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AEROSPACE TECHNOLOGIES FOR ASSESSING SOIL CONTAMINATION

Actuality. Studies of soil pollution assessment are based on scientific principles that define a complex system of environmental safety management in the context of increased exposure to sources of secondary dust pollution of the atmosphere. To ensure environmental safety under conditions of high levels of dust pollution, it is necessary to apply and improve the relevant models. Among the many types of environmental pollution, dust pollution of the atmospheric air and the deposition of harmful substances on the soil are particularly dangerous. This pollution can take two forms: direct emissions from industrial enterprises (primary) or the formation of secondary pollution through physical and chemical processes in places where dust-like waste is stored. Fine waste after air purification with dimensions of less than 100 microns is particularly hazardous. In modern environmental monitoring and assessment of soil pollution, special attention is paid to remote methods that allow for more effective monitoring of the impact of human activity and solving environmental problems. The use of unmanned aerial vehicles is one such method that has positive results. **The purpose of the article** is to solve the scientific problem of improving aerospace methods based on unmanned aerial vehicles (UAVs) for monitoring and assessing the quality of soil pollution. **The object of the study** is the use of aerospace tools for monitoring and assessing the condition of soil cover. To achieve this goal, the following tasks have been defined: to study the current state and ways to improve the efficiency of UAVs in the system of environmental monitoring of soils; to develop models of environmental assessment; to analyze existing approaches to the use of aerospace assets for monitoring and assessing the state of soil cover. **Conclusions:** a methodological approach based on a modified method of the comprehensive assessment of the level of technogenic hazard of industrial facilities is proposed to assess the state of environmental safety in conditions of intense dust pollution of the atmospheric air.

Keywords: information technology; technogenic hazard; soil cover; dust pollution; atmospheric air; technical solutions; environmental safety; morbidity.

Introduction

The scientific basis of soil pollution research is the need to determine the place of environmental hazards in the hierarchy of soil research. To ensure environmental safety in conditions of high levels of dust pollution, it is necessary to apply and improve the relevant models. At the current stage of soil research, five main areas of research are identified:

– production (for the production of products and raw materials for industry)

– preservation of the gene pool, reproduction of living beings;

– information (for scientific, cultural, educational and other information);

– engineering (for the creation and placement of engineering facilities, structures, roads, etc;)

– general environmental (global biochemical cycles, regulation of surface runoff, climate management and chemical element flows).

When conducting research to assess soil quality, it is necessary to distinguish between primary and secondary soil contamination and differentiate between sources of environmental hazards. Among the many types of environmental pollution, dust pollution of the air and the deposition of harmful dust on the soil cover pose a significant danger. This pollution can be caused both by direct emissions from industrial enterprises (primary) and secondary formation as a result of physical and chemical processes in places where dusty industrial waste is stored. Fine waste after air purification (<100 microns) is considered particularly hazardous [1].

The creation of new and improvement of existing methods for constructing cartographic models for assessing soil quality is possible only on the basis of the integrated use of aerospace and contact measurements.

Analysis of recent studies and publications

Experimental studies on soil contamination are based on the use of expert assessment methods and information technology. Some laws of Ukraine, namely: "On Land Protection", "On Monitoring", "On State Control over Land Use and Protection", refer to the protection of lands that require special attention from the state, but are identified by the results of remote sensing. To determine the destructive processes of soil cover, it is necessary to have a database to update periodic information and build the dynamics of any processes. In order to make management decisions

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on land use and protection, a full package of various information should be available to managers of different levels, including local governments and control bodies. The scientometric analysis of the study area revealed many environmental problems that need to be addressed. An analysis of previous studies suggests that the impact of secondary dust pollution on the ecology of the region is of considerable interest to such scientists: O. Adamenko [1], Y. Adamenko, L. Arkhipova, O. Mandryk, O. Mashkov, M. Malovanyi, H. Rudko, O. Trofymchuk [2], V. Trisniuk, et al. [3, 4].

The aim of the article is to solve the scientific problem of improving aerospace methods based on an unmanned aerial vehicle for monitoring and determining the quality of soil pollution.

The object of the study is information technologies for comprehensive soil monitoring based on aerospace and contact methods.

To achieve this goal, the following tasks have been defined: to study the current state and ways to improve the efficiency of UAVs in the system of environmental soil monitoring; to develop models of environmental assessment; to analyze existing approaches to the use of aerospace tools for monitoring and assessing the state of soil cover.

Analysis of the problem and methods of soil contamination detection

Soil contamination can occur both as a result of primary emissions from industrial enterprises and as a result of physical and chemical processes in places where dusty industrial waste is stored, especially fine dust removal waste. This secondary type of pollution is quite widespread, as there are currently no effective technologies for utilizing this waste. Failure to consider secondary soil contamination when monitoring environmental hazards can lead to underestimation of the environmental risk. In such cases, it is important to assess the impact of soil pollution sources in the formation of an industrial hazard. Typically, the technogenic hazard indicator is determined by the formula

$$T = K_T K_{KM} K_p \frac{\sum_{i=1}^{N} K_{ui} a_i M_i}{N}, \quad (1)$$

where T – is an indicator of technogenic hazard due to soil pollution;

K_T – coefficient of regional economic activity;

K_{KM} – coefficient of the number of citizens exposed to pollution;

K_p – coefficient that takes into account the terrain;

K_{ui} – coefficient depending on the characteristics of emission sources;

a_i – air emission rate;

M_i – annual weight of ingredients contained in emissions to soils, tons per year;

N – the number of ingredients..

Assessment of ecosystem dynamics under conditions of anthropogenic dust pollution of atmosphere air

A geodatabase has been created to assess changes in the ecosystems of the Carpathian region as a result of man-made dust pollution. It contains satellite images obtained from Landsat 7 satellites (shown in Figures 1 and 2), topographic maps, and digital elevation models with different levels of detail [5].

Fig. 1. Landsat 7 satellite image with a resolution of 30 m (10.05.2021)

Fig. 2. Landsat 7 satellite image with a resolution of 30 m (20.07.2021)

Since most anthropogenic phenomena and processes are multifactorial, it is impossible to take into account

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the degree of influence of each factor on the formation of the phenomenon. Therefore, a probabilistic approach based on the construction of interpretation and extrapolation models using monitoring results, such as observation series, and methods of mathematical statistics and probability theory, is effective for predicting environmental hazards. This approach makes it possible to take into account the multifactorial nature and uncertainty of the impact of individual factors on the result [6] (Fig. 3).

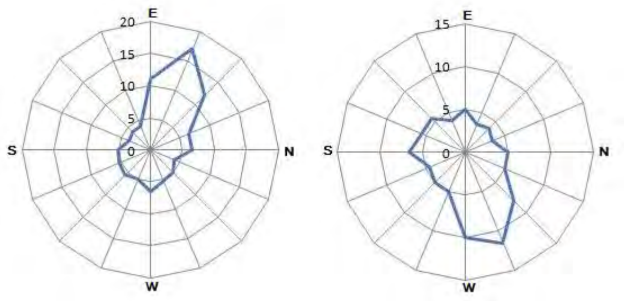

Fig. 3. Wind rose diagram of Burshtynska TPP

The wind rose and the probabilistic approach to predicting the environmental hazard of Burshtyn TPP are associated with the multifactorial nature of techno-natural phenomena and processes.

It is impossible to take into account the influence of each factor on the formation of the phenomenon, so it is advisable to use a probabilistic approach. This approach consists in building interpretation and extrapolation models based on monitoring data and methods of mathematical statistics and probability theory.

The wind rose is a tool for determining the directions of pollution spread, which can be used to improve the forecasting of environmental hazards from the Burshtyn TPP [7, 8].

In predicting maximum environmental performance, such as safety and pollution levels, a mathematical random variable model is often used as a simple and popular probabilistic approach. This model is the most effective. Sulphur dioxide in the atmosphere can react with water to become an acid, which is then likely to fall to the ground as rain. Today, sulphur dioxide emissions are the most acute problem, as they exceed European standards. Carbon monoxide, in turn, changes the greenhouse effect.

To promptly detect, localise, identify and monitor the anthropogenic and environmental impact of pollution on aquatic ecosystems and, as a result, on human activity, there is an effective method for building multi-criteria mapping models of the area in combination with remote sensing data analysis. This method, proposed by G. Krasovsky [2], makes it possible to determine the degree of combinatorial influence of the factors that cause a hazardous phenomenon. Contact methods for determining the areas affected by erosion processes involve a set of field and desk-based work. Field work involves surveying the territory, measuring habitat areas using GPS equipment, and taking samples of soil chemical composition. Desk-based work involves processing field data and forecasting the further development of these processes. The advantage of contact methods is the high accuracy of measurements of soil chemical composition and vegetation [9].

Thus, the creation of new and improvement of existing methods for building cartographic models of environmental assessment of agricultural land is possible only on the basis of the integrated use of aerospace and contact measurements, taking into account the variety of grain crop hybrids grown, the quality of agrochemical measures, meteorological conditions and the characteristics of the analysed area [10].

An analysis of methods for monitoring changes in the environmental state of the region showed that remote sensing data processing is the most efficient in terms of efficiency and retrospectivity of data, as well as in terms of labour and material costs. The results of multispectral imagery can be analysed semi-automatically by calculating the so-called vegetation indices. When they are calculated, new images of the area are created, where certain objects are highlighted by colour gradation. Out of the variety of vegetation indices, we selected the two most relevant to the subject of the research – the NDVI and NDWI indices.

The NDVI indicates the difference in vegetation levels for each field and is calculated using the formula

$$NDVI = \frac{NIR - RED}{NIR + RED}, \quad (2)$$

where NIR is the reflection value in the near-infrared spectrum;

RED – the value of reflection in the red part of the spectrum.

The NDWI index indicates the level of surface moisture and is calculated by the formula

$$NDWI = \frac{NIR - SWIR}{NIR + SWIR}, \quad (3)$$

where NIR is the reflectance value in the near-infrared spectrum;

SWIR – reflectance value in the short-wave infrared spectrum.

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It is outlined that remote sensing methods have a number of features (time of survey, meteorological conditions, type of equipment, image resolution, etc.) in the context of determining the factors influencing the reflectivity of soils and vegetation and have been studied in detail. However, their main disadvantage is that in order to be confident in the results of remote sensing data processing, it is necessary to have at least some a priori information about the study area. After collecting, processing and analysing field and laboratory data from each site, soil contamination is calculated.

Building digital terrain models and creating cartographic models of surface slopes, combined with meteorological data, allows us to determine the impact of agricultural land on the aquatic ecosystem and soil pollution. Retrospective monitoring of the study areas based on remote sensing data reveals the effects of agricultural soil use on the ecological state of the region. In this way, a structural scheme for monitoring and assessing the impact of agricultural processes on the environmental safety of the territories was formed [11, 12]. Based on the results of remote sensing, the terrain is analysed and retrospective monitoring of land use for agricultural production is carried out.

The use of unmanned aerial vehicles has many advantages, including fast and accurate information about the state of the environment in a given area, the ability to reach hard-to-reach areas, and the ability to modify UAV onboard systems depending on the monitoring task. Modern UAVs have many capabilities, such as photo and video surveillance in the visible spectrum, as well as thermal and radar imaging. In addition, an approach has been developed to formulate a time or economic criterion to determine whether UAVs can be used at minimal cost to perform environmental tasks. An additional advantage of using UAVs for environmental control is the ability to respond quickly to the detection of pollution and take timely measures to eliminate it. The use of UAVs also reduces the risk for people who carry out observations in hazardous conditions, such as in pollution zones where exposure to toxic substances is possible. The use of UAVs in environmental control is an important element of the strategy for preserving the natural environment and improving environmental safety. In solving the problems of monitoring geo-environmental systems using unmanned aerial vehicles, the landscape approach is key. It considers the image of the earth's surface obtained with the help of technology as a complex geo-environmental system where all elements are closely connected and interact with each other. The landscape is seen as a result of natural and human activity, while it retains traces of different stages of development, which makes it possible to assess the importance of the landscape for the study of geo-environmental systems in both spatial and temporal aspects.

Contact methods provide information on the current agrochemical state of air, soil and water, as well as check the adequacy of remote sensing data processing results. Internet services provide information on the legal regime of land use for agricultural activities, as well as the legal framework for regulating the environmental condition of the area. This information makes it possible to build thematic mapping models and develop protection measures against harmful substances to ensure a sustainable environmental state of the region and maintain the level of agricultural production of grain crops. In addition, the information obtained reveals areas where there is an increased risk of erosion processes, and therefore the need for constant monitoring. The end result of data processing, analysis and interpretation is geomodels of the studied areas with a corresponding database that can be filled with new information or serve as a basis for making management decisions on the development of the region's environmental status [13].

Remote sensing makes it possible to detect erosion processes in soils, as they have a significant impact on optical properties. This is because erosion reduces the amount of humus and clay in soils, which leads to an increase in the brightness of their surface. This phenomenon is amplified when lighter rocks come to the surface after the upper soil layers are washed away. Erodibility is an important soil characteristic that can be detected on satellite imagery, and it can help monitor soil conditions and avoid negative impacts of economic activities. Soil erosion can be caused by either water erosion or wind deflation. One of the main factors of water erosion is surface water runoff. The flow regime depends on various factors, such as rainfall, topography, soil properties, vegetation cover, land use and many other factors.

Linear erosion forms, such as gullies and ravines, can be tracked on satellite images. These forms appear on images with a spatial resolution of 1 to 2 m as clearly defined contours with a jagged shape. On images with a spatial resolution of more than 10 m, gullies are usually not visible, but networks of gullies with elongated wavy tree-like shapes are clearly visible. The bottoms and slopes of gullies are usually occupied by natural vegetation, which is denser and more moisture-loving in the lower parts of the slopes and along the bottoms.

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Specialists of the Institute of Telecommunications and Global Information Space of the National Academy of Sciences of Ukraine have developed a clustering algorithm that allows for clearer detection of gully structures on satellite images in combination with digital elevation model (DEM) data. Remote sensing is a powerful tool for obtaining information about different areas, especially for objects that are inaccessible or difficult to reach. For example, the study of gully structures, forms and soil types in Boryspil, Kyiv region, and Pancheve village, Novoukrainskyi district. Pancheve in Novoukrainsky district of Kirovograd region can be used for detailed cartography, land use, industrial planning and other purposes.

To analyse and process the results obtained, the modelling tools of the ERDAS Imagine package were used, which performs various image processing operations, including classification and clustering. The developed clustering algorithm makes it possible to determine the similarity of objects in the image and to distinguish them from others. Thus, the results of the study may be relevant for various purposes, such as land management, environmental protection, transport infrastructure planning, construction and industrial development planning, etc.

This indicates that land resources have been exploited for decades without taking into account natural factors and the principles of sustainable development. As a result, serious problems have arisen: natural ecosystems have been destroyed, their biodiversity has decreased, the environment has been polluted and the climate has changed. Such processes are typical for many regions of the world where soil degradation is occurring, especially on land used for growing crops. The deterioration of the humus condition of soils leads to a decrease in their fertility and bioproductivity. This ultimately reduces the quality of crops and increases dependence on chemical fertilisers and pesticides. In addition, soil degradation can lead to a decline in biodiversity, in particular through the loss of natural habitats for various plant and animal species. This can have a negative impact on ecosystem services, which ensure the environmental sustainability and resilience of geosystems. Therefore, it is important to ensure sustainable and environmentally sound development of agricultural areas, taking into account the impact on natural resources and ecosystems.

It is important to pay attention to the use of land resources, taking into account their natural characteristics and potential. It is necessary to develop land use with a view to sustainable development and preservation of ecological balance. To this end, it is important to use scientifically sound methods and principles of soil, water and forest conservation, and to reduce the environmental impact of industry and other activities. It is also important to create special protection zones for natural complexes and ensure their effective functioning. The deductive approach to landscape research is to study individual characteristics of landscape systems to understand their organisation as holistic entities. The use of remote sensing and multidimensional spatial analysis allows us to identify patterns of landscape structure and genetic relationships between individual landscape elements.

Some landscapes may have similar or even identical spectral characteristics that make it impossible to distinguish them on images. This can be caused, for example, by sparse and small plant communities, soil cover, moisture, and other factors. To solve these problems, complex analysis methods are usually used, including additional information from other sources and manual work by interpreters. Targeted use of industrial and agricultural waste can help improve the ecological state of the pedosphere. For example, using organic waste as fertiliser can reduce dependence on chemical fertilisers and improve soil quality. Using industrial waste to build roads and other structures will reduce the negative impact on the environment and reduce the need for the extraction of new materials. It is also necessary to take into account the impact of human activity on natural ecosystems and implement measures to preserve them, such as gr een plantations, restoration of river ecosystems, creation of nature reserves, etc.

The classified image clearly shows linear objects such as dirt roads, roads and railways, forest clearings and clearings with power lines. They are particularly visible where they cross forests due to their light tone. The most visible are dirt roads built on the highest ground, with their lithological base being sands. But within settlements, they often disappear, as they have identical or similar brightness to other elements that form the settlement. Due to their special internal organisation, settlements can be clearly identified against a less structured background. The rectangular shape of buildings and gardens and the network of roads leading to or crossing them play a significant role in this.

It should be noted that due to the complex colour scheme, the detail of the settlements in the classified image is much higher than in the panchromatic satellite image. Colour combination is also an identifying feature of the natural conditions and location of the territory.

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While the colours of peat bogs, forests, and meadows dominate on the interfluve, and the colours that reflect different degrees of humusification of arable land are much less common, the ratio of cover and, therefore, their brightness is somewhat different on the birch terraces of the Dniester River. In the second case, additional deciphering features of settlements are the large size of the surrounding agricultural land, while in the interfluves it is smaller. Thus, satellite imagery is a useful tool for determining landscape features of a territory, but it cannot be relied upon entirely for landscape mapping.

The boundaries of plant communities on the images may not coincide with the boundaries of landforms, which complicates the process of delineating tracts. In addition, the images may contain patches of developed areas covering several landscape systems. This makes it difficult to identify them in black and white images. Deciduous and coniferous forests can be shown in the same tone in panchromatic images, which also makes it difficult to distinguish them if they are located side by side.

The advantage of classified images is the ability to use digital processing techniques to automate the process of extracting image elements and classifying them. For example, machine learning algorithms can be used to identify soil types, which is faster and more accurate than a human expert. In addition, digital methods allow for the rapid processing of large amounts of data, which results in faster and more efficient mapping.

The colour scheme and detail of image elements on classified maps can make it difficult to understand and perceive the landscape. For example, if the colour of a satellite image is uniform, different elements on a classified map may stand out, which is likely to change the perception and understanding of the boundaries of the territory. For example, identifying areas with shallow groundwater using remote sensing is a rather difficult task. However, some features may indicate the presence of such zones, as mentioned above, such as increased topsoil moisture and moisture-loving vegetation.

Soil moisture can be determined using different spectral ranges. For example, in the optical range, measurements are made by determining the coefficients of spectral brightness and reflectivity of dry and wet soils, as well as the polarisation of reflected light. In addition, increased soil moisture can be detected in the infrared and microwave ranges by measuring the radiance temperature of the soil throughout the day. However, it should be noted that these methods do not directly indicate the occurrence of groundwater, but only provide indirect indications of the presence of high soil moisture. Therefore, a combination of several methods and detailed geological and hydrogeological information about the study area may be required to more accurately identify areas with shallow groundwater.

In addition, the variation of brightness values can lead to a sharp difference in the display of trace elements, which can make it difficult to perceive individual details on maps. Therefore, when constructing landscape boundaries, it is necessary to take into account not only classified maps, but also additional information about the landscape, in particular, orientation to the terrain, taking into account its physical and natural features. However, it should be noted that image classification has its limitations and drawbacks. For example, when using colour classification, errors can occur due to the similarity of colours of different objects.

Also, when processing large amounts of data, errors may occur due to incomplete or incorrect information, as well as the lack of a priori information about objects in images. Therefore, it is important to follow the correct methods of data processing and analysis, as well as to take into account possible errors and limitations when interpreting the results. These methods have their drawbacks. First and foremost, it is the insufficient study of moisture and the complexity of its interpretation.

Radar surveying methods determine the areas of waterlogging and the depth of groundwater occurrence using the complex permittivity of soils. However, given the lack of a priori information, it is difficult to adapt them to forecast the development of flooding processes. The method of cosmobioindication developed by G. Krasovsky makes it possible to control waterlogged areas by determining the state of vegetation cover by vegetation indices according to the degree of waterlogging. However, the application of this method is limited to uncultivated wetlands and ponds. Remote methods help to accurately determine the contours of flooded areas based on indicative signs and conduct operational monitoring. However, these methods have insufficient accuracy in determining the depth of groundwater.

Anthropogenic soil erosion is a complex phenomenon caused by both natural and economic factors. A set of measures to protect soils from erosion and rational land management can help maintain landscape balance in the face of complex terrain and diverse soil cover. The study of erosion processes and the formation of eroded soils is important for the development and implementation of effective erosion control systems and the rational use

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of eroded land. This allows us to get a complete picture of the condition and characteristics of eroded areas, identify their potential opportunities and limitations, and develop scientifically sound recommendations for the restoration and protection of these lands. Such research is an important element of the soil conservation strategy, as it allows for optimal use of resources and increased soil productivity. They also help to identify effective measures to combat soil erosion and prevent its further spread. The hydrothermal coefficient (HTC) is used to estimate the moisture availability of plants during the growing season and is calculated using the following formula:

$$HTC = \frac{(Tav+10)}{(Cav+10)}, \quad (4)$$

where Tav is the average air temperature during the growing season (usually from March to October), and Ccp is the average precipitation during the same period.

The HTC value is expressed as a percentage. The higher the HTC value, the greater the potential for plant productivity and soil erosion protection. For example, in regions with an HTC of more than 1.5, greenbelts are installed to protect against soil erosion. This is an effective method. Air humidity and winds have a significant impact on the intensity of erosion and on the evaporation of soil moisture, which can lead to a decrease in soil moisture turnover and an increase in the risk of erosion. In addition, strong winds can redistribute snow over the territory and lead to uneven freezing of the soil, which can increase the intensity of erosion. Taking these factors into account is important when designing erosion protection measures. Relief is an important factor that determines the nature of erosion processes. The example of the Holohori-Kremenets Ridge shows how a steep and high escarpment can increase the erosion activity of the river network and cause dismemberment of the relief. On the other hand, the mature denudation pattern that characterizes most of the area may reduce the intensity of erosion processes, as it has already passed the stages of active denudation and river valley formation. However, the topography is not the only factor that determines erosion processes in the region. The terrain can also be affected by climatic conditions, land use, and other factors. It is worth noting that, in addition to satellite imagery, geographic information technologies include other tools, such as geographic information systems (GIS). GIS can be used to process and analyze various geoinformation data, including satellite images, and create digital maps of various parameters of objects. Such maps can help to establish the relationship between various factors affecting erosion processes and identify the most vulnerable areas of the earth's surface. In addition, GIS can be used to predict the development of erosion processes based on mathematical models, as well as to develop and evaluate the effectiveness of erosion prevention measures.

The methodology for identifying patterns of landscape structure based on multidimensional spatial analysis using the theory of nonlinear oscillations allows us to study the influence of various factors on landscape formation and determine their interrelationships. The results obtained can be used for genetic interpretation of landscape habitats and understanding of the processes taking place in them.

Thus, it is important to take into account a systems approach in environmental research, as environmental problems are complex interactive systems that contain not only biological but also social and economic components. For example, morbidity and mortality rates can be caused not only by environmental factors, but also by social factors, such as living standards, access to medical care, etc. However, environmental factors can be one of the main causes affecting human health and the ecosystem as a whole. Therefore, to address environmental and health issues, it is important to conduct comprehensive research that takes into account various factors and the interrelationships between them.

To determine the impact of the hazard on the health of the local population, we identified areas of agricultural development with high dust concentrations located near industrial enterprises, the main sources of secondary air pollution [14]. The size of these zones was determined by calculating emission dispersion using the EOL software package.

The use of geoinformation technologies, in particular GIS and remote sensing, provides more accurate and complete information on the state of the environment and the development of environmental problems. This allows for more informed decision-making in the environmental sphere, reducing the risks of negative impact on the environment and public health.

Environmental forecasting based on geoinformation data helps to identify potential negative consequences of the development of settlements depending on various factors, such as air, water and soil pollution, ecosystem destruction, etc. Such analysis allows us to develop effective measures to reduce the negative impact on the environment, improve the health of technologically

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polluted areas and create more comfortable living conditions for the population. An important component of the successful solution of environmental problems is ensuring access to quality and reliable information for making informed decisions.

Based on the results of the study, it was determined that in the areas of direct impact of sources of secondary dust pollution, the impact of environmental hazards on the incidence of diseases among the population is increasing. The system of environmental safety management in a region with a high level of secondary dust air pollution involves a comprehensive system of technical and technological factors operating under conditions of intensive exposure to pollution sources. This system is based on the principles developed after a comprehensive analysis and synthesis of the results of previous theoretical and practical studies on environmental safety management at the regional level [15].

The effectiveness of departmental surveillance systems in relation to the defined tasks can be assessed within the framework of the following proposed assessments:

– spatial and temporal resolution of the network (minimum size and variability of the observed objects);

– parametric composition of observations (adequacy, necessity and sufficiency of the number of measured indicators to characterise the state of the monitored objects);

– efficiency of the observation network, i.e. the time of sending standard and extreme information to the consumer (this relative indicator is compared with the time of preparing a management decision, since for each type of object this time period may differ depending on the characteristic period of its variability);

– the degree of informatisation of the monitoring network (automation of collection, storage, processing and sending of monitoring data to the consumer);

– compliance with the goal set by the monitoring entity (target orientation to a specific type of management decision).

This means that the implementation of the management solution will reduce the amount of waste transported to storage sites by 2500–3000 tonnes per year. This reduction in waste will lead to a decrease in the level of man-made dust pollution in the study area [16]. The use of various on-board equipment on UAVs makes it possible to improve the monitoring system for assessing the risks of man-made pollution [17]. It is also possible to monitor, model and predict the state of the environment in a given region.

These are very interesting research results that demonstrate the potential of using the latest technologies to solve environmental problems. In particular, the environmental safety management system created for the hazards associated with secondary dust air pollution can help to effectively control and reduce the level of environmental pollution.

The developed technical solutions for eliminating hazard sources by involving fine dust waste in the manufacturing process of targeted products indicate the possibility of using this waste as secondary raw materials. Thus, the implementation of these technical solutions can reduce the negative impact of the industry on the environment. This will help ensure environmentally friendly production and preserve natural resources

Conclusions

The study found that dust pollution can pose an environmental hazard. The necessity of distinguishing between primary and secondary sources of danger in accordance with the main technological process of production is proved. A methodological approach to assessing environmental safety in conditions of intense dust pollution is proposed. The creation of new and improvement of existing methods for building cartographic models of environmental soil assessment is considered. This approach is based on the use of the method of comprehensive assessment of the level of technogenic hazard of industrial facilities and time series analysis. It has been established that manifestations of environmental hazards affect the morbidity of the population directly exposed to sources of secondary dust pollution of the atmospheric air.

In further research, it is advisable to analyse the state and trends in the development of methods, technologies and mathematical apparatus for the creation and application of systems for detecting and polluting soils using UAVs and other aerospace vehicles; to improve methods for detecting soil pollution using UAVs and satellite imagery.

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АЕРОКОСМІЧНІ ТЕХНОЛОГІЇ ВИЗНАЧЕННЯ ОЦІНКИ ЗАБРУДНЕННЯ ҐРУНТІВ

Актуальність. Дослідження оцінки забруднення ґрунтів оновані на наукових принципах, що визначають складну систему управління екологічною безпекою в умовах посиленої дії джерел вторинного пилового забруднення атмосферного повітря. Для забезпечення екологічної безпеки в умовах високого рівня пилового забруднення необхідно застосовувати та вдосконалювати відповідні моделі. Серед багатьох видів засмічення довкілля особливо небезпечним є пилове забруднення атмосферного повітря та осідання шкідливих речовин на ґрунті. Це забруднення може мати дві форми: пряме викидання забруднень від промислових підприємств (первинне) або формування вторинних забруднень через фізико-хімічні процеси в місцях зберігання пилоподібних відходів. Тонкодисперсні відходи після очищення повітря з розмірами менше ніж 100 мкм є особливо небезпечними. У сучасному екологічному спостереженні та оцінюванні забруднення ґрунтів особливу увагу звертають на дистанційні методи, що дають змогу ефективніше відслідковувати вплив людської діяльності та вирішувати екологічні проблеми. Використання безпілотних літальних апаратів є одним із таких методів, що має позитивні результати. **Мета статті** – розв’язання наукової проблеми вдосконалення аерокосмічних методів на основі безпілотного літального апарата (БПЛА) з метою моніторингу та оцінювання якості забруднення ґрунтів. **Об’єктом дослідження** є застосування аерокосмічних засобів для моніторингу та оцінювання стану ґрунтового покриву. Для реалізації цієї мети визначено такі **завдання:** дослідити сучасний стан і шляхи підвищення ефективності роботи БПЛА в системі екологічного моніторингу ґрунтів; розробити моделі екологічної оцінки; проаналізувати наявні підходи щодо застосування аерокосмічних засобів для моніторингу та оцінювання стану ґрунтового покриву. **Висновки:** для оцінювання стану екологічної безпеки в умовах інтенсивного пилового забруднення атмосферного повітря запропоновано методичний підхід, оснований на модифікованому методі комплексного оцінювання рівня техногенної небезпеки промислових об’єктів.

Ключові слова: інформаційні технології; техногенна небезпека; ґрунтовий покрив; пилове забруднення; атмосферне повітря; технічні рішення; екологічна безпека; захворюваність населення.

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AUTOMATED RESOURCE MANAGEMENT SYSTEM FOR THE UTILITY SECTOR BASED ON WIRELESS SENSOR NETWORKS

The subject of this study is methods, tools and automated resource management systems for the housing and communal sector. The object of research is the process of controlling resource consumption at housing and communal facilities. **The aim of the study** is to develop an automated resource management system for the utility sector based on wireless sensor networks. To achieve this goal, the following tasks were **solved**: a review and analysis of existing methods, tools and automated resource management systems; selection of system components based on technical requirements and taking into account the selected LoRaWAN wireless connection technology; development of a structural diagram and algorithm for the operation of an automated resource management system based on wireless sensor networks; modelling of the process of managing the resources of the utility sector using a wireless sensor network based on t The following **methods** are used in the work: critical analysis of LoRa technology and other wireless IoT technologies, FOREL and K-means clustering methods. The following results were **obtained**: a general description of the automated resource management system was carried out, its composition and main tasks were determined, and technical requirements for it were established, wireless data transmission technology was selected, on the basis of which the automated resource management system was built, an in-depth comparative analysis of the most effective modern wireless technologies – LoRaWAN and NB-IoT – was carried out, system components were selected, a structural diagram and algorithm for the automated resource management system were developed, and the process of the automated resource management system was modelled. **Conclusions**: the application of the proposed automated resource management system provides high-quality control of energy consumption at the facilities of the housing and communal sector, makes it possible to control their volume, monitor and analyse energy consumption data, and manage the entire energy supply network as a single system, which is especially necessary in martial law. This approach allows rationalising the consumption of resources by household consumers, which means that the financial costs of energy supply will decrease and the level of energy savings in the country will increase.

Keywords: energy supply; wireless sensor network; automation; gateway; monitoring; sensor node; base station.

Introduction

The current state of the housing and communal sector of Ukraine requires innovative approaches in the technological aspects of energy management.

The studied concept of an automated resource management system based on wireless sensor networks (WSNs) is used to modernise the system of accounting for household subscribers and maintenance of in-building supply networks for resources (electricity, hot and cold water, gas, heating), to manage their supply and to provide information services to consumers of the supplying company.

Given the challenging economic situation in Ukraine amidst martial law and active hostilities, it became necessary to initiate a regime of rational and economical use of resources.

A modern method of solving the problem of regulating energy consumption is to create an automated resource management system (ARMS) based on the WSN with the ability to remotely monitor resource consumption and store the information received in an independent audit and control service centre.

Thus, the integration of functionally different wireless devices (meters, sensors, sensors) into a single system for accounting and management of resource consumption is in line with the global trend of smart grids based on the principles of energy saving and energy efficiency, and the construction of such grids at housing and communal services (HCS) facilities [1].

Resource conservation is the most effective way to modernise HCS. The total cost of generating one kilowatt of aggregate capacity through energy saving measures is less than 10% of the required investment in the construction of the corresponding generating capacity. The energy saving potential of HCS is 65%. More than 50% of this potential can be realised through the introduction of system metering based on modern innovative IT technologies.

Today, suppliers and utilities have an unprecedented opportunity to transform their supply networks into smart grids that allow them to manage the entire supply network as a single system. At the same time, consumers can not only receive a reliable report on the resources consumed online, but also directly participate in regulating energy consumption in their homes and

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apartments. This is facilitated by a new generation of smart metering devices and devices that support a bidirectional communication and control interface [2].

Thus, the task of developing an ARMS for the utility sector based on WSNs is relevant.

Analysis of recent research and publications

Most modern flow control systems are a complex of functionally integrated hardware and software and include sensor nodes with built-in data collection and transmission devices based on wireless technologies (Wi-Fi, GSM, LoRa, NB-IoT, etc.). The information is sent to the control and data transmission units (gateways or base stations), where it is read, processed and transmitted to the network server for further provision to external software applications, in particular, automated workstations for dispatch control.

The concept discussed in this article is very relevant and has been widely discussed in many scientific papers. For example, paper [3] provides a literature review of recent research on energy management systems and classifies works based on several factors, namely, energy management goals, approaches adopted for energy management, and solution algorithms. In addition, the paper discusses some of the most advanced methods and methodologies adopted or developed to address the energy management problem and provides a table for comparing such methods. The paper concludes by explaining the current challenges and limitations of energy management systems and outlines future research directions.

Paper [4] identifies external factors that influence the perception of the Building Energy Management System (BEMS) from the management perspective. An extended model based on the Technology Acceptance Model (TAM) was created to assess the implementation of BEMS in manufacturing industries. The model is analysed using the structural equation modelling (SEM) approach, where the external variables are taken as compatibility, features, technology complexity and perceived risk, and the internal variables are five dimensions: perceived ease of use, perceived usefulness, attitude, user satisfaction and behavioural intentions.

The study [5] describes the use and importance of energy management systems (EMS) used by utilities and end-users as a means of controlling electricity use and achieving energy savings. This approach also involves a comparative analysis of existing systems and devices, as well as the growing use of EMS in the latest smart grids.

Paper [6] investigated ways to increase the data rate in WSNs using LoRa and obtained analytical dependencies for building a signal structure taking into account the overlap factor and inter-symbol interference.

Article [7] describes smart grid projects implemented in Europe and presents their technological solutions with a priority on the use of smart metering in low-voltage networks. The article considers the telecommunication technologies chosen by several European utilities to implement smart meters at the national level. Further research will be conducted on the basis of European smart grid projects, highlighting their technological capabilities. The range of projects analysed includes both those that include smart metering and those in which smart metering applications play a significant role in the overall success of the project.

There are automated energy management systems and tools from Smartico. The company actively develops and manufactures hardware devices for IoT. These devices help solve many technological problems in both the industrial and utility sectors. The devices operate using the latest algorithms for energy-efficient LPWAN radio networks – LoRaWAN and NB-IoT.

Main areas of activity:

– development and production of smart meters for gas, water, electricity, heat with wireless data transmission and the ability to remotely block energy supply;

– telemetric energy management systems (ASCOE, ASTUE) to monitor the consumption of gas, heat, water, electricity with further analytics during the processing of the data, generation of reports and data transfer to the company’s accounting systems;

– control systems for the receipt, storage and delivery of fuel for the company’s process vehicles (equipment of fuel and lubricants depots);

– development of telemetry radio terminals for remote control of technological facilities (mobile and stationary objects, GPS monitoring);

– control of technological parameters of mining special equipment (car video surveillance and adaptive driver assistance systems);

– control over the operation of fuel dispensers (equipment with automated mobile fuel dispensing modules);

– development and production of devices for the Internet of Things. Production of sensors with autonomous power supply and wireless data transmission;

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– implementation of integrated solutions for the organisation of intelligent industrial and street lighting ("smart light");

– contract manufacturing of electronic equipment using its own production lines;

– development of equipment according to customer specifications;

– construction of wireless broadband transmission systems (organisation of wireless systems in the bands from 2 GHz to 5 GHz at speeds up to 200 Mbit/s);

– assistance in the development of technical specifications for the construction of control systems and control systems for technological equipment of various categories of complexity;

– process automation systems (solutions for automation of control, management and analytics processes at the enterprise);

– SCADA systems for automated and supervisory control of technological processes (automated process control systems using logic controllers and software);

– systems with the use of human-machine interfaces (HMI, Human-machine interface) for monitoring, controlling and programming technological processes;

– software development for automation of a wide range of technological processes for the enterprise [8].

There are also automated monitoring systems from YASNO. The management system allows us to increase control over the use of energy resources and reduce energy consumption through organisational measures, staff training, and the introduction of energy-efficient approaches in all key business processes.

Energy management involves building a mechanism for continuous improvement in reducing resource consumption based on the "plan – do – check – adjust" principle.

Advantages of monitoring systems from YASNO:

– cross-platform – the systems are capable of running on different devices and can be integrated into existing infrastructure;

– wireless transmission – information on energy consumption from the object of measurement is transmitted via GSM communication;

– versatility – control of electricity, water, gas, heat consumption, analysis of temperature, humidity, pressure, CO_2 and other resources;

– visualisation – flexible and customised dashboards for analysing and tracking consumption trends;

– measurement accuracy – the ability to use proven devices for commercial metering with a guaranteed low level of error;

– notifications – warning messages in case of emergencies, e-mail and messenger notifications;

– archiving and export – archiving of metering data for three years and the ability to export information to files.

It is also possible to integrate monitoring systems to meet customer needs. It is used when there are clear requirements for:

– flexibility of interface configuration;

– the ability to connect existing equipment;

– high metrological accuracy.

All the company’s offers include:

– system design – monitoring the energy consumption of devices from small businesses to large industrial enterprises;

– equipment package – depending on the project, the system may include smart meters, sensors, modems, controllers, etc;

– installation and integration – installation of equipment, integration into existing infrastructure, software configuration;

– analytics and reports – assessing the potential for savings in the event of changes in consumption or equipment [9].

The results showed that various topics are directly or indirectly related to the application of smart metering, such as smart home/building, energy management, network monitoring, and integration of renewable energy sources (RES).

Material and study results

The main task of ARMS is to fully or partially automate the processes of monitoring information and managing the results of the volume of consumed resources (electricity, gas, heating, hot and cold water) at HCS facilities using special metering devices, as well as creating a database of data obtained for previous periods, monitoring the state of the energy system of HCS facilities.

ARMS plays an important role in informing the policy of resource conservation and cost rationalisation in the process of interaction between executive authorities, supplier companies and consumers.

The system has the following tasks:

– high-quality remote monitoring of resource consumption, as well as reading and transmitting data from heat, hot and cold water, electricity and gas metering devices;

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– operational dispatch management and control of the HCS facility's power system.

An automated resource management system consists of:

– resource consumption metering devices (sensors, flow meters, etc.)

– pulse radio modem (gateway);

– hub (base station);

– ARMS server.

The proposed resource management system consists of sensors, recorders, means of collecting, transmitting, displaying and processing information.

To implement the function of collecting data from metering and control devices, ARMS provides for bi-directional signal transmission in the areas "metering device – radio modem – hub – server".

Information is transferred from the metering devices to the server automatically at a specified frequency or upon request from the server.

ARMS transmits the stored data from metering devices to external automated systems, service companies and consumers.

The software of the server, concentrators and radio modems must be adaptive to function with different metering devices via a digital interface.

To ensure information security, the data transmission channels between the radio modem, hub and server must be encrypted and noise-resistant coding must be applied to transmit the data.

The radio modems and hub contain a universal control and wireless communication unit for wireless data transmission.

Communication is one of the most important parts of any resource management system. Today, there are a significant number of wireless communication standards, but not all of them meet the necessary requirements for their use in ARMS. The main such standards are power consumption, coverage radius and bandwidth. A comparison of technologies in terms of range and operating frequency range is shown in Figs. 1 i 2.

Fig. 1. Wireless communication technologies by range

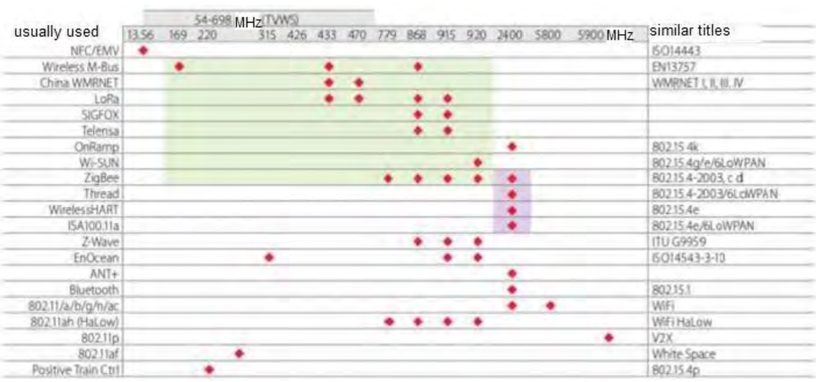

Fig. 2. Operating frequency ranges of wireless technologies

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Most standards, such as ZigBee, WiFi, etc., have a short range. And others, such as 3G and LTE, are very power-hungry and their range is not guaranteed. Although these technologies and communication modes are suitable for certain projects, they have limitations, such as difficulties in using them in areas without cellular coverage (GPRS, EDGE, 3G, LTE/4G) and the need for licensing. The parameters of the technologies are shown in Table 1.

Table 1. *Parameters of wireless technologies*

Parameter	LoRaWan	LTE-M	Sigfox	NB-IoT	BLE	Wi-Fi	Z-Wave	ZigBee
Communication standard	own	3GPP	own	3GPP	Bluetooth SIG	802.11	own	IEEE 802.15.4
Frequency	433 MHz, 868 MHz, 915 MHz.	from 700 MHz up to 2,2 GHz. from 452,5 MHz up to 467,5 MHz	868 MHz, 915 MHz, 921 MHz.	from 700 MHz up to 2,2 GHz, from 452,5 MHz up to 467,5 MHz	13,56 MHz.	2,4/5,0 GHz	from 868 MHz up to 926 MHz.	2,4 GHz
	RX 290 bit/s TX 50 Kbit/s	1 Mbit/s	0,1 Kbit/s	~200 Kbit/s	from 125 Kbit/s up to 2 Mbit/s	up to 150 Mbit/s	100 Kbit/s	250 Kbit/s
Transmission speed	star	star	star	star	P2P	star	Mesh	Mesh
Network topology	very high	very high	very high	very high	20	100	232	250+
Number of devices	from 5 km up to 15 km	5 km	from 10 km up to 50 km	5 км	from 40 m up to 1000 m	from 40 m up to 100 m	from 40 m up to 100 m	from 40 m up to 100 m
Radius of action	medium	high	medium	high	low	medium	medium	medium
Power consumption	mobile/local	mobile/local	mobile/local	mobile/local	local	local	local	local

Having analysed the characteristics of modern wireless communication technologies, as well as the technical requirements for modern resource management systems, it can be concluded that the ARMS under development requires an effective communication environment that meets the technical requirements, in particular, low power and wide range, as well as low cost, security and ease of deployment.

LPWAN technologies are most effective for connecting devices that need to transmit small amounts of information over long distances while ensuring long battery life. The low power consumption of these devices allows them to perform tasks at a low cost and with very little battery replacement. This distinguishes LPWAN from other wireless network standards such as Bluetooth, RFID, and ZigBee [10].

Fig. 3 shows a diagram of the bandwidth and range of various wireless standards. For example, Wi-Fi, with its high bandwidth of several Mbit/s and limited range of 100 m to 200 m, is most often used to form wireless local area networks within an office or apartment, but will be ineffective for use in large control system networks.

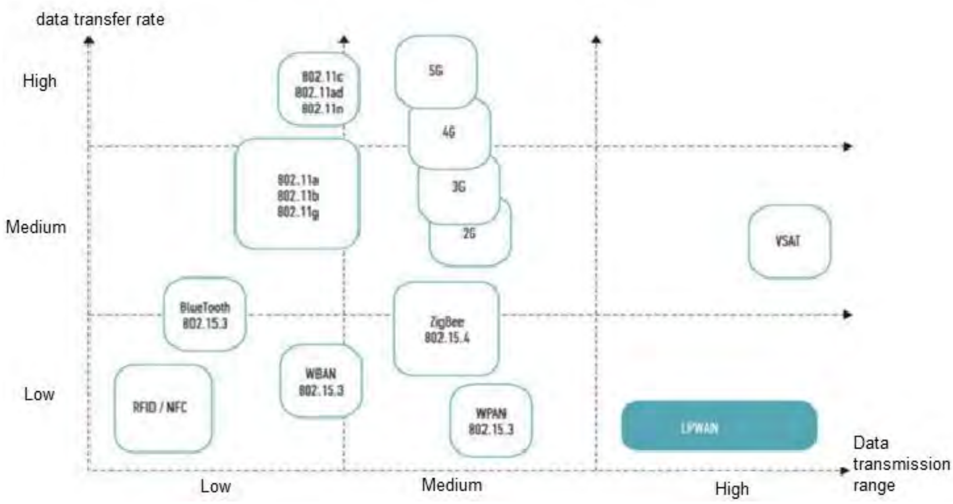

Fig. 3. Wireless technologies in terms of range and data transmission speed

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When choosing the optimal LPWAN technology for ARMS, the following factors should be taken into account: quality of service, battery life, latency, scalability, payload duration, coverage area, range, deployment, and cost.

Let's take a closer look at the characteristics of two similar modern LPWAN standards, namely LoRaWAN and NB-IoT, which are best suited for the resource management system being developed [11].

LoRaWAN is an open-architecture LPWAN system developed and standardised by the LoRa Alliance, a non-profit association of companies with more than 500 members. LoRa is a modulation technology applied at the physical layer that enables long-distance transmission of information using CSS (Chirp Spread Spectrum) modulation, which spreads narrowband signals over an extended channel, and provides high resilience and low signal-to-noise ratios.

NB-IoT operates in a licensed band and, similar to LTE, uses frequency division multiple access (FDMA) in the uplink, orthogonal FDMA (OFDMA) in the downlink, and QPSK (Quadrature Phase Shift Keying) modulation.

Both LoRaWAN and NB-IoT devices reduce their own power consumption when they go into sleep mode. However, as a synchronous protocol, NB-IoT consumes more power during operation than LoRaWAN, which is an asynchronous protocol, and for measurements with the same bandwidth, NB-IoT uses a higher peak current required for OFDM/FDMA modulation.

One of the factors that affects the cost and efficiency of LoRaWAN and NB-IoT is the better penetration of LoRaWAN in buildings. The maximum communication loss (MCL) for LoRaWAN uplink and downlink is 165 dB. At the same time, the loss for NB-IoT ranges from 145 dB to 169 dB for the uplink and 151 dB for the downlink, depending on the device class [12].

The lower energy potential of the communication line in NB-IoT leads to a significant reduction in battery life.

In addition, flexibility is a significant advantage of LoRaWAN technology. Unlike NB-IoT, LoRaWAN offers the deployment of a local network, i.e. a local network using a LoRa gateway, as well as the operation of a public network through base stations.

LoRaWAN technology has a fairly wide range (up to 20 km), meaning that it requires only three base stations to cover an entire city.

NB-IoT has a shorter coverage radius (i.e., the range is less than 10 km). The focus is on a class of devices that are installed in places far from the typical reach of cellular networks. Another problem is that NB-IoT deployment is limited to LTE base stations. This means that this technology cannot be used in rural or suburban areas where there is no LTE coverage.

Both technologies can compete in terms of service, as shown in Table 2 and Fig. 4.

It is also important to take into account the following types of costs: spectrum (licence), network/deployment and device costs (Table 3).

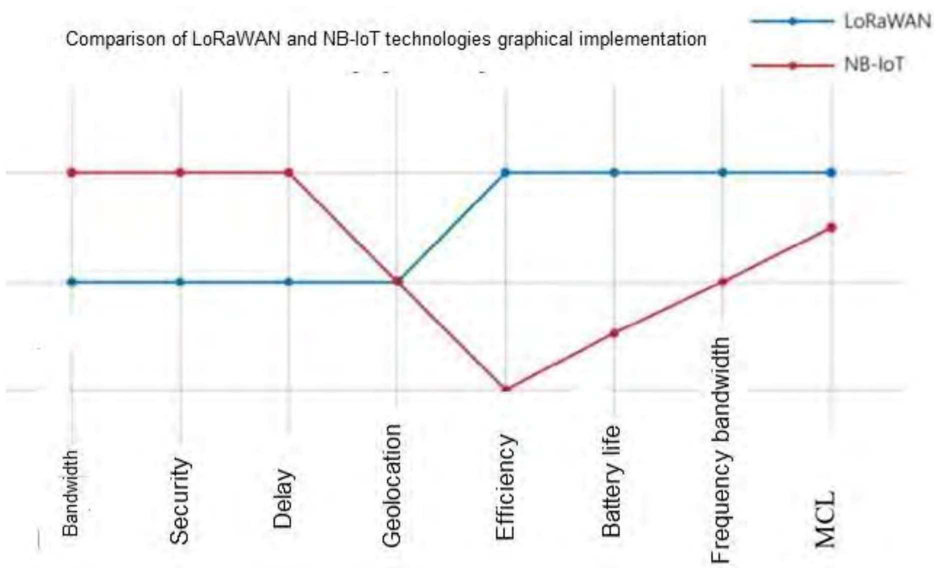

Fig. 4. Graphical visualisation of the comparison of LoRaWAN and NB-IoT technologies

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Table 2. *LoRaWAN and NB-IoT technical specifications*

Technical characteristics	LoRaWAN	NB-IoT
Modulation method	CSS	OFDMA/DSSS
Range	ISM	lisensed
Speed	from 0.3 kbit/s up to 50 kbit/s	UL: 1 kbit/s to 144 kbit/s DL: 1 kbit/s to 200 kbit/s
Autonomy	more than 10 years	up to 10 years
Range of action, km	5 (urban), 20 (rural)	1 (urban), 10 (rural)
Frequency band, kHz	125	180
MCL, dB	165	164
Peak current, mA	32	120
Current in sleep mode, μA	1	5
Safety	AES 128 bit	3GPP from 128 бiт up to 256 bit
Cost efficiency	high	middle
Support	LoRa Alliance, IBM, Cisco, Actility, Semtech…	3GPP, Ericson, Nokia, Huawei, Intel…
Private network permission	yes	no
Ecosystem	Communication services are available in 40 countries and 250 cities. LoRaWAN is already an IoT network standard in many countries. The LoRa Alliance covers more than 500 companies.	According to the GSMA, in April 2017, 40 NB-IoT networks were tested worldwide, and only four networks were fully operational.

Table 3. *Types of LoRaWAN and NB-IoT costs*

	LoRaWAN	**NB-IoT**
Spectrum cost, €	free	> 500 / MHz
Cost of deployment cost, €	>> 100 / gateway	> 15 000 / base station
Cost of the end device, €	> 1000 / base station	> 20

After analysing the information in Tables 2 and 3 comparing the two technologies, it becomes obvious that, unlike NB-IoT, LoRaWAN is optimal in most respects for its implementation in the ARMS under development.

Study results and their discussion

After selecting the communication standard, the ARMS structural diagram was created, and the main operating functions of each element of the system were identified and analysed (Fig. 5).

The end devices (sensor nodes) are connected to the LoRaWAN gateway in a star topology, and signals are transmitted between them using LoRa modulation. Within the LoRaWAN technology, this topology allows for the connection of new sensor nodes, and their number is not determined by the power consumption of the latter. Thanks to the peer-to-peer point-to-point connection, the star topology is more efficient and cheaper to implement than the mesh topology. The level of network security is much higher because endpoints operate independently. In the event of an attack on a node, the rest of the network will remain intact [13].

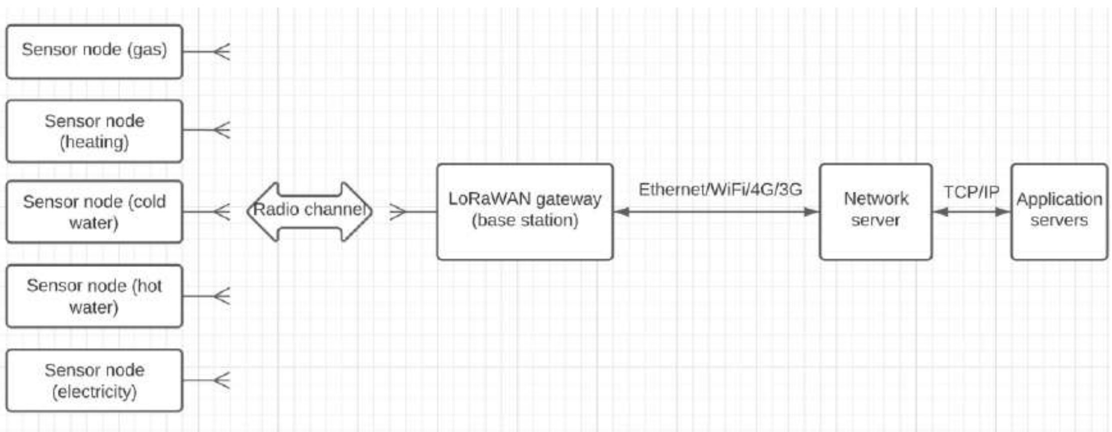

Fig. 5. Block diagram of an automated resource management system

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In addition, it should be noted that this topology allows you to offload the server, and the probability of collisions is very low due to the peculiarities of the base station (BS). This is because in this case, frequency channels are switched in an unlicensed frequency range.

Thus, the star topology network is optimal for minimal power consumption and provides the longest battery life on the sensor node side.

Sensor nodes perform control and measurement functions [14]. They include the necessary sensors and controls. Sensor nodes can be located at a considerable distance from the gateway and are powered by a battery. Each of them establishes communication with the gateway via the LoRaWAN radio channel, which allows for a large number of connections.

A gateway (BS or hub) is a device that receives signals from sensor nodes via a radio channel and sends them to a transit network. The transit network can be Ethernet, WiFi, 3G, 4G, or mobile radio networks. The gateway and sensor nodes form a star network topology. The gateway has many multi-channel receivers to process signals in several channels simultaneously or even several signals in one channel. Accordingly, several such devices provide network coverage and transparent information transfer between sensor nodes and the server [15].

The network server performs the following control functions in the network: speed adaptation, storage and processing of information.

The application server can also remotely monitor the operation of sensor nodes and collect the necessary information from them.

The element base for the automated resource management system was selected, where the LoRaWAN Conduit IP67 from Multi-Tech was chosen as the main base station or gateway. The gateway kit includes a 12 V power supply, a 3G/LTE antenna, microUSB and Ethernet cables, a manual, and a LoRaWAN module (MTACLORA-868).

Pin antennas for the 868 MHz band are used in security alarm devices and operate in the range from 868 MHz to 868.2 MHz. The W1063 antenna is recommended by MultiTech for use with MTDOT-868 LoRa modules and LoRaWAN gateways. The 868 MHz antenna with a circular radiation pattern and 5 dB gain is used as a "base" antenna in data collection systems with a short communication range.

The Metromatic™ WSII water meter was chosen – an ultrasonic flow meter for measuring the consumption of cold and hot water in residential or commercial premises. The meter is supplied with an integrated communication system with low power consumption over long distances, LoRaWAN or NB-IoT, as well as a wireless backup OMS. Data is collected in real time, processed automatically and made available to the IoT service provider.

We chose a Smartico Gas Meter ultrasonic gas meter for domestic use. Such meters are available in the G-1.6, G-2.5, G-4, G-6 size range and are used to measure the volume of natural and liquefied gas. The meter allows for visual and remote data acquisition.

A three-phase electricity meter was selected – MTX direct connection with a built-in LoRaWAN radio module. The device is designed to measure the consumed and generated active and reactive electricity in AC networks with a rated voltage of 3x220/380 V and automatically transmit the readings to the supplier.

A compact heat meter HYDROCAL-M4 was selected for energy measurement. The device is used for heating and/or cooling in premises served by centralised systems. The processing of data on the temperature difference between the supply and return pipes (DT), together with data on the volume of heat transfer fluid used by each user, allows for an accurate calculation of the amount of energy consumed.

The Jooby universal interface radio module with a pulse counter was selected. The purpose of the radio module is to read pulses from all types of resource meters. The information is transmitted to the server via the LoRaWAN wireless network, where it is converted into indicators. Intelligent sensors detect external interference with the radio module and immediately alert you. The radio module is fixed near the metering devices in several ways: with a DIN rail, cable tie, or screws to the wall. After that, the device is activated in the installer’s mobile application. The whole process takes a few minutes and does not require the meter to be removed.

An ARMS algorithm has also been developed, consisting of six main sequential stages (Fig. 6).

At stage I, the end devices measure the flow rate.

At stage II, the information is transmitted to the gateway via a radio channel.

At the third stage, the gateway processes the information.

Stage IV – data transfer from the gateway to the network server.

The following stages involve the server processing the information and then transferring it to the application servers.

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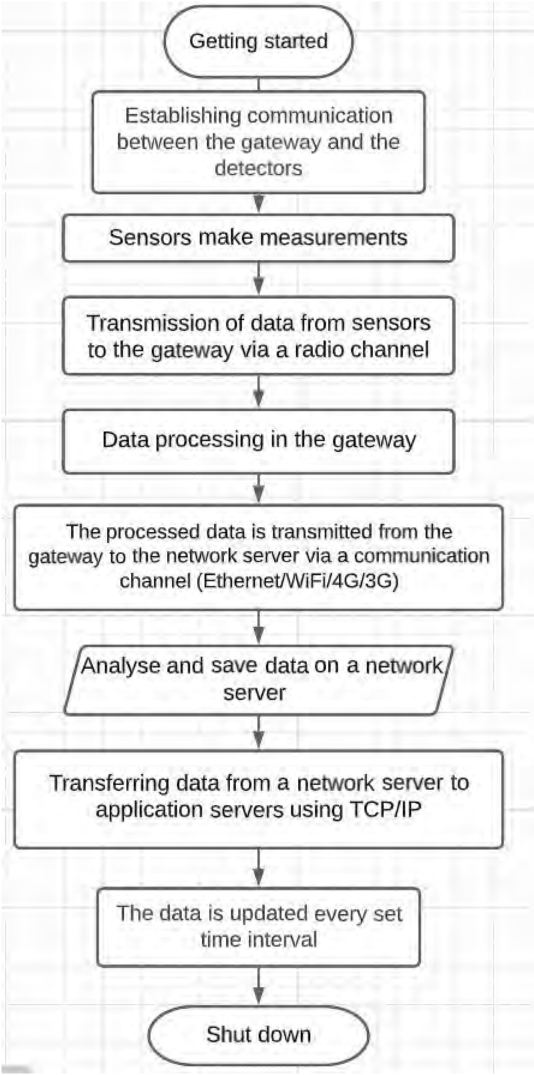

Fig. 6. The ARMS operation algorithm

After completing these stages, the information is updated after a specified period of time.

The clustering of nodes around the base stations was carried out using the FOREL and K-means methods.

The use of both of these basic clustering algorithms allows us to obtain accurate and independent results that can be further analysed and compared.

For this purpose, we consider a network of 20 thousand nodes in a city area with sides of 7 km. All nodes are randomly distributed according to a uniform distribution law. The maximum range of a gateway is 824 m. The FOREL clustering method was used to determine the gateway locations.

This method solves the problem of minimising the total distance between the centres of mass of the clusters and the elements of these clusters (1–2).

$$\{x_i, y_i\} = \arg\min_{x_i, y_i} \sum_{j=1}^{k} \sum_{r=1}^{n_j} d\left(C_j, e_{j,r}\right), \ i = 1...k, \qquad (1)$$

where $\left(C_j, e_j, r\right)$ is the distance between the centre of mass of the j-th cluster C_j and the r-th element of the j-th cluster e_j, r.

Coordinates of the centre of mass of the j-th cluster

$$C_j = \{x_j, y_j\}, \ x_j = \frac{1}{n_j} \sum_{r=1}^{n_j} x_{j,r} \qquad y_j = \frac{1}{n_j} \sum_{r=1}^{n_j} y_{j,r}, \qquad (2)$$

where n_j – number of elements in j-th cluster;

$x_{j,r}$, $y_{j,r}$ – coordinates of the r-th element in j-th cluster.

This algorithm determines the coordinates of the centres of mass of the clusters, which can be used as positions for the placement of gateways.

The FOREL clustering modelling resulted in a network containing 25 clusters (base stations). The result of this modelling is illustrated in Fig. 7, *a*.

The network clustering was also modelled using the K-means method [16]. For 25 base stations, this method divided the network into clusters as shown in Fig. 7, *b*.

In Fig. 8 (*a* – for the K-means clustering method, *b* – for the FOREL clustering method – a formal element) shows the relative distribution of IoT devices in the considered LoRaWAN network for both algorithms. The vertical axis in Fig. 8 indicates the number of IoT devices, and the horizontal axis indicates the relative distance between the IoT device and the cluster centre.

A negative value of the relative distance in the figures indicates that the device is located to the right of the cluster centre. As we can see in Fig. 8, IoT devices are mostly distributed around the cluster centre for both clustering methods.

Therefore, the average number of nodes in each SF zone can be determined. Fig. 9 shows the average number of nodes in each SF zone for different clustering methods: *a* – for the K-means clustering method, *b* – for the FOREL clustering method.

In addition, the capacity of the LoRa base station was calculated (results in Table 4).

Let us calculate the capacity of a LoRa base station for the two clustering methods considered, where the nodes are distributed differently by the area of radio coverage zones (Fig. 10).

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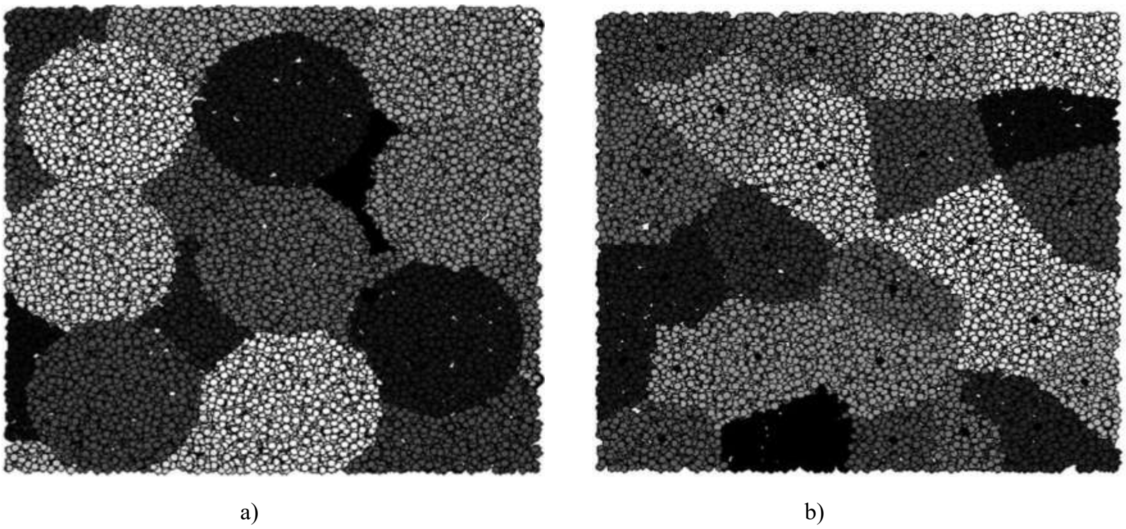

Fig. 7. Modelling results: a) FOREL clustering method; b) K -means clustering method

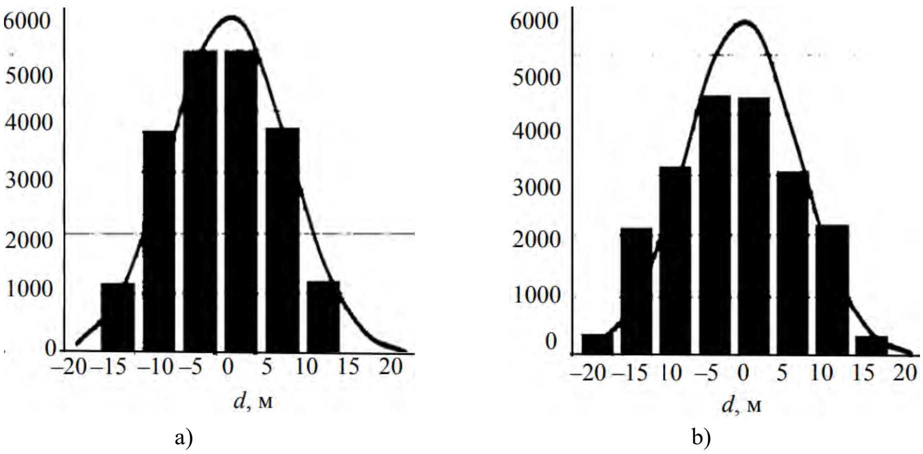

Fig. 8. Relative distribution of IoT devices in the considered network:
a) for the K -means clustering method; b) for the FOREL clustering method

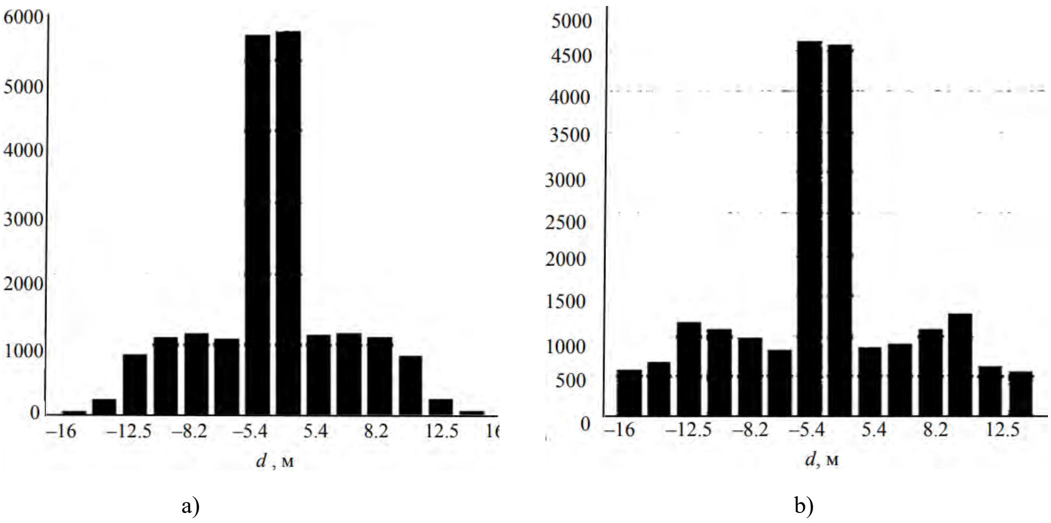

Fig. 9. Average number of nodes in each SF zone for different clustering methods:
a) for the K -means method; b) for the FOREL method

Table 4. *Results of calculating the capacity of the BS*

Clustering method	N_{ENpac} per day	Flow intensity λ at $P_{los} = 2\%$	Number of packets per day	Number of devices per BS
FOREL	24	0,01	79223	3300
K -means	24	0,01	92292	3845

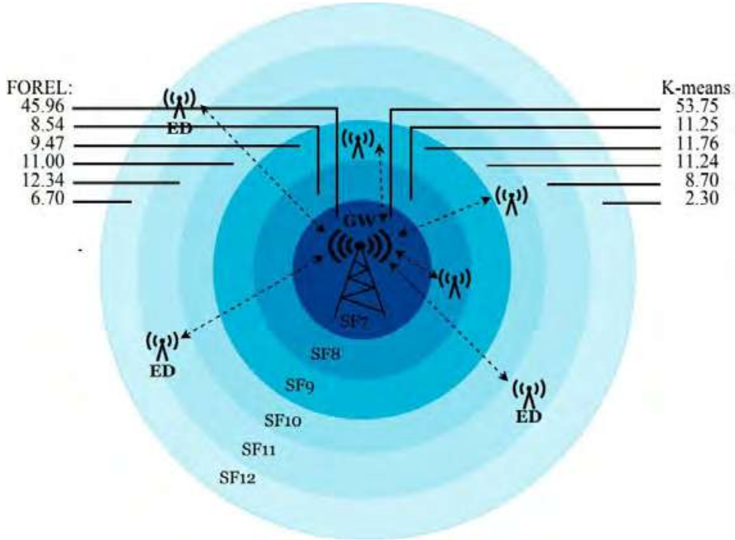

Fig. 10. The probability of using nodes in different *SF* zones if they are distributed by two methods of clustering

Fig. 10 shows the probability of using nodes in different SF zones if they are distributed according to the FOREL method, which is 45.96%, 8.54%, 9.47%, 11%, 12.34%, 6.7 For the K -means method, the probability of node utilisation is 53.75%, 11.25%, 11.76%, 11.24%, 8.7%, 2.3%.

Conclusion

Thus, the main modern technologies and standards of wireless information transmission are considered. A comparative analysis of them is carried out and the main advantages and disadvantages in the process of their use in modern commercial wireless systems for monitoring and management of resources present in the Ukrainian market are identified. The wireless data transmission technology has been selected, on the basis of which an automated resource management system has been built.

An in-depth comparative analysis of the most effective modern wireless technologies LoRaWAN and NB-IoT for building such a system was carried out. To create an automated resource management system, the LoRaWAN technology was chosen, which proved to be optimal for most technical requirements.

The simulation results made it possible to calculate the capacity of the LoRa base station for the two clustering methods considered and, accordingly, the number of end nodes per base station.

Implementation of the proposed automated resource management system at HCS facilities has the following advantages: reduction of resource consumption; transmission of information in different modes with a given frequency or at the request of the server; free access to viewing the volume of costs for dispatchers of service organizations and for consumers; notification of emergency situations and a quick response to them; increasing the energy efficiency of HCS facilities; creation of an effective dispatching system; reduction of operating costs of the HCS facility; forecasting of the future. The use of the system ensures rational consumption of resources by household consumers, which means that the financial costs of supplying resources will decrease and the level of energy savings in the country will increase.

In the future, the automated resource management system can be improved by modernising and expanding its functionality and increasing its overall efficiency. This can be achieved by adding additional types of sensor nodes to the system (ventilation, lighting, fire alarm, leakage sensors, etc.), expanding and optimising the software, adding backup power supplies, and replacing the standard antennas with more powerful ones.

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АВТОМАТИЗОВАНА СИСТЕМА УПРАВЛІННЯ РЕСУРСАМИ ДЛЯ КОМУНАЛЬНОГО СЕКТОРА НА БАЗІ БЕЗДРОТОВИХ СЕНСОРНИХ МЕРЕЖ

Предметом дослідження є методи, засоби й автоматизовані системи управління ресурсами для житлово-комунального сектора. **Об’єктом** є процес контролю витрат ресурсів на об’єктах житлово-комунального господарства. **Мета статті –** розроблення автоматизованої системи управління ресурсами для комунального сектора на базі бездротових сенсорних мереж. Для досягнення поставленої мети вирішені такі **завдання**: розглянуто й проаналізовано наявні методи, засоби автоматизованих систем управління ресурсами; обрано компоненти системи на основі технічних вимог до неї та з урахуванням обраної технології бездротового з’єднання LoRaWAN; розроблено структурну схему й алгоритм роботи автоматизованої системи управління ресурсами на базі бездротових сенсорних мереж; проведено моделювання процесу управління ресурсами комунального сектора з використанням бездротової сенсорної мережі на базі технології LoRa. У роботі застосовано такі **методи:** критичний аналіз технології LoRa та інших бездротових технологій IoT, методи кластеризації FOREL і K-means. Здобуто такі **результати:** здійснено загальний опис автоматизованої системи управління ресурсами, визначено її склад та основні завдання, а також встановлено технічні вимоги до неї, обрано технологію бездротової передачі даних, на основі якої побудовано автоматизовану систему управління ресурсами, проведено глибокий порівняльний аналіз найефективніших сучасних бездротових технологій – LoRaWAN та NB-IoT, обрано компоненти системи, розроблено структурну схему й алгоритм роботи автоматизованої системи управління ресурсами, змодельовано процес управління ресурсами комунального сектора з використанням бездротової сенсорної мережі на базі технології LoRa. **Висновки:** застосування запропонованої автоматизованої системи управління ресурсами забезпечує якісний контроль енерговитрат на об’єктах житлово-комунального сектора, дає змогу контролювати їх обсяг, проводити моніторинг та аналіз інформації про енерговитрати, керувати всією мережею енергопостачання як єдиною системою, що особливо необхідно в умовах воєнного стану. Такий підхід допомагає раціоналізувати споживання ресурсів побутовими споживачами, а це означає, що фінансові витрати на енергопостачання зменшаться, а рівень економії енергоресурсів у державі загалом зросте.

Ключові слова: енергопостачання; бездротова сенсорна мережа; автоматизація; шлюз; моніторинг; сенсорний вузол; базова станція.

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