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INTEGRATED MODEL FOR ASSESSING THE ENVIRONMENTAL SAFETY OF URBAN WATER SUPPLY AND SEWAGE SYSTEMS

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Abstract. The study presents a systematic approach to improve the environmental safety of urban water supply and sanitation systems through the development of a hierarchical logical-mathematical model. The proposed model combines quantitative and qualitative assessment criteria for classifying the safety status of individual subsystems and the system as a whole. The methodology was tested on the example of a territorial community in south-eastern Ukraine, which made it possible to identify critical infrastructure elements and justify the implementation of technical and organisational measures, in particular, the reconstruction of water supply networks, the modernization of pumping equipment, and the installation of local treatment facilities to ensure compliance with environmental and sanitary standards. The paper proposes a method for integrating blue-green infrastructure elements into urban drainage systems. A multi-level integration scheme, from the household to the district level, has been developed to promote rainwater infiltration, reduce surface runoff, and water pollution. The results of numerical modelling confirm the effectiveness of combined green solutions for improving the environmental performance and sustainability of urban water systems. It has been proven that the implementation of integrated engineering and environmental models is a key factor in the sustainable management of water supply and drainage in conditions of increasing anthropogenic and climatic stress.

Keywords: environmental safety, urban water supply, wastewater disposal, blue-green infrastructure, system modelling, stormwater management, sustainable development of the urban environment

1.Introduction. Research into the issue of ensuring the environmental safety of various urban wastewater disposal systems is one of the priority areas of modern science. Therefore, to formulate the category of ‘environmental safety of urban sewage systems’, we will consider it from the modern perspective of this issue. The term ‘urban wastewater systems’ in this work refers to centralized or decentralized wastewater systems and surface runoff management systems of all forms of ownership that serve individual settlements and/or Amalgamated Territorial Communities (ATCs). The authors [1] define the environmental safety of the state as a concept related to the protection of natural resources and environmental balance, ensuring sustainable economic development, preventing environmental crises, and ensuring an adequate standard of living for the population. We should agree with the opinion of scientists [2] who consider man-made emergencies to be one of the main internal threats to environmental safety in Ukraine. According to open sources, from 1991 to 2023, man-made emergencies accounted for 59% of the total number in Ukraine (Fig. 1).

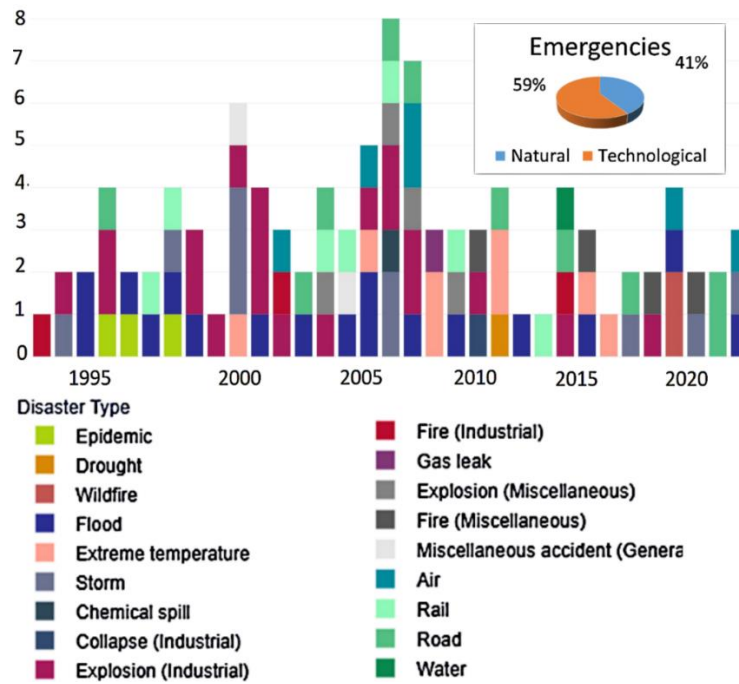


Fig. 1. Emergency situations in Ukraine from 1991 to 2023

The authors [3], focusing on the security aspects of sustainable development, note that environmental security is a key factor in achieving sustainable development, and that the diversity of countries' levels of development in the context of globalisation can lead to exacerbated environmental safety problems and challenges for sustainable development. In his work 'The Economics of Climate Change: The Stern Review,' Stern N. [4], analysing the economic consequences of climate change and their impact on human and property safety, insists on the need for urgent action and notes that the price of inaction exceeds the cost of action. At the same time, the authors [5] argue that the introduction of an environmental accounting system may negatively affect the financial performance of corporations, but will not significantly improve their environmental performance. There should be a positive correlation between environmental performance and the financial results of companies.

Virakun T. et al. [6] propose in their work the application of an interdisciplinary approach to wastewater treatment management to meet the growing demand for safe and clean water in the future. Proskurin O. and colleagues [7] propose to consider the definition of the environmental risk of treatment facilities as the probability of violating the established water quality standards of a water body due to wastewater discharge and to calculate the permissible concentrations of substances in wastewater based on an assessment of the environmental risk caused by the discharge of wastewater into a water body.

Taiwanese scientists [8] assessed the environmental impact based on the EPD 2018 method, using a number of parameters to measure the environmental impact, where the measured environmental indicators were eutrophication, Global Warming Potential over 100 years (GWP100), Biological Oxygen Demand (BOD), and water deficit. Loy-Pilch M. and Zakrzewski A. [9] consider the use of mixed methods, which in turn involves the simultaneous application of quantitative and qualitative methods, to be the most optimal for assessing environmental risk. The authors [10] propose to assess the environmental safety risk of treatment facilities using the Root Cause Analysis (RCA) method, followed by processing the results using the Failure Mode and Effects Analysis (FMEA) method to obtain a Risk Priority Number (RPN). The use of the FMEA method to assess individual risks arising at treatment facilities is also supported by other researchers [11].

Despite the considerable attention and relevance of issues of environmental safety of wastewater systems and the operational reliability of their individual components, the assessment of the environmental safety of urban wastewater systems as a whole remains insufficiently covered in the scientific literature. This also applies to the integration and interaction between water supply and

wastewater systems, which significantly affect the overall efficiency and environmental safety of water resources. Water supply and wastewater systems are closely interrelated. However, in many cases, these systems are analysed and evaluated separately, which can lead to an incomplete understanding of their interaction and insufficiently effective environmental safety management.

The **aim** of this work is to develop a comprehensive approach to assessing and ensuring the environmental safety of urban water supply and wastewater systems by developing an integrated logical mathematical model that takes into account the interrelationships between these systems, allows the identification of potential environmental risks, and justifies effective management and technical solutions to improve the sustainability of water management complexes in urban areas.

2.Methodological principles for assessing the environmental safety of urban water supply and wastewater disposal systems. A scientific approach should be used when developing a strategy to improve the environmental safety of all water supply and sewerage facilities. This approach should take into account a complex set of numerous and unrelated factors that may directly or indirectly affect the lifespan of each element of the system and its performance of relevant sanitary and environmental functions to varying degrees. Therefore, the coordinating vector of the system model should be the use of integrated indicators of the state of the system elements.

To assess environmental safety, a systemic model called the ‘Urban Water Supply and Sewerage System’ (UWSS) is being developed, which uses a structural approach to organizing data and information, allowing complex systems to be systematized. The hierarchical logical-mathematical structure of the Municipal Water Supply and Wastewater System (MWSWS) model is used to classify the safety status of the urban water supply and wastewater disposal system (Fig. 2) and consists of two systems: ‘Municipal Water Supply System’ and ‘Municipal Wastewater Disposal System’.

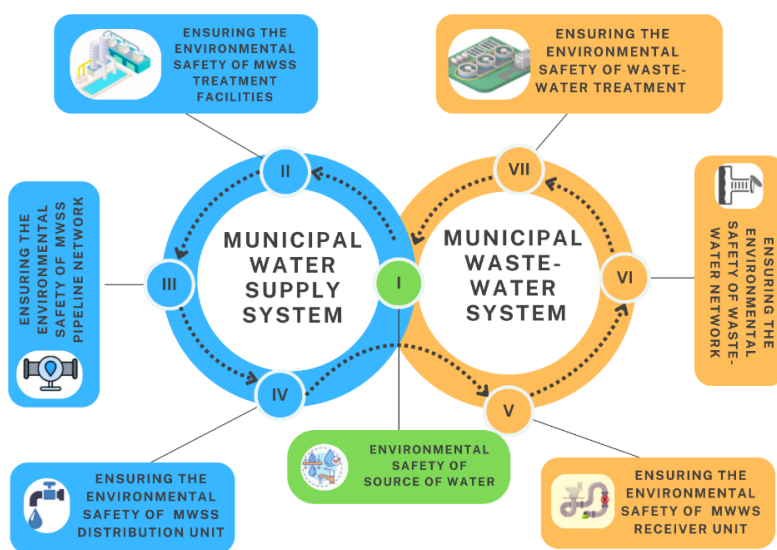


Fig. 2. Block diagram of the model of the ‘Urban Water Supply and Wastewater System’: MWSS – Municipal Water Supply System; MWWS – Municipal Wastewater System

The assessment of the condition of systems and subsystems in the ‘Urban Water Supply and Sewerage System’ model is performed in parallel using two approaches: quantitative and qualitative. A logical function based on a set of qualitative states of individual indicators classifies the qualitative state of the entire system. Quantitative measurement is performed on many states of individual subsystems. The quantitative indicator of the entire system is determined from the quantitative indicators of individual subsystems. The environmental safety of the system is assessed according to the degree of approximation of measures to a specific standard (Fig. 3). Let us consider a step-by-step assessment of the criteria using the example of the ‘Water receiver node’ subsystem.

A step-by-step assessment of the criteria is carried out using the example of the MWWS receiving unit subsystem. The MWWS receiving unit subsystem consists of three units: Chemical

Contamination, Bacteriological Contamination, and Receiver Operation. The 'Receiver Operation' unit is designed to assess the main factors affecting the environmental safety and reliability of internal drainage systems directly at consumers, as well as local treatment facilities located directly at the consumer:

z_1 are physical and design features (pipeline material, service life and wear, and design features);

z_2 are hydraulic features (wastewater flow rate, which is directly related to the water supply schedule, reliability of the consumer's drainage system, and type of the consumer's drainage system);

z_3 are operational features.

The state of the subsystem for each factor is assessed by a set of logical alternatives for the state of the system, which can be represented by a vector: $Z(z_i) = Z_1, Z_2, Z_3$ = 'environmentally safe system', 'conditionally environmentally safe system', 'environmentally unsafe system', the components of which are determined by the following equation:

$$Z(z_i) = \begin{cases} Z_3, & \text{if } z_i < N_1^i \\ Z_2, & \text{if } N_1^i < z_i \leq N_2^i \\ Z_1, & \text{if } z_i > N_3^i \end{cases} \quad i = 1, 2, 3. \quad (1)$$

The standards for this block can be determined based on the reliability index of the drainage system. The main parameters of the reliability of internal drainage systems are the probability of their failure-free operation $P(t)$, the probability that under specified operating conditions, no element will fail within a certain period of time. The parameter $P(t)$ is calculated using the equation:

$$P(t) = \frac{8760 - t_{br}}{8760}, \quad (2)$$

where t_{br} is the duration of interruptions in water supply; $8760 = 24 \cdot 365$ is the number of hours in a calendar year.

To evaluate the aggregated system criterion, the logical measurement function is determined:

$$T_{ij} = \varphi_k(Z) = \begin{cases} -1, & \text{if } Z = Z_3 \\ 0, & \text{if } Z = Z_2 \\ 1, & \text{if } Z = Z_1 \end{cases} \quad k = 1, 2, 3. \quad (3)$$

The assessment of the condition of the 'municipal wastewater drainage receiving unit' is carried out according to the worst value of the indicators of the 'Sewage receiving unit', which informs about the development of a set of measures to improve the reliability of internal networks and plumbing, as well as to improve the environmental safety of wastewater.

The assessment of consumer effluents in terms of chemical pollution is represented by the vector {'environmentally hazardous', 'conditionally environmentally safe', 'environmentally safe'}. These components of the vector are determined by the following logical function:

$$C_s(j_i) = \begin{cases} C_{s3}, & \text{if } j_i > J_0 \\ C_{s2}, & \text{if } J_1 < j_i \leq J_0 \\ C_{s1}, & \text{if } j_i \leq J_1 \end{cases} \quad (4)$$

The assessment of environmental safety for the 'Chemical pollution' block is determined by the following condition:

$$C_s = \max C_s(j_i) \quad (5)$$

The state of the block on the set of classes C_{si} is assessed by the measure $\varphi_r(C_{si})$:

$$\varphi_r(C_{si}) = \begin{cases} -3, & \text{if } C_{si} = C_{s3} \\ -2, & \text{if } C_{si} = C_{s2} \\ 0, & \text{if } C_{si} = C_{s1} \end{cases} \quad r = 1, 2, 3. \quad (6)$$

The assessment algorithm in the 'Bacteriological contamination' block is based on the same principle as in the 'Chemical contamination' block. The graduated levels of the bacteriological contamination criterion determine the situation vector $B_s(w_i)$:

$$B_s(w_i) = \begin{cases} B_{s3}, & \text{if } w_i > W_0 \\ B_{s2}, & \text{if } W_1 < w_i \leq W_0. \\ B_{s1}, & \text{if } w_i \leq W_1 \end{cases} \quad (7)$$

where vector B_s represents a set of alternatives: {‘environmentally hazardous’, ‘conditionally environmentally safe’, ‘environmentally safe’}.

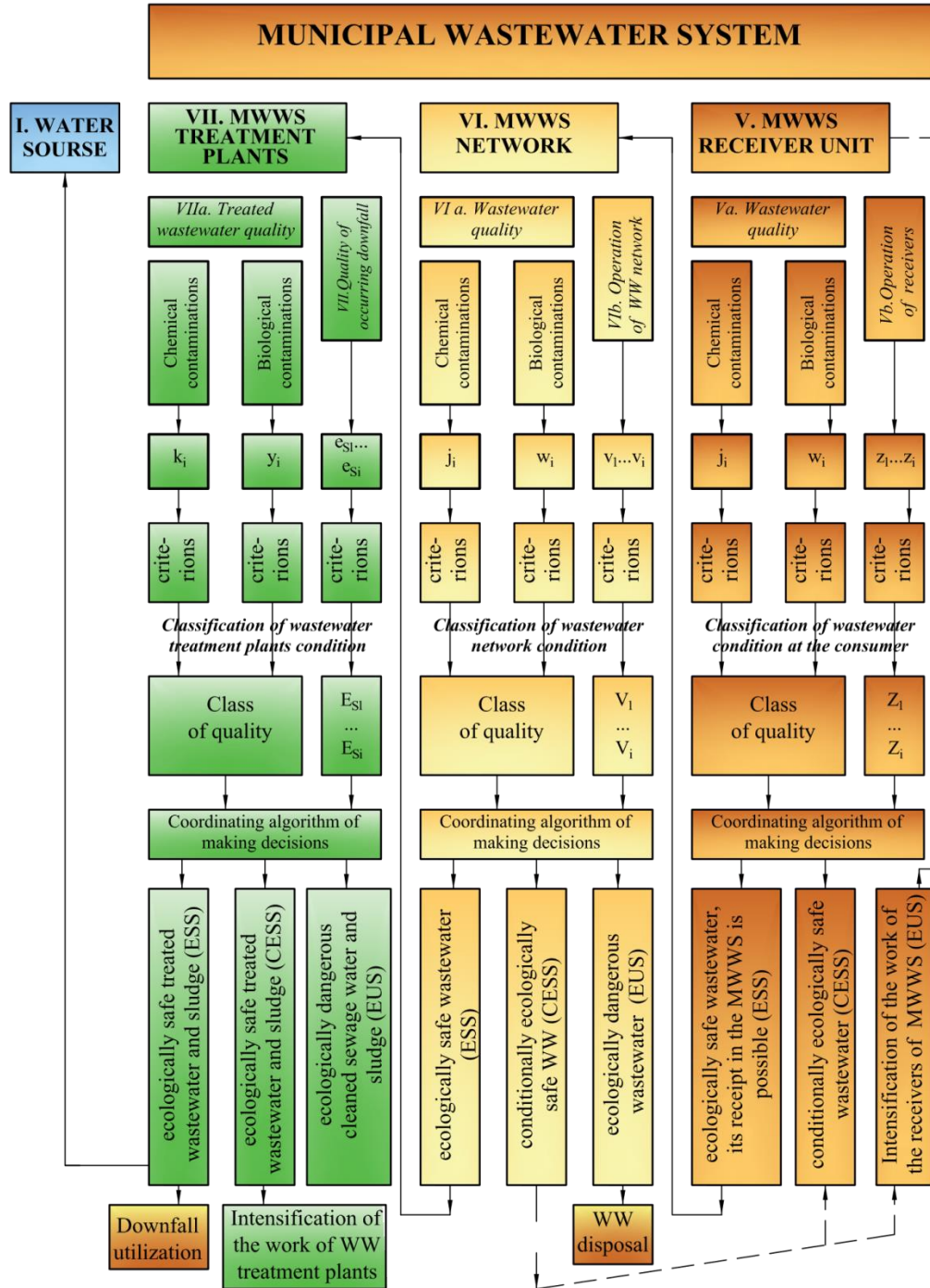


Fig. 3. Structural diagram of the ‘Urban Water Disposal System’ as part of the general logical-mathematical model ‘MWWS’

A numerical measure function is defined on the set of alternatives (8):

$$\varphi_r(B_{si}) = \begin{cases} -3, \text{ if } B_{si} = B_{s3} \\ -1, \text{ if } B_{si} = B_{s2} \\ 0, \text{ if } B_{si} = B_{s1} \end{cases} \quad r = 1, 2, 3 \quad (8)$$

Thus, the quality assessment of wastewater discharged into municipal sewage systems is determined by the following expression (9):

$$C_s B_s = O_s - \operatorname{argmin} \begin{cases} \varphi(C_{si}) \\ \varphi(B_{si}) \end{cases} \quad (9)$$

If the water quality is assessed as 'conditionally environmentally safe' or 'environmentally hazardous', it is necessary to repeat the calculation, having previously carried out an analysis and intensified the work (or installation) of local treatment facilities at the reception point, based on the maximum pollution indicators. If the assessment is 'conditionally environmentally safe wastewater,' it is necessary to analyze the reasons for this situation and take measures to intensify the work of the reception points. After receiving the assessment 'environmentally safe wastewater,' the wastewater is sent to the sewerage system. The 'Sewerage' and 'Wastewater Treatment' subsystems are assessed in a similar manner.

3.Results of the environmental safety assessment of urban water supply and wastewater disposal systems. Figure 4 shows the results of the environmental safety assessment of the urban water supply and wastewater disposal system conducted within the rural united territorial community of south-eastern Ukraine based on the proposed system model. The water supply system of the settlements of the studied amalgamated territorial community showed that they operate in conditions of water supply shortage, and the flow rate of water intake sources and individual wells in the area has decreased during operation. Two alternatives were considered to solve this problem: connection to the existing municipal water supply system and the construction of new wells. Therefore, based on the technical and economic feasibility study, groundwater from new wells located near settlements can be recommended as additional sources of water supply. In addition, it is proposed to reconstruct existing wells and construct new ones, establish sanitary protection zones, and construct reservoirs (measures related to subsystem I).

The quality of water from water supply sources is characterised by an increased salt content. The wear and tear of the water supply network exceeds 50%. The quality of water at the consumer point is unsatisfactory, primarily due to the deterioration of water quality in the system during transportation through worn-out pipelines. Therefore, the following measures are proposed to ensure the comprehensive environmental safety of water supply systems:

- reconstruction of the network;
- replacement of the pumping station's pumping equipment with energy-efficient alternatives (measures relating to subsystem III);
- improvement of the quality indicators of purification at the end of the water treatment process to such an extent that, taking into account the inevitable contamination during transportation, the water at the consumer point meets the established standards: installation of local treatment facilities.

One of the settlements lacks a centralised drainage system and treatment facilities, which has a negative impact on the environmental condition of the area. The existing treatment facilities are in a state of disrepair. During prolonged operation, the wear and tear of building structures causes damage of communications and the structures themselves. Therefore, it is necessary to

- replace the pumping units, electrical cables, and shut-off valves at the sewage pumping stations;
- construct new centralized wastewater disposal systems;
- reconstruct existing networks (measures related to subsystem VI); connect new subscribers (measures related to subsystem V).

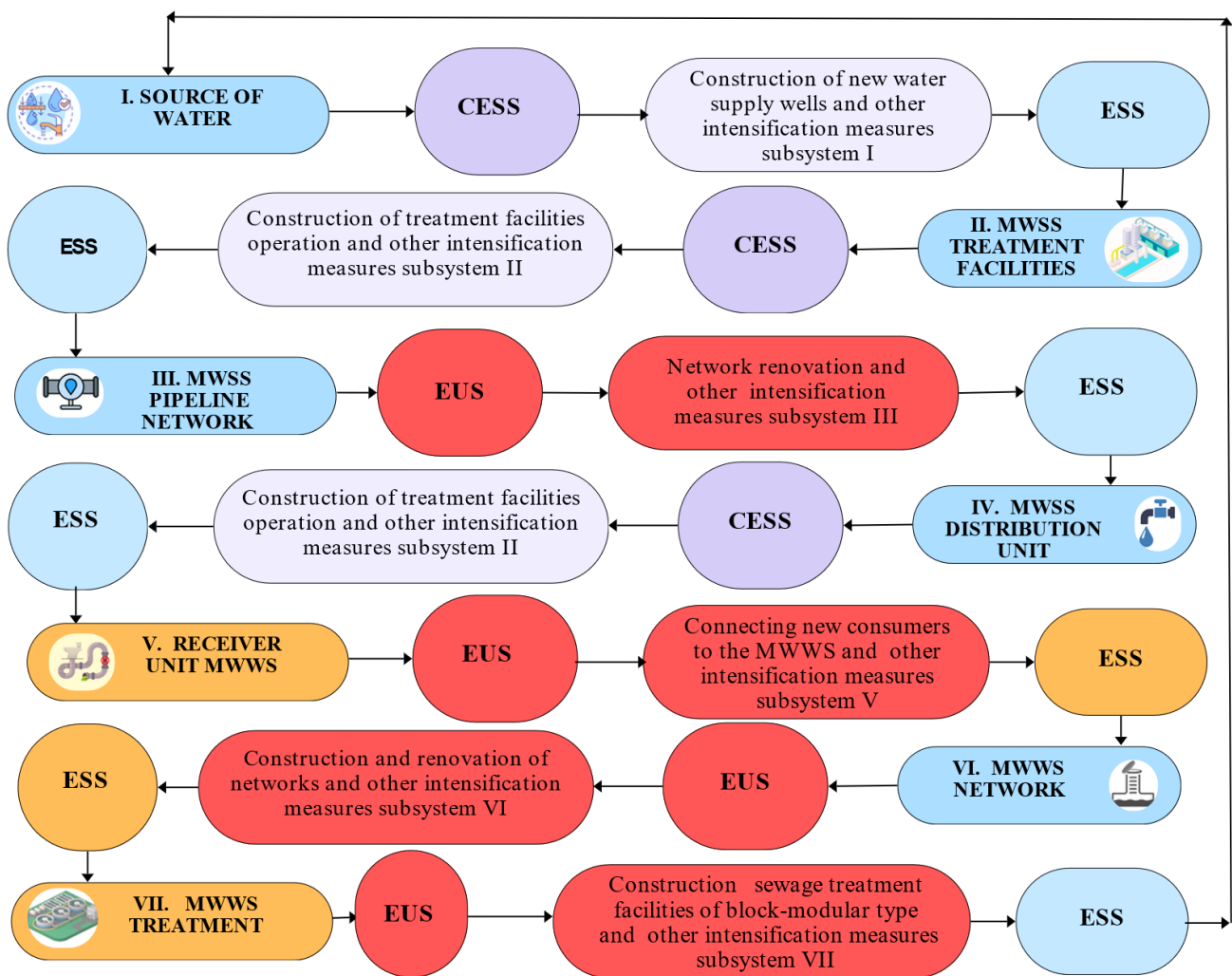


Fig. 4. Structural diagram of the results of the environmental safety assessment of the ‘Urban water supply and sanitation system’: CESS – Conditionally Environmentally Safe System; ESS – Environmentally Safe System; EUS – Environmentally Unsafe System

4.Integration of blue-green infrastructure into the urban drainage system. Issues of environmental safety in cities are closely linked to the effective management of water supply and drainage systems. This area covers a range of issues, including the management of domestic and industrial wastewater, improving the environmental safety of water supply and sewerage facilities, and controlling surface runoff, which plays an important role in minimising negative impacts on aquatic ecosystems and the urban environment. The problem is complicated by the fact that combined sewerage systems, unlike separate ones, collect surface runoff and storm water together with domestic and industrial wastewater before sending it to treatment plants. Such systems consist of a network of pipes used to collect all types of wastewaters simultaneously, which is then transported to treatment plants through a single pipeline system. In dry weather, all effluents are directed to treatment plants. However, during heavy rains or snowmelt, when the volume of wastewater exceeds treatment capacity, the system may direct excess water directly into natural water bodies such as rivers or lakes. If overflow is not possible, untreated wastewater can flood basements and streets, posing a threat to human health and polluting the environment. This phenomenon, known as combined sewer overflows, is one of the main causes of surface water pollution with heavy metals (Cd, Cr, Cu, Ni, Pb, Zn), pathogenic microorganisms, nutrients, pesticides, microplastics, and petroleum hydrocarbons [12].

In addition to traditional strategies for managing urban water supply and wastewater systems, the integration of blue-green infrastructure into the urban environment plays an important role in improving the environmental safety of water supply and sewerage facilities. We propose a blue-green

infrastructure framework for managing surface runoff in urban environments, where the main water retention and drainage elements are permeable pavements and green structures such as rain gardens, green roofs and green walls (Fig. 5). In the urban environment, this infrastructure complements grey drainage systems (sewer networks, reservoirs and treatment plants), providing a comprehensive and balanced approach to managing the overall urban water supply and drainage system.

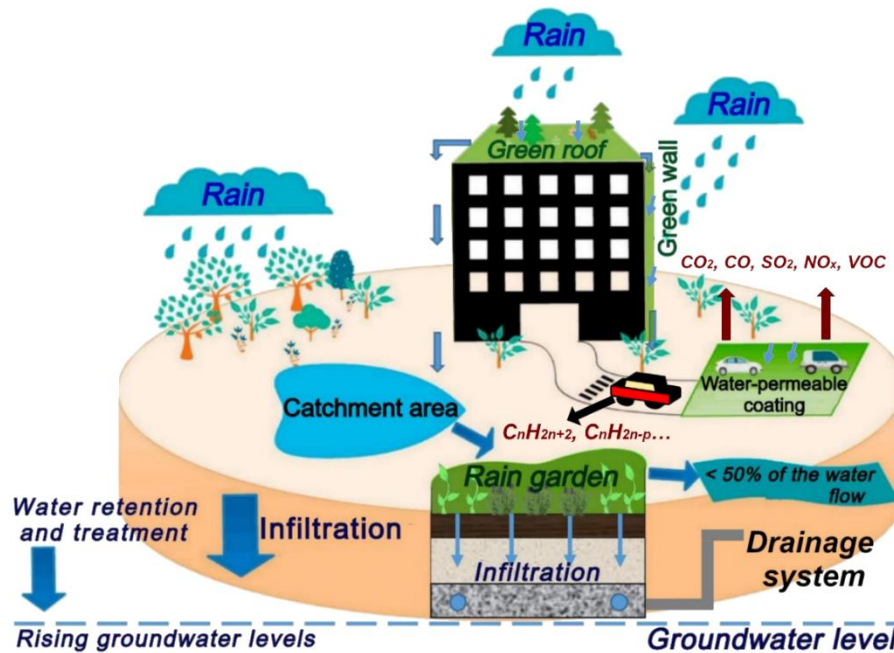


Fig. 5. The principle of blue-green infrastructure in managing surface runoff in urban environments.
Adapted from [13]

The first facilities in the rainwater capture chain in the blue-green infrastructure system are green roofs, which are the first to receive and retain rainwater during a rainfall event. Depending on the intensity and direction of precipitation, some rainwater may fall on green walls, especially during slanting rain. Vertical design, in particular green walls, plays an important role in the selection and design of surface runoff management elements. Since water flow depends on gravity, the location of elements and their relative positioning largely determine how water will pass through the designed system and how it can be treated, stored, or reused.

The remaining water reaches the ground and road surface, forming surface runoff that must be absorbed through green areas, permeable surfaces of eco-friendly parking spaces, roads, pavements, and rain garden structures. In the absence of stormwater sewerage, these structures become the last facilities in surface runoff management, ensuring the retention, filtration, and reduction of the volume of water entering water bodies. Where there are engineering systems, the previous facilities act as the penultimate step in the management, completing the process of absorbing runoff before it is finally discharged into the general sewerage network. Integrated structures of this type improve stormwater infiltration, increase the capacity to retain urban water catchment, and regulate the timing of discharge into the sewerage system, which are key factors for the effective functioning of a city's water supply and sewerage complex.

We propose a method for developing scenarios for integrating blue-green infrastructure into the urban drainage system, consisting of three stages:

1. Identification of infrastructure elements (including types of green structures) and their possible combinations.
2. Calculation of the available area for each element.
3. Forming final scenarios that combine the selected combinations with different implementation rates depending on available resources and priorities.

The first stage involves identifying possible combinations of blue-green infrastructure elements, which include green structures (green roofs, green walls, rain gardens) and engineering solutions such as permeable pavements. These elements can be implemented on different types of land use, such as vegetated surfaces, car parkings, roads, and buildings, maximizing the potential of blue-green infrastructure while minimizing changes in land use and providing multifunctional benefits aimed at improving environmental safety.

In the second stage, the potentially available area for each type of blue-green infrastructure is calculated, taking into account the land use characteristics of the catchment area. Rain gardens are implemented on permeable surfaces, permeable pavements on impermeable surfaces, green roofs on buildings with flat roofs, and green walls on vertical surfaces. Recently, a number of tools have been developed for designing green structures, including rain gardens, using numerical modelling of the hydrological characteristics of the system [14,15]. This includes, in particular, calculating the ratio of the catchment area to the area of the structure, which allows for a more accurate assessment of the effectiveness of runoff management and optimisation of structural parameters to achieve maximum environmental and technical results.

At the final stage, depending on available resources and priorities, possible combinations of blue-green infrastructure elements are generated, taking into account the available area, the wastewater flow system is determined using green structures, and the levels of their integration into the urban infrastructure are established.

The green structure implementation ratio IR_i [%] is determined as the percentage of the corresponding area $A_{sponge,i}$ for a specific type of blue-green infrastructure within the catchment area $A_{basin,i}$ [m²]. Thus, the total surface area of all n types of blue-green infrastructure considered in the scenario is [m²]

$$A_{sponge} = \frac{\sum_{i=1}^n (IR_i \cdot A_{basin,i})}{100}. \quad (10)$$

For each combination of blue-green infrastructure, four possible implementation ratio values are determined: 25 %, 50 %, 75 % and 100 % of the area suitable for a specific type of green structure.

The analysis is conducted at the level of the catchment area, which means that changes in the pace of blue-green infrastructure implementation do not affect its spatial distribution within the sewerage catchment area. For example, implementing blue-green infrastructure on 50 % of the relevant area means that half of this area in each catchment area is covered with green structures, while the overall spatial distribution of the infrastructure remains unchanged.

The characteristics of the surface runoff system play a key role in the ability of combined types of green structures within blue-green infrastructure to influence the efficiency of urban drainage. If the runoff from outside is not directed to the rain garden structure (i.e., the system collects only rainfall that falls directly on it), the effectiveness of combined types is almost the same as that of individual types of blue-green infrastructure, with a difference of 1.2 % to 2.6 % [16]. These minor differences are explained by the greater accuracy of the assessment, which takes into account the simultaneous impact of several elements of blue-green infrastructure.

When runoff is directed from impervious surfaces to a rain garden structure, the combined use of different types of infrastructure provides a significantly greater reduction in runoff volume and improvement in runoff quality compared to the simple sum of the effects of individual elements. This is particularly noticeable when rain gardens are combined with permeable pavements and green roofs. If these elements are assessed separately, runoff from permeable pavements or green surfaces may be counted twice: once as flow to the rain garden and again directly through the assessment of the effectiveness of these structures. This approach can lead to an overestimation of runoff reduction compared to more accurate combined modelling. These aspects highlight the importance of an integrated approach to the use of different types of green structures within an urban catchment, taking into account the characteristics of surface runoff.

The final stage of integrating green structures into the urban drainage system is determining the levels of their integration into the overall urban infrastructure. Green structures within the blue-green infrastructure concept can be integrated into the urban environment as point, linear, or surface systems,

depending on their shape, scale and location. This approach reproduces and supports natural hydrological processes in the urban environment, forming environmental corridors and nodal zones with a linear organisation. Green roofs, green walls and rain gardens play a key role in this, ensuring the infiltration of surface runoff, reducing its volume, and performing a number of environmental, social and economic functions. The basic principle of this system is not only spatial integration, but also a five-level approach to implementation [17]: from local solutions, such as systems for individual buildings or neighbourhoods, to large-scale measures covering residential complexes and districts and integrated into city master plans (Fig. 6).

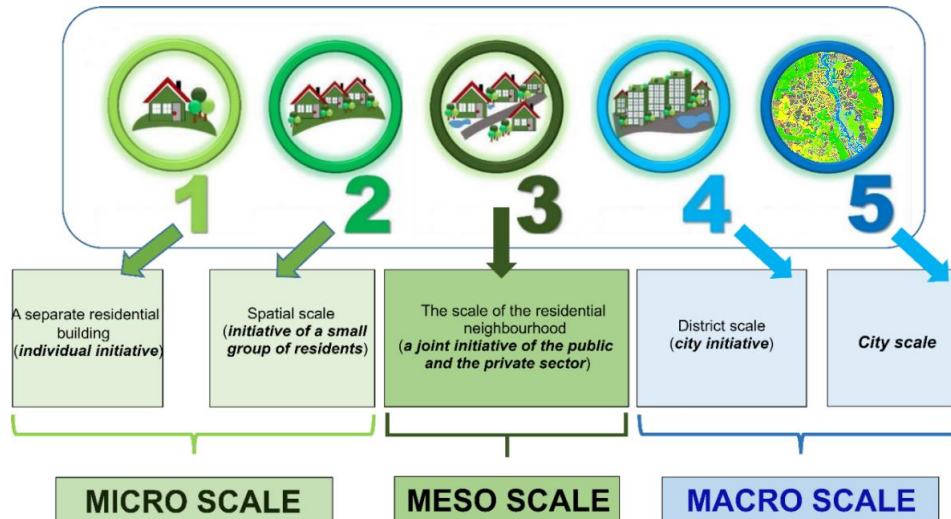


Fig. 6. Levels of integration of green structures into the blue-green infrastructure of the city.
Adapted from [17]

Level 1. Micro scale: individual residential building (individual initiative). At this level, owners of individual residential buildings can implement green structures through simple and effective environmental solutions. Examples of such measures include the creation of rain gardens, green roofs, or green walls, which contribute to local surface runoff purification. Such initiatives not only reduce the load on the urban drainage system, but also have a positive impact on the overall environmental balance of the city.

Level 2. Micro-scale: local spatial level (initiative of a small group of residents). At this level, the implementation of blue-green infrastructure covers larger-scale initiatives organized by small groups of residents. This may include the creation of green areas, rain gardens, or multifunctional public spaces that combine environmental and social functions. Although the scale remains relatively small, such solutions can significantly improve the local environmental situation, increase the efficiency of urban drainage, and contribute to the formation of a sustainable urban environment.

Level 3. Mesoscale: joint initiative of the public and private sectors. At this level, elements of blue-green infrastructure are integrated in the form of linear surface systems. For example, after heavy rain, water flowing from the streets can be collected in underground storage tanks for later use during droughts. Water purified by green structures can be used for landscaping or street washing. This approach creates the basis for a closed or semi-closed water circulation system within the city, which reduces the load on the general sewerage network and promotes the rational use of water resources.

Level 4. Macro scale: district scale (urban initiative). Planning blue-green infrastructure at the district level requires the integration of larger-scale solutions that can affect adjacent areas. The introduction of natural filtration systems in surface residential areas or central areas of the city is particularly relevant.

Level 5. Macro scale: city scale. At the city level, surface runoff management strategies focus on protection from the effects of extreme weather events such as floods or droughts. Engineering solutions include the synergistic interaction of different types of green structures (rain gardens, green

roofs, walls) with technical elements of grey infrastructure. This integration provides a comprehensive solution to urban drainage problems, reducing the risks of natural disasters and promoting the sustainable development of urban areas.

5.Conclusions. The developed systemic model for assessing the environmental safety of urban water supply and wastewater disposal systems allows for a comprehensive analysis of the functional state of all subsystems based on a combination of qualitative and quantitative criteria. The use of a hierarchical logical-mathematical structure makes it possible to classify the state of environmental safety and identify priority areas for system modernization. The results of testing the model on the example of a territorial community in south-eastern Ukraine have proven its effectiveness in identifying critical areas and developing technically and economically sound measures to improve infrastructure reliability, reduce chemical and bacteriological pollution, and ensure sanitary and environmental standards for water supply and wastewater disposal. The integration of blue-green infrastructure into urban wastewater systems is seen as a promising way to improve the environmental safety of urban areas, helping to reduce surface runoff, improve water quality, and create urban ecosystems that are resilient to climate change. The proposed approach can be used in the planning and modernisation of water supply and sewerage systems to achieve a balance between technical efficiency, environmental safety and sustainable development of the urban environment.

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