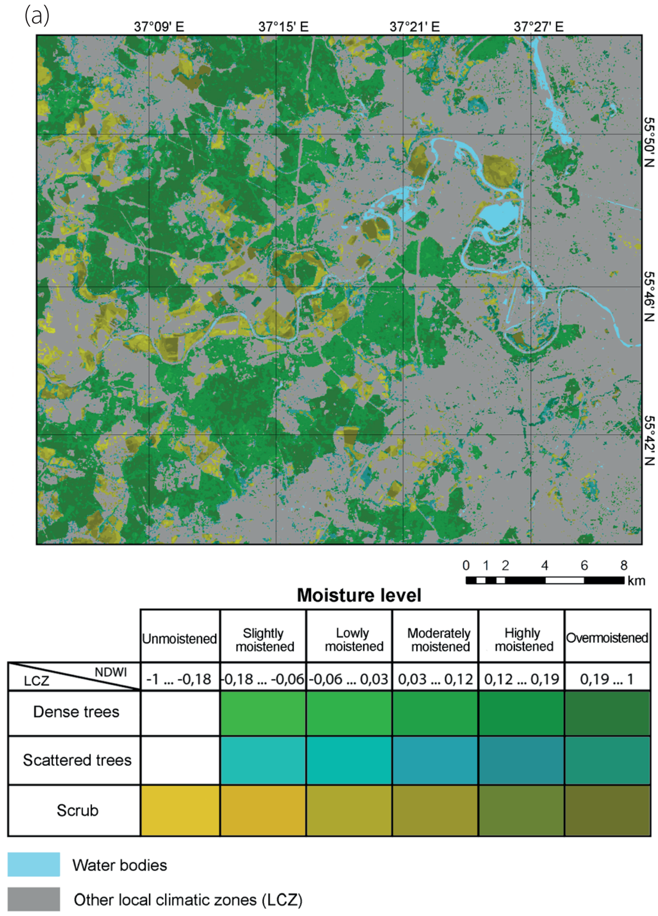
by spatial sampling based on watercourses flowing out of them, water bodies are divided into effluent and non-drainage ones, as this factor directly affects the creation of conditions for mosquitoes to breed in water bodies.

RESULTS

The resulting index images are the basis for refining the LCZ classification. Integration of LCZ and the results of indices calculation gives us maps of local climate subzones, each of which contains the LCZ type of vegetation cover with an indication of the degree of moisture. A total of six maps of local climate vegetation subzones were made for three-time intervals (outbreak period and periods before and after the outbreak) for each area. Fig. 3 shows maps of local climate subzones of vegetation of the study areas for the period of outbreaks.

All LCZs that are not defined as vegetation are grayed out because they are secondary objects of the study. Gradual darkening of color scales for LCZ vegetation occurs as Gao NDWI index values increase. The main goal of these maps was to reflect as accurately as possible the differentiation of subzones varying in LCZ and Gao NDWI values.

High index values prevailed during outbreak periods for Volgograd and the Moscow region, indicating that vegetation zones are more watered during outbreak periods as compared to the periods before and after them. This result is quite expected and confirms the fact that the moisture content of the vegetation is an indicator of the epidemiological situation. Series of these maps can serve both as intermediate materials for assessing epidemiological risks and as full-fledged materials for studying the nature and changes of vegetation moisture.
In order to study the dynamics of LCZ variability during the study periods, we analyzed the ratio of the obtained zones within the study area for the Volgograd region and the



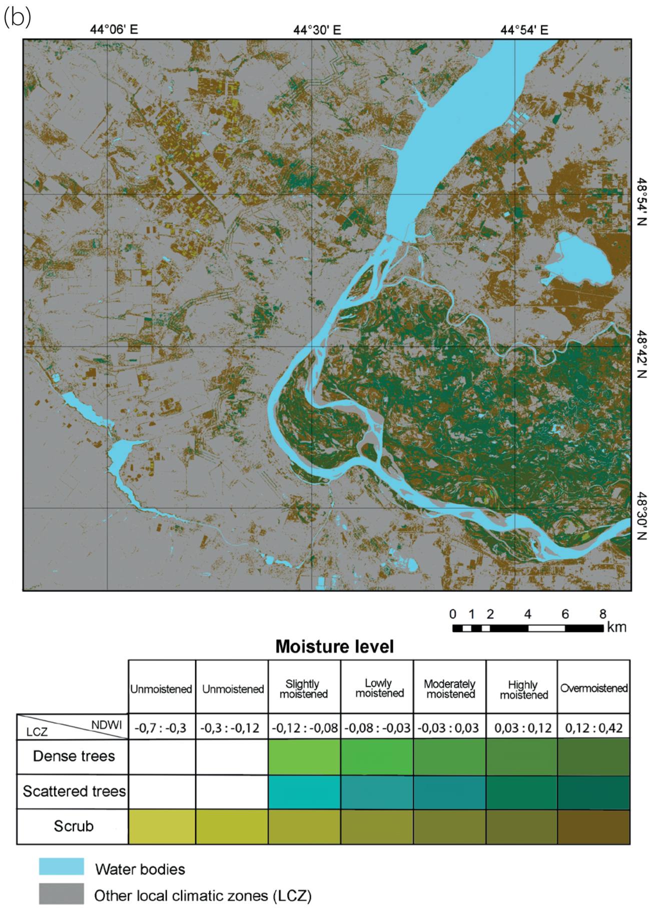


Fig. 3. Maps of local climate subzones of vegetation during outbreaks of vector-borne diseases: a) the western part of the Moscow region; b) Volgograd and the surrounding area

Moscow region. The results are presented as logarithmic scales and are shown in Fig. 4. The saturation of color corresponds to different years (darker ones are earlier).

The assessment revealed three types of LCZ changes during the study periods. They are the following: steady increase in LCZ area, increase during an outbreak, and decrease during an outbreak. Of greatest interest are the LCZs, the area of which increased during the outbreaks of West Nile fever and vivax malaria. This suggests that an increase of certain types of LCZs areas could have been associated with the outbreaks. The attention must be focused as on potential indicators of the emergence of an unfavorable epidemiological situation.

In LCZ natural surface cover, LCZ A (dense trees) and LCZ B (scattered trees) are the leaders in increasing area during the outbreak in both regions. The increase in LCZ F (bare rock/paved) is due to the construction of asphalt roads. As for water bodies, during the studied periods there is a small, stable increase in their area.

Along with statistical data on infections, maps of local climate sub-zones formed the basis for the assessment of epidemiological risks. The year 2011 for Volgograd and 2001 for Moscow were chosen for the analysis, since according to the initial data set on infections, these years account for the largest number of localizations of possible human infection sites and pathogen detection sites in the nature (see for detail: Mironova et al. 2020; Shartova et al. 2022). First, it calculates percentage of the sites of detected diseases for each LCZ. After that, the number of sites in every local climate subzone is determined. Based on the statistical data obtained, risk matrices were compiled. They form the basis of medical geographical zoning maps for the areas under study. The matrices are presented in the explanation of each map.

The principle of all risk matrices is to determine the level of risk, taking into account the category of probability and severity of consequences (Korolkova 2013). The matrices are built according to the following principle: the parameters under consideration (in our case, these are vegetation LCZs and Gao NDWI steps) are indicated horizontally and vertically in the order of increasing their degree of favorability for vectors depending on the degree of vegetation moistening. Thus, when moving from the beginning of the axes to the upper right corner of the matrix, there is an increase in the degree of favorability. Based on the risk matrices, maps of medical geographical zoning were made. The matrices are presented in the explanation of each map (Fig. 5).

The trend of increasing in favorability of areas for vector-borne transmission can be clearly seen in the matrix for Volgograd. The greatest number of possible human infection sites and virus detection sites in the nature occurred in LCZ D (low plants) and in subzones with Gao NDWI values ranging from 0.12 to 0.42 (with overwatering). When comparing these data, it appears that the areas that correspond to LCZ D and Gao NDWI group 7 at the same time are potentially the most dangerous for the territory of Volgograd. These are the areas in the upper right corner of the matrix. By the same principle, for each subzone a place in the risk matrix is determined. Thus, the position in the matrix and color saturation reflects the level of favorability of vegetation zones based on the degree of moisture for the natural foci activity (the darker, the more favorable).

For the Moscow region the most dangerous are the areas of LCZ A (dense trees) with 3-step Gao NDWI values (low-moisture type). However, test sites with such values do not form large continuous arrays and are practically not visible on the map. The predominant part of suburban areas is covered by forests (LCZ 101) with maximum Gao NDWI values (over-moisture type) and low plants (LCZ 104) with the 3rd stage of boundary index values (low-moisture type). Thus, for the Moscow region, the most dangerous areas are forests of the over- moisture type.

Based on the obtained maps of medical geographical zoning it is possible to identify favorable areas for the development of vectors, as well as the most favorable parts of the inhabited zone in terms of epidemiological conditions. The maps can be used to differentiate the

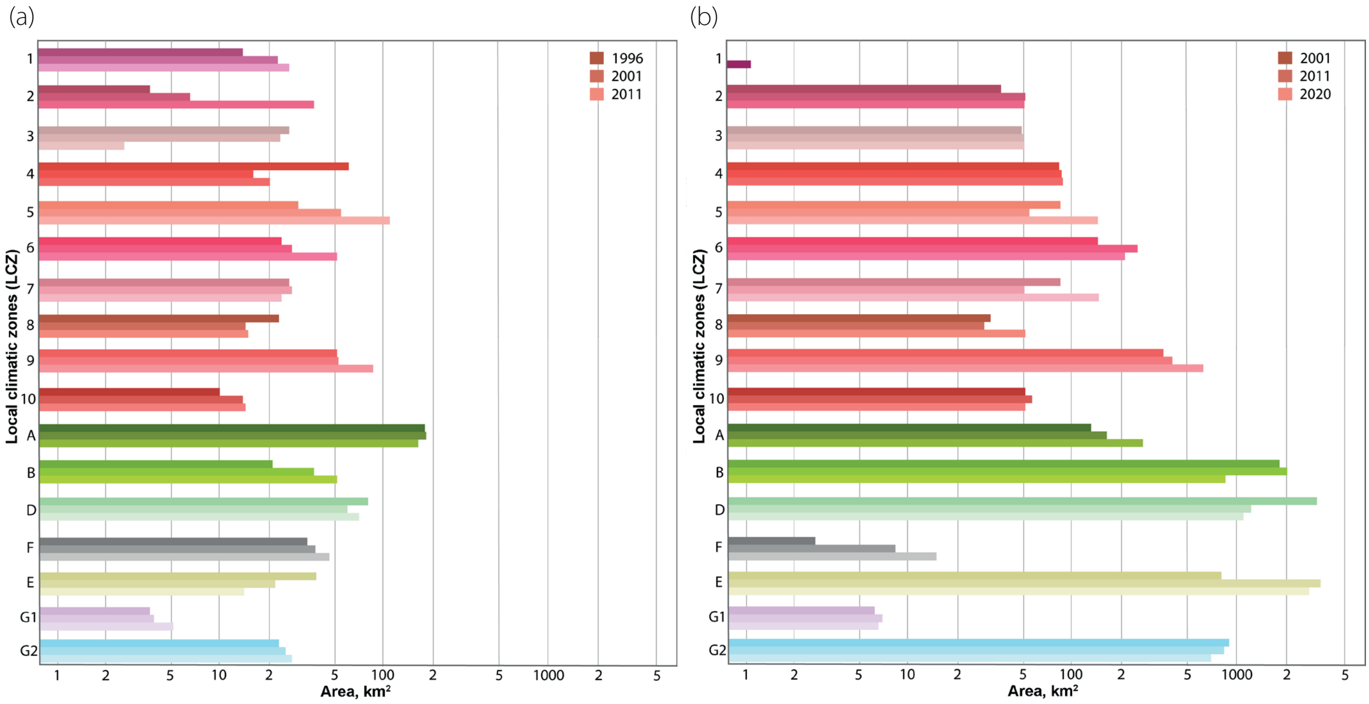
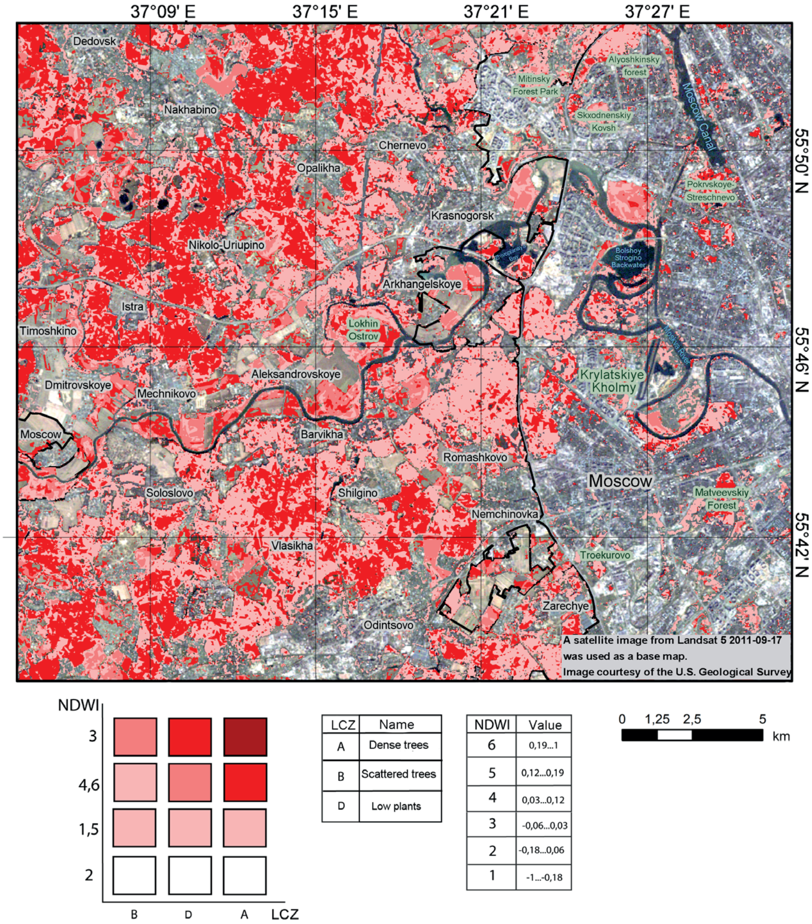


Fig. 4. LCZ types areas ratio for study areas (scale is logarithmic): a) the western part of the Moscow region; b) Volgograd and the surrounding area. Local Climate Zones codes: 1 – compact high-rise, 2 – compact mid-rise, 3 – compact low-rise, 4 – open high-rise, 5 – open mid-rise, 6 – open low-rise, 7 – lightweight low-rise, 8 – large low-rise, 9 – sparsely built, 10 – heavy industry, A – dense trees, B – scattered trees, C – bush, scrub, D – low plants, E – bare rock / paved, F – bare soil / sand, G1 – water (sewage), G2 – water (endorheic)

(a)



(b)

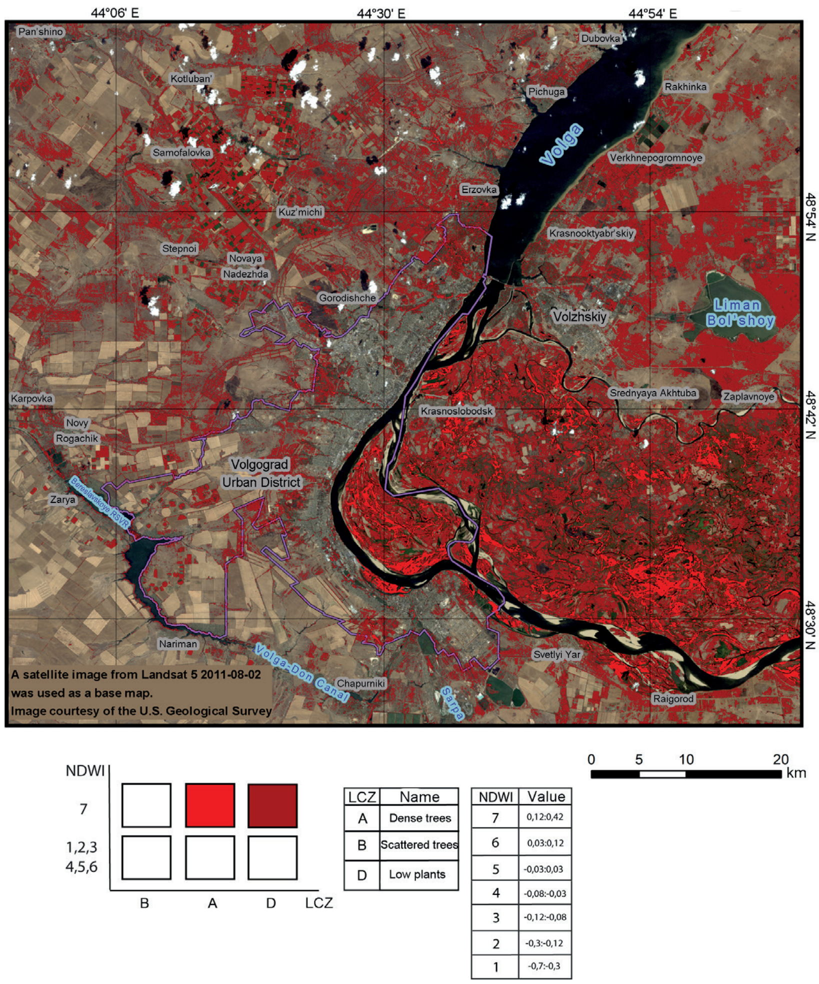


Fig. 5. Maps of medical geographic risks of the study areas: a) the western part of the Moscow region; b) Volgograd and the surrounding area

residential area by medical geographical conditions. On its basis, it is possible to develop a set of protective measures of the study area and to apply such measures (for example, increase the volume of sanitary treatment of water bodies of forest and forest-park zones).

CONCLUSION

The study of local climate zones was a big step in the analysis of the urban climate. It has no less potential for the purposes of medical geography. Despite the various methods used to detail LCZ, the goal of all research is to improve understanding of the mechanism of epidemics and to elaborate the potential of LCZ theory to model epidemiological situations for urban areas. In our study, we developed an improved algorithm for identifying local climate subzones for urban and suburban areas to provide medical geographical zoning and assessment of epidemiological risks of vector-borne diseases. Using the normalized water index (Gao NDWI), it became possible to develop a more detailed classification taking into account the moisture content of the vegetation cover, which can greatly contribute to the identification of the most favorable areas for the development of disease vectors. Based on the numerical values of the index, subzones with different types of moisture, from non-watered to over-watered (six types for the Moscow region and seven types for Volgograd) were identified.

The study revealed changes in the areas of different LCZs before and after outbreak periods, which may reflect changes in conditions and an increase in the degree of favorability for vectors. Thus, LCZs can be used as indicators of changes in the natural and man-made environment that can provoke disease outbreaks.

Maps of epidemiological risks make it possible to assess on which LCZs the preventive measures should be focused.

By increasing the spatial resolution of publicly available satellite imagery, LCZ can be identified with a higher geometric accuracy, which will also increase the information content of the proposed method.

This methodology was developed using the outbreaks of West Nile fever and vivax malaria as examples, but it can be used to analyze the spread of other mosquito-borne diseases as well.

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