THEORETICAL ISSUES OF CARTOGRAPHIC STUDY OF SETTLEMENTS BASED ON REMOTE SENSING MATERIALS AND GIS TECHNOLOGIES

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Abstract. *The article covers theoretical and methodological issues of studying settlements based on remote sensing materials and geographic information systems (GIS) technologies. It also analyzes the possibilities of using space images to determine the territorial development of settlements, the expansion of built-up areas, land cover changes, the formation of functional zones and the location of infrastructure facilities. Detailed information is provided on the theoretical foundations of processing, classification, decoding of Sentinel-2, Landsat and high-resolution satellite images, as well as comparison of data from different periods.*

Keywords: *Remote sensing materials, GIS, settlement, space image, land cover, urban planning, spatial analysis, digital mapping, geodatabase, satellite images, Sentinel-2, Landsat, monitoring, administrative boundary, functional boundary, spatial modeling.*

Аннотация. *В статье рассматриваются теоретические и методологические вопросы изучения населенных пунктов на основе материалов дистанционного зондирования и технологий географических информационных систем (ГИС). Также анализируются возможности использования космических изображений для определения территориального развития населенных пунктов, расширения застроенных территорий, изменений землепользования, формирования функциональных зон и размещения объектов инфраструктуры. Представлена подробная информация о теоретических основах обработки, классификации и декодирования спутниковых снимков Sentinel-2, Landsat и изображений высокого разрешения, а также сравнение данных за разные периоды.*

Ключевые слова: *материалы дистанционного зондирования, ГИС, населенный пункт, космическое изображение, землепользование, градостроительство, пространственный анализ, цифровое картографирование, геобаза данных, спутниковые снимки, Sentinel-2, Landsat, мониторинг, административная граница, функциональная граница, пространственное моделирование.*

Introduction

Settlements are a complex spatial system reflecting the socio-economic, demographic, and territorial development of society. Construction processes taking place in cities, towns, and rural settlements, the emergence of new residential areas, the expansion of transport and engineering infrastructure, and changes in the forms of land resource use directly affect their territorial structure. Promptly detecting and regularly monitoring such processes is one of the important conditions for territorial planning, land accounting, updating cadastral data, and forming a comfortable living environment for the population.

Traditional topographic-geodetic and field surveys make it possible to obtain reliable information about settlements. However, they require a great deal of time and resources when studying large territories within a short period, regularly monitoring rapidly changing objects, and comparing conditions across different periods. For this reason, the use of remote sensing materials and GIS technologies is rapidly developing as one of the modern, efficient, and effective directions for studying settlements.

Main Part

The study of population and settlements is carried out within the framework of socio-economic cartographic research. On population maps, practical solutions can be developed by depicting, in an interconnected and visual manner, processes such as population distribution, settlements, composition, and dynamics, along with their territorial aspects. The depiction of settlements on a map is carried out primarily depending on its purpose and scale. The type of settlement is depicted through the appearance of the font of its name label and the characteristics of the cartographic representation [6]. For example, on large-scale topographic and cadastral maps, the type of settlement, its political-administrative significance, population number (number of households, number of quarters), boundary, and objects serving as landmarks are depicted. On general geographic maps of all scales, cities are depicted in 7 gradations by population, ranging from 1 million and above to 2,000 and fewer; rural and farmstead-type settlements on maps of scale 1:25,000–1:200,000 are depicted in 5 gradations, from 1,000 and more people down to no fewer than 10 people [1]. On small-scale geographic maps, the depiction of population and settlements is compiled through the generalization of large-scale maps. Initially, in compiling maps of population and settlements, field surveying, census data, and other sociological and statistical sources were used [4]. Today, GIS technologies and remote sensing material methods are widely used in the cartographic study of population distribution and the territorial characteristics of their natural, economic-social, and ecological processes.

Remote sensing data make it possible to record the spectral, geometric, and temporal characteristics of objects on the earth's surface from a distance. Through

satellite images of varying spatial resolution, it is possible to identify residential buildings, industrial areas, road networks, open lands, green areas, water bodies, and other types of land cover. Comparing images taken at different dates makes it possible to assess the rate of expansion of settlements, identify new construction areas, observe the conversion of agricultural land into built-up areas, and determine the main directions of territorial change.

In studying settlements based on remote sensing, the spatial, spectral, radiometric, and temporal resolution of images is of important theoretical significance. Spatial resolution determines the smallest object size that can be identified in an image, while spectral resolution determines the ability to distinguish objects on the earth's surface according to their reflectance characteristics. Temporal resolution is related to how frequently a territory is imaged and is important for observing seasonal and long-term changes. Radiometric resolution expresses the ability to distinguish the levels of energy recorded by the sensor.

Satellite imagery is widely used to detect changes in population distribution, and this work is mainly applied to solving the following three tasks:

Detecting and delineating changes in urban or rural boundaries;

Monitoring changes in the internal structure of settlements;

Observing changes in systems consisting of settlements.

To solve each task, aerial photographic, scanned, and infrared images taken at different periods are used, and comparing them makes it possible to detect changes. In doing so, in addition to satellite images, various topographic and thematic maps as well as statistical data are also used [5].

When comparing images, changes in the image — that is, changes in the size, shape, and spectral indicators of cities and villages — are examined. To perform these measurements, the images must have the same geometric and optical characteristics and preferably be at the same scale; in other words, it is preferable to use images obtained from the same imaging systems [2]. Land use, as well as urban land reserves and the characteristics of external transport arteries — that is, their width, length, and other indicators — make it possible to forecast the spatial growth of settlements in advance [3].

To study the territorial dynamics of settlements, it is recommended to use satellite images spanning an interval of at least 15–20 years. The spatial expansion of a territory becomes clearly visible precisely over such time intervals, and based on the intensity of territorial change, the directions of expansion can also be forecast.

Today, numerous satellites are continuously monitoring the earth's surface worldwide. Each satellite has a defined mission and a number of corresponding characteristics such as orbital direction, periodicity, and spatial or geometric resolution.

In addition, some satellite data are open for public use, while others are paid (for commercial purposes) or intended for confidential military purposes.

In studying settlements, data from the Landsat 1–8 (Landsat 4-5-7-8) and Sentinel-2 satellites have been used; below we discuss some of their aspects.

In mapping the expansion of settlements, data from the Landsat 4-5 TM, Landsat 7 ETM, and Landsat 8 OLI/TIRS satellites were used. Landsat 4-5 TM (Thematic Mapper) image data files consist of 7 spectral bands. Its spatial resolution is 30 meters. The Landsat Plus (ETM+) sensor aboard the Landsat 7 Enhanced Thematic Mapper satellite has been capturing near-continuous images of the earth with a 16-day repeat cycle since April 1999. Due to the failure of the Scan Line Corrector (SLC) in all Landsat 7 scenes collected since May 30, 2003, data gaps exist. Landsat 7 scenes acquired after this date are classified as "SLC-off." It consists of eight spectral bands, numbered 1 through 7, with a spatial resolution of 30 meters. Band 8, the panchromatic band, has a spatial resolution of 15 meters. The Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) aboard the Landsat 8 satellite began capturing images of the earth in February 2013.

The Landsat 9 OLI-2 and TIRS-2 satellite was launched on September 27, 2021. Each of the sensors collects images of the earth with a 16-day repeat cycle. Landsat 8-9 image data files consist of 11 spectral bands with a spatial resolution of 30 meters for bands 1–7 and 9–11; for band 8, the panchromatic band, it is 15 meters.

The Sentinel satellite system was launched by the European Space Agency as part of the Copernicus program for the purposes of monitoring and observing processes on the earth's surface, managing land use, and monitoring and preventing natural disasters, and includes Sentinel-2A (2015) and Sentinel-2B (2017). Sentinel data have the following advantages and characteristics: a multispectral database with 13 bands (colors corresponding to wavelengths within a specific range of the electromagnetic spectrum), including visible, near-infrared, and short-wave infrared radiation; systematic coverage of the earth's surface between 56° south and 84° north latitude, with a revisit period of 5 days at the same viewing angle; at higher latitudes, image swaths overlap, so certain areas are imaged two or more times within 5 days (but at different angles); the image resolution is 10, 20, and 60 meters, which can be widely used for scientific and technical purposes.

Band 1 is used to detect atmospheric conditions and coastal aerosols; Bands 2-3-4 form a true color combination and are useful for classifying and monitoring the condition of the earth's surface and for other analyses. Bands 5-6-7 depict the variable zone near the infrared wavelength where vegetation reflects sunlight. For this reason, these wavelengths are called the "vegetation red edge." Chlorophyll granules absorb most of the visible sunlight in the spectrum and sharply reflect wavelengths beyond

680 nm, meaning albedo increases from 5% to 50%. This condition is convenient for determining the vegetation index. Bands 10-11-12 depict short-wave infrared radiation, making it possible to identify dry and wet earth surfaces.

Proper use of satellite images requires their preliminary processing. This includes reducing atmospheric effects, applying geometric and radiometric corrections, bringing images into a unified coordinate system, and separating cloud- and shadow-covered areas. In the next stage, images are processed using visual interpretation, supervised or unsupervised classification, object-oriented analysis, and machine learning methods. As a result, thematic layers reflecting built-up areas, green areas, water bodies, transport networks, and open lands are created.

GIS technologies make it possible to integrate remote sensing results with topographic maps, orthophotoplans, digital elevation models, cadastral data, administrative boundaries, demographic-statistical indicators, and field observations. Combining this data in a unified geodatabase serves to comprehensively assess the area, structure, density, functional zones, and infrastructure provision of settlements. In this environment, methods such as buffering, overlay, distance calculation, proximity analysis, network analysis, and multi-criteria spatial analysis can be used.

One of the important theoretical issues of the research is determining the difference between the administrative boundary of a settlement and its actual built-up or functional territory. In some cases, construction extends beyond the established administrative boundary, while in other cases a significant amount of agricultural or unused land exists within the administrative boundary. Remote sensing and GIS data help identify these discrepancies, scientifically refine boundaries, and assess the real territorial condition of settlements.

To ensure the reliability of the obtained results, objects identified based on satellite images must be verified against field data, high-resolution images, and existing cartographic sources. Classification results are assessed based on indicators such as the error matrix, overall accuracy, user's accuracy, and producer's accuracy. In addition, differences in the date, scale, coordinate system, and level of accuracy of data from various sources must also be taken into account.

Conclusion

Remote sensing materials and GIS technologies constitute an important scientific-methodological basis for comprehensively studying settlements, determining their current condition, and regularly monitoring their territorial development. Through their ability to simultaneously cover large territories, conduct repeated observations, and compare conditions across different periods, satellite images effectively complement traditional research methods.

In studying settlements, it is necessary to take into account the spatial, spectral,

radiometric, and temporal resolution of satellite images. Selecting a processing and classification method appropriate to the characteristics of the images makes it possible to reliably identify built-up areas, green spaces, water bodies, open lands, transport networks, and other functional elements. Based on multi-temporal images, it is possible to assess new construction areas, directions of territorial expansion, land cover changes, and the dynamics of building density.

Integrating remote sensing results with geodetic, cartographic, cadastral, statistical, and field data within a GIS environment serves to form a unified spatial information system for settlements. Such a system makes it possible to compare the administrative and actual built-up boundaries of settlements, delineate functional zones, assess infrastructure provision, and identify promising areas for future development.

The accuracy of the research results depends on high-quality preliminary processing of images, bringing data from various sources into a unified coordinate system, and verifying the results with field observations. For this reason, quantitatively assessing classification and interpretation results, identifying sources of error, and indicating the level of uncertainty should be an integral part of the research.

Overall, the integrated use of remote sensing and GIS technologies increases the effectiveness of accounting for settlements, refining boundaries, updating cadastral data, detecting illegal or unregulated construction, monitoring urban development processes, and rationally managing land resources. The geodatabases and thematic maps created based on these technologies serve as an important source of information for scientifically substantiating territorial planning decisions, ensuring the sustainable development of settlements, and forecasting future changes.

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