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Olha Starkova,
Olena Shapovalova,
Alevtyna Aleinikova,
Ganna Solodovnyk,
Petro Liubynskyi

DEVELOPMENT OF A SYSTEM OF INDICES FOR MONITORING AND ASSESSING THE SUSTAINABILITY OF UNDERGROUND UTILITIES

The object of research is the exploitative sustainability of the urban underground utility system. The subject of research is performance indices and methodological approaches to assess the sustainability and performance of urban underground utility systems.

The research study proposes a comprehensive system of indices to monitor and assess the sustainability of urban underground utilities and address critical issues such as aging infrastructure, aggressive operating environments, and financial constraints. The research study identifies seven categories of performance indices such as availability, funding sources, effectiveness of rehabilitation work, accident mitigation, environmental safety, efficient use of funds and efficiency of monitoring implementation. Each index is intended to measure a specific aspect of utility performance and provide a clearly defined basis to assess operational reliability and sustainability. Each of these indexes serves to evaluate a certain aspect of engineering networks functioning. This creates a firmly formalized foundation to the following analysis of the exploitation reliability and network durability. The methodology used regulations the calculation of these indexes, establishes the range of values and their possible variations; also, defines correlations between indexes and characteristics of sustainability of engineering communications. Indexes presented in this research provide an opportunity to predictive planning, increase efficiency of reconstruction and modernization strategies and ensure optimal resource allocation, which increases the operational safety. The methodology used regulations the calculation of these indexes, establishes the range of values and their possible variations; also, defines correlations between indexes and characteristics of sustainability of engineering communications. Indexes presented in this research provide an opportunity to predictive planning, increase efficiency of reconstruction and modernization strategies and ensure optimal resource allocation, which increases the operational safety.

Practical value of the results obtained in this research consists in the possibility of the heads of municipal utilities to take grounded management decisions. The research shows the level of impact of synergistic combination modern technology and financial planning on forming long-term stability of engineering structures. The proposed research allows improving the quality of urban infrastructure management. The application of the developed tools contributes to the stability of service provision and reduces the level of risks associated with the aging of engineering networks.

***Keywords**: indicator, operational sustainability, indicative planning, technical condition of networks, organizational and technological monitoring.*

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1. Introduction

Today, an essential component of the uninterrupted operation of the urban utilities is to maintain all of their parts in proper condition to prevent emergencies. Given the length of time the utility networks are in use, the aggressive environments in which they operate, demanding external circumstances and restrained budgets, this cannot be achieved without implementing a system for monitoring their condition and developing long-term renovation plans. All of the above fully applies to the underground utility line facilities. Monitoring plays a crucial role in tracking changes in resources, processes, and final outcomes over time. An important component of the measures ensuring the stable operation of urban life-support communications is monitoring the dynamics of accounting indicators and establishing a system of control measurements of the system's condition at specific time intervals. The results of research on the operational characteristics of sewerage networks and facilities are recorded and subsequently analyzed [1]. This analysis provides the basis for making well-informed management decisions.

To ensure the stable operation of the underground utility infrastructure, the following tasks must be addressed during the monitoring process:

– tracking the compliance of planned and actually provided centralized wastewater disposal services in terms of both volume and quality;
– controlling the conformity of planned and actual renovation indicators of underground utility networks, including both the scope and list of scheduled maintenance works;
– continuous monitoring and control of the condition of underground utility systems to prevent accidents during operation;
– ensuring environmental protection by preventing potential emissions in case of system failures and developing preventive environmental measures;

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– integrating modern equipment and advanced technologies for monitoring and controlling construction activities related to underground utility infrastructure;
– controlling the compliance of planned and actual financial project indicators related to maintaining the stable operation of municipal infrastructure (in terms of both the volume and structure of allocated funds).

To accomplish the aforementioned tasks and assess the effectiveness of their implementation, a system of metrics must be developed. The indicators forming this system are quantitative in nature, enabling the evaluation of the success level in monitoring the system and identifying trends in the processes occurring within the underground utility infrastructure.

Recent research has focused on indicator-based methods to assess the sustainability and resilience of underground utility networks [2–5]. The studies are concerned with the measurement of sustainability, expert evaluation, and algorithmic decision-making support systems. Several main areas can be identified.

A number of studies have developed indicator systems and calculation methods for underground utilities [2]. These include economic, environmental, and technical parameters. Comprehensive approaches integrate the life span, cost, and environmental impact when assessing the sustainability of urban infrastructure.

Some studies explore the resilience of underground networks to natural and man-made hazards [3]. They propose quantitative models to assess "lifetime resilience" and predict failures in water supply and sewer systems.

Researchers have developed key performance indicators (KPIs) for water supply and wastewater disposal companies [4]. These indicators measure failure rates, repair times, service quality, and financial stability. These KPIs are used as templates for assessing other underground systems.

Approaches to decision-making support are being developed. Expert systems, fuzzy logic, and hybrid models help to assess risks and identify maintenance priorities [5]. Fuzzy logic is useful where data is uncertain and helps to formalize expert knowledge.

Finally, recent reviews indicate significant gaps in research [6]. Data related to underground utilities remain incomplete. Assessment criteria are inconsistent, and there is no unified set of indicators. Environmental and financial aspects are often considered separately from technical aspects. The practical implementation of indicator systems in urban areas is still limited.

Various indicators are used in different sectors of the economy and industry at both micro- and macroeconomic levels. These indicators consider the specific characteristics of the industry where they are applied and serve as indicators of certain trends in that industry in terms of economic, financial, or integrated levels of development.

The work [7] examines how sustainability criteria were considered in road infrastructure projects and identifies gaps in economic, environmental, and social indicators. It provides a methodological framework to develop sustainability indicators applicable to underground utilities. The research study [8] contains step-by-step guidelines for developing indicator systems for critical infrastructure using a multi-criteria approach. Although the methodology focuses on roads and transportation, the approach is versatile and can be adapted for underground utilities.

The work [9] develops a quantitative model to assess the resilience of underground infrastructure (tunnels) to various hazards, including aging and unexpected accidents. It provides information to formalize network functionality, losses, and repair time, which is important for indicators such as repair efficiency and accident mitigation.

Although the paper [10] focuses on wastewater treatment plants, this paper presents KPI-based monitoring and control for complex engineering systems. It describes how KPI methodology can be formalized in complex settings and can inform indicators such as the use of funds, efficiency of monitoring, and efficiency of rehabilitation work. The review paper [11] summarizes existing guidelines, tools, and standards for sustainable and resilient infrastructure, highlighting gaps in standardization and indicator unification. It is a valuable reference for identifying missing elements when developing an indicator system for underground utilities.

The paper [12] examines indices that assess the economic maturity of a number of countries to join the EU. The composite index for economic integration proposed by the authors considers five main criteria. The first criterion is functioning market economy, measured by the transformation index (BTI) and the corruption perceptions index (CPI). The second is competitiveness, measured by the global competitiveness index (GCI) and the labor force participation (LFP) rate. The third is macroeconomic stability, assessed using GDP growth rates, unemployment, inflation, and the current account balance. The fourth is convergence, measured by GDP per capita, the human development index (HDI), government debt to GDP, internet access, and fiscal balance. The fifth is financial capacity, which includes foreign direct investment (FDI), non-performing loans, and the use of IMF loans. The methodology used to assess countries by means of a composite index was based on the collection and standardization of the latest data, analysis of correlations between variables, and the creation of weighted coefficients for each criterion.

The application of a similar approach to the analysis of the sustainability of underground utilities is of great relevance today, but requires the adaptation of the methodology to the domain area and thorough selection of both the main criteria and the indices within the criterion.

The paper [13] proposes a framework of performance indices for assessing the quality of sewerage system services, in particular, on the example of the Seoul Metropolitan Subway. Based on a survey of experts and using the analytic hierarchy process (AHP) method, the weight of criteria and alternatives was determined.

At the highest level, the authors propose three main objectives of sewerage services, that is, "environmental water safety", "sustainability of sewerage services" and "customer compliance" as indices. The middle level contains ten performance indices, which are meant to be publicly available after conversion into scores, and the lower level contains twenty technical performance indices.

The proposed structure of performance indices can be used to develop a draft site plan for the Seoul subway wastewater and drainage system. However, this structure requires major revision, addition, and improvement. These changes are necessary to meet the needs of planning and to assess the development prospects of the sewerage system in an average Ukrainian city.

A similar approach is used in the paper [14], where a system for evaluating the effectiveness of rural sewage treatment facilities was developed based on the analytic hierarchy process (AHP). The positive achievements of the authors include the quite logical distribution of indices at the highest level of the hierarchy into three categories: economic, technical and managerial, and the use of Yaahp10.3 software to automate the processing of the judgment matrix. However, as in the previous case, the results obtained cannot be applied to urban underground utilities without significant modification.

The processes of data collection and analysis, which form the foundation of monitoring, are subsequently utilized for the management and control of the observed system. Monitoring the dynamics of indices related to assessing the efficiency of various aspects of the operation and renovation of underground utility networks and facilities provides insights into current trends. This, in turn, allows for their consideration in pricing formation and tariff regulation for wastewater disposal services, as well as in addressing other tasks aimed at ensuring the system's stable operation.

The successful implementation of a monitoring system for underground networks and facilities to ensure their stable operation is possible under the fulfillment of several key requirements such as:
– strict adherence to the methodology for tracking and controlling the studied indicators while maintaining the quality of wastewater disposal services at a level no lower than the specified standard;

– monitoring the correlation between the degree of implementation of the monitoring system and the mechanisms for assessing service quality;
– controlling the end-to-end performance indicators of the municipal utility organization;
– verifying the accuracy of the interpretation of monitoring indicators and data [1].

The monitoring methodology is based on a system of models that form the foundation for tracking and controlling the system, as well as analyzing the efficiency of this process. It includes a sequence of measures for the regular collection of information, followed by an assessment of the functional efficiency of system operations and service provision, particularly centralized wastewater disposal. Additionally, it evaluates changes and costs associated with the monitored processes [15, 16]. Furthermore, within the monitoring methodology, the structure and description of the constituent elements of the studied system must be outlined.

The object of research is the operational sustainability of urban underground utility systems.

The aim of research is to establish a system of indices for monitoring and assessing the sustainability of underground utilities in the urban environment.

To achieve this aim, the following tasks should be addressed:
– to form groups of indices according to the relevant criteria based on the objectives of monitoring;
– to examine the patterns of formation of each of the indices within the group and formalize the process of its calculation;
– to investigate the numerical limits of variation of each of the indices and to identify the correlation between the value of the indices and its impact on the stable operation of the underground utility line facilities.

2. Materials and Methods

The efficiency of monitoring in achieving the set goals is assessed using a number of different indicators, including:
– growth or decline rates, which characterize absolute deviations of relevant indicators (resources, processes, outcomes) from the average value over time;
– indicators that show changes in the structure of the set of monitored parameters;
– indicators of compliance (or non-compliance) between interrelated indicators;
– ratios of different indicators;
– comparative characteristics of the monitored indicators.

Quantitative indicators are used to forecast development trends in various areas and serve as a key tool for analyzing and monitoring the operation of underground engineering infrastructure.

One of the most up-to-date challenges for modern society which requires a integrated approach is maintaining the exploitative efficiency of underground utility infrastructure facilities and carrying out their step-by-step improvement.

The enhancement of a system of metrics which enables the assessment and monitoring of the stability of underground networks and facilities is a crucial component to successfully addressing this challenge.

Solving the problem of a thorough selection of a set of indicators that would cover technical and economic aspects of the research object should contribute to the assessment of the effectiveness of the implemented solutions. The segregation of indicators into categories and taking into account the specifics of the assessment within the categories should contribute to providing the implementation of an organizational and technological monitoring system to ensure the stable functioning of underground engineering networks and structures [15].

Analytical, statistical and modeling methods were used to estimate the level of deterioration of underground utility infrastructure and the possibility of being efficient in the work process.

The methodology is based on empirical data, regulatory frameworks, and performance indicators applicable to centralized wastewater disposal networks. Data sources, methods and research steps were shown in Table 1.

Table 1

Data sources, methods and research steps

Data sources	Analytical and theoretical methods	Research steps
Statistical indicators related to failures in the operation of municipal underground engineering networks and troubleshooting, such as failure frequency, statistics on service interruptions, data from maintenance logs, information on reconstructions, etc.	Statistical approach, trend watching, identifying trends of certain indicators based on the analysis of statistical data	Formation of groups of indicators of the upper level of the hierarchy for evaluating the system according to various principles
Reports on the costs and effectiveness of the use of funds for rehabilitation works provided by wastewater service providers	Correlation analysis to identify connection between different processes	Collection and pre-processing of research data from utility operators and open municipal datasets
Regulatory documents relating to technical and service quality standards	Analytical grouping method	Computing of indices and their statistical variations, such as deviation measures, structural changes indicators, correlations coefficients etc.
Technical documentation for the construction of underground utility systems	–	Model validity testing using statistical data

The data used in the research are generalized in nature. No personal data or sensitive technical information was processed.

3. Results and Discussion

Recommendations for indicative planning of the development of underground utility networks are of advisory nature. The development of the plan involves determining the indicator parameters such as predictive, directive, and calculated indicators, including indices of value changes, structural ratios, and others. Predictive indicative plans are designed to assist legal entities managing sewer systems in determining and developing their own plans based on future forecasts from government bodies. These forecasts are scientifically justified by research conducted by relevant organizations.

Indicative planning helps to harmonize and centralize objectives and production plans, and to further coordinate capital investments.

The development trajectory of underground utility networks and facilities is determined by the implementation of the developed indicative plan. The plan's development is based on the formalization of a system of indicators that take into account the technical and economic parameters of the underground infrastructure at the beginning and end of the plan's implementation. The outcomes of implementing the indicative plan include several key improvements. First, there is a better balance in the structure of the underground utility network. Second, efficiency is enhanced in both technical and economic aspects. Third, the stability and reliability of operation are increased. Fourth, the quality of centralized wastewater disposal services is improved. Finally, costs are reduced, as reflected in lower unit costs.

The set of indicators in the developed plan should reflect the technical condition of the system, its level of safety, the favorability of external conditions for the operation of life-support systems, financial stability, and the economic feasibility of the proposed organizational and technological measures. During comparative analysis, the set of indicators should provide a comprehensive description of the system's condition while remaining compact. Moreover, quantitative indicators must be comparable both over time and in consideration of the spatial distribution of sewerage network facilities, which significantly contributes to determining the target values of the indicators.

As part of the research, indicators were developed for implementing a system of organizational and technological monitoring to ensure the stable operation of the sewerage networks and facilities [2]. These indicators were grouped into the following categories:

– provision of the sewerage networks and facilities complex;
– inflows of capital investments from various sources;
– efficiency of the renovation works for the sewerage networks and facilities complex;
– efficiency of the repair works addressing the consequences of emergency damages in the municipal sewerage system;
– environmental sustainability of the sewerage system complex usage;
– effectiveness of financial resources allocated for renovations and elimination of emergency damage consequences;
– efficiency of organizational and technological monitoring and ensuring the uninterrupted operation of the municipal sewerage system.

The first category of indicators reflects the level of provision of the city with underground utility networks, including pipes of various diameters, networks, collectors, sewer tunnels, shafts, and dissipation chambers.

The indicators in this category are determined by the ratio of the length of utility networks to the total area of the city and the number of facilities relative to the area. When calculating the indicator, the following data are taken into account (Table 2):

– the number and length of each type of utility facility across the city (measured in kilometers and natural units);
– the total area of the city (measured in square kilometers).

Table 2

Indices of availability of the urban underground utility line facilities

No.	Indices name	Formula	Unit of measurement
1.1	Urban sewer network availability level, U_{s1}	$U_{s1} = L_{s1}/S$, where L_{s1} is the length of the sewer network, km; S is the area of the city, km^2	km/km^2
1.2	Urban collector availability level, U_{c2}	$U_{c2} = L_{c2}/S$, where L_{c2} is the length of the collector network, km; S is the area of the city, km^2	km/km^2
1.3	Urban sewer tunnel availability level, U_{st}	$U_{st} = L_{st}/S$, where L_{st} is the length of the sewer tunnels in kilometers; S is the area of the city, km^2	km/km^2
1.4	Urban sewer shaft availability level, U_{sh}	$U_{sh} = N_{sh}/S$, where N_{sh} is the number of sewer shafts, units; S is the area of the city, km^2	units/km^2
1.5	Urban stilling chamber availability level, U_{stch}	$U_{stch} = N_{stch}/S$, where N_{stch} is the number of stilling chambers, units; S is the area of the city, km^2	units/km^2

The second category of indices describes the inflow of financial resources from specific sources. These include relevant items of the city budget and funds of the municipal utility. They also cover finances from the European Bank for Reconstruction and Development. Additionally, investments from construction companies are considered, particularly when new construction projects increase the load on local utility facilities.

The indicators in this category are calculated based on the specific weight of each source of financing. Table 3 presents data obtained based on information regarding the comprehensive development of the municipal sewerage system.

The third category of indicators determines the efficiency of renovation work on the underground municipal utilities. The indicators in this category are calculated as the ratio of the actual volume of work to the planned volume, expressed as a percentage (Table 4).

Table 3

Indices grouped by funding source distribution criterion

No.	Indices name	Formula	Unit of measurement
2.1	Share of municipal budget funding, U_b	$U_b = F_b/F_{total} \cdot 100\%$, where F_b is the amount of funding from the municipal budget, thousand UAH; F_{total} is the total amount of funding, thousand UAH	%
2.2	Share of operating company funding, U_{comp}	$U_{comp} = F_{comp}/F_{total} \cdot 100\%$, where $F_{company}$ is the amount of funding from the operating companies, thousand UAH; F_{total} is the total amount of funding, in thousand UAH	%
2.3	Share of European Bank for Reconstruction and Development (EBRD) funding, U_{EBRD}	$U_{EBRD} = F_{EBRD}/F_{total} \cdot 100\%$, where F_{EBRD} is the amount of funding from the EBRD, thousand UAH; F_{total} is the total amount of funding, thousand UAH	%
2.4	Share of construction organizations' co-funding, $U_{co\text{-}constr}$	$U_{co\text{-}constr} = F_{co\text{-}constr}/F_{total} \cdot 100\%$, where $F_{co\text{-}constr}$ is the amount of co-funding from construction organizations, thousand UAH; F_{total} is the total amount of funding, thousand UAH	%

Table 4

Indices of the effectiveness of rehabilitation work
for the underground utility line facilities

No.	Indices name	Formula	Unit of measurement
3.1	Performance index for sewer network rehabilitation work, $I^{s1}_{perform}$	$I^{s1}_{perform} = V^{s1}_{real}/V^{s1}_{plan} \cdot 100\%$, where V^{s1}_{real} is real volume of sewer network rehabilitation work; V^{s1}_{plan} is planned volume of sewer network rehabilitation work	%
3.2	Performance index for collector rehabilitation work, $I^{c2}_{perform}$	$I^{c2}_{perform} = V^{c2}_{real}/V^{c2}_{plan} \cdot 100\%$, where V^{c2}_{real} is real volume of collector rehabilitation work; V^{c2}_{plan} is planned volume of collector rehabilitation work	%
3.3	Performance index for sewer tunnel rehabilitation work, $I^{st}_{perform}$	$I^{st}_{perform} = V^{st}_{real}/V^{st}_{plan} \cdot 100\%$, where V^{st}_{real} is real volume of sewer tunnel rehabilitation work; V^{st}_{plan} is planned volume of sewer tunnel rehabilitation work	%
3.4	Performance index for sewer shaft rehabilitation work, $I^{sh}_{perform}$	$I^{sh}_{perform} = V^{sh}_{real}/V^{sh}_{plan} \cdot 100\%$, where V^{sh}_{real} is real volume of sewer shaft rehabilitation work; V^{sh}_{plan} is planned volume of sewer shaft rehabilitation work	%
3.5	Performance index for stilling chamber rehabilitation work, $I^{stch}_{perform}$	$I^{stch}_{perform} = V^{stch}_{real}/V^{stch}_{plan} \cdot 100\%$, where V^{stch}_{real} is real volume of stilling chamber rehabilitation work; V^{stch}_{plan} is planned volume of stilling chamber rehabilitation work	%

The fourth category of indicators illustrates the efficiency of remedial works in case of emergency damage to the underground utility systems (Table 5). This category includes indicators for all parts of the sewerage system, including pipes of various diameters, networks, collectors, sewer tunnels, shafts, and dissipation chambers. The indicators in this category are determined as the ratio of the number of emergency damages in each part of the utility system to the total number of such emergencies, expressed as a percentage [12].

Table 5

The indices of the effectiveness of work performance to eliminate accident-caused damage to the underground utility line facilities

No.	Indices name	Formula	Unit of measurement
4.1	Performance indices for emergency sewer network repairs, $I^{s1}_{perf\_damage}$	$I^{s1}_{perf\_damage} = N^{s1}_{damage}/N^{s1}_{total} \cdot 100\%$, where N^{s1}_{damage} is number of accident-caused damages in sewer networks, units/year; N^{s1}_{total} is total number of accident-caused damages, units/year	%
4.2	Performance indices for emergency collector repairs, $I^{c2}_{perf\_damage}$	$I^{c2}_{perf\_damage} = N^{c2}_{damage}/N^{c2}_{total} \cdot 100\%$, where N^{c2}_{damage} is number of accident-caused damages in collectors, units/year; N^{c2}_{total} is total number of accident-caused damages, units/year	%
4.3	Performance indices for emergency sewer tunnel repairs, $I^{st}_{perf\_damage}$	$I^{st}_{perf\_damage} = N^{st}_{damage}/N^{st}_{total} \cdot 100\%$, where N^{st}_{damage} is number of accident-caused damages in sewer tunnels, units/year; N^{st}_{total} is total number of accident-caused damages, units/year	%
4.4	Performance indices for emergency sewer shaft repairs, $I^{sh}_{perf\_damage}$	$I^{sh}_{perf\_damage} = N^{sh}_{damage}/N^{sh}_{total} \cdot 100\%$, where N^{sh}_{damage} is number of accident-caused damages in sewer shalfs, units/year; N^{sh}_{total} is total number of accident-caused damages, units/year	%
4.5	Performance indices for emergency stilling chamber repairs, $I^{stch}_{perf\_damage}$	$I^{stch}_{perf\_damage} = N^{stch}_{damage}/N^{stch}_{total} \cdot 100\%$, where N^{stch}_{damage} is number of accident-caused damages in stilling chambers, units/year; N^{stch}_{total} is total number of accident-caused damages, units/year	%

Indicators of the fifth category should determine the level of environmental safety throughout the entire lifecycle of the underground engineering structures system. These indicators are calculated according to the methodology for determining the degree of environmental risk. The indicators in this category also cover all parts of the underground engineering structures system. The indicators are defined as the ratio of the degree of environmental risk for using each part of the system to the overall level of risk for the use of the entire system of underground engineering structures (Table 6).

The sixth category includes indicators of the efficiency of financial resources allocated to improving the reliability of the underground engineering structures system, expressed in monetary terms. The indicators in this category are determined as the ratio of the actual amount of financial resources allocated for implementing relevant measures to the planned amount, expressed as a percentage [11]. The normative value of this indicator equals 100%. Exceeding the normative value indicates the efficient use of financial resources or the overperformance of the planned scope of work. An indicator value below the normative level indicates an insufficient utilization of funds (Table 7).

Table 6

Indices of environmental risk of damage of the underground utility line facilities

No.	Indices name	Formula	Unit of measurement
5.1	Environmental risk indices for sewer network operation, I^{s1}_{env}	$I^{s1}_{env} = R^{s1}_{env}/R^{total}_{env} \cdot 100\%$, where R^{s1}_{env} is the level of environmental risk in sewer network operation; R^{total}_{env} is total risk level of the sewer network and associated facilities	%
5.2	Environmental risk indices for collector operation, I^{c2}_{env}	$I^{c2}_{env} = R^{c2}_{env}/R^{total}_{env} \cdot 100\%$, where R^{c2}_{env} is the level of environmental risk in collector operation; R^{total}_{env} is total risk level of the sewer network and associated facilities	%
5.3	Environmental risk indices for sewer tunnel operation, I^{st}_{env}	$I^{st}_{env} = R^{st}_{env}/R^{total}_{env} \cdot 100\%$, where R^{st}_{env} is the level of environmental risk in sewer tunnel operation; R^{total}_{env} is total risk level of the sewer network and associated facilities	%
5.4	Environmental risk indices for sewer shaft operation, I^{sh}_{env}	$I^{sh}_{env} = R^{sh}_{env}/R^{total}_{env} \cdot 100\%$, where R^{sh}_{env} is the level of environmental risk in sewer shaft operation; R^{total}_{env} is total risk level of the sewer network and associated facilities	%
5.5	Environmental risk indices for stilling chamber operation, I^{stch}_{env}	$I^{stch}_{env} = R^{stch}_{env}/R^{total}_{env} \cdot 100\%$, where R^{stch}_{env} is the level of environmental risk in stilling chamber operation; R^{total}_{env} is total risk level of the sewer network and associated facilities	%

Table 7

Indices of the use of funds to ensure the sustainability of underground utility line facilities

No.	Indices name	Formula	Unit of measurement
6.1	Indices of fund utilization for sewer network resilience, I_{s1}	$I_{s1} = F^{s1}_{real}/F^{s1}_{plan} \cdot 100\%$, where F^{s1}_{real} is real funding volumes for sewer network works, thousand UAH; F^{s1}_{plan} is planned funding volumes for sewer network works, thousand UAH	%
6.2	Indices of fund utilization for collector resilience, I_{c2}	$I_{c2} = F^{c2}_{real}/F^{c2}_{plan} \cdot 100\%$, where F^{c2}_{real} is real funding volumes for sewer network works, thousand UAH; F^{c2}_{plan} is planned funding volumes for sewer network works, thousand UAH	%
6.3	Indices of fund utilization for sewer tunnel resilience, I_{st}	$I_{st} = F^{st}_{real}/F^{st}_{plan} \cdot 100\%$, where F^{st}_{real} is real funding volumes for sewer network works, thousand UAH; F^{st}_{plan} is planned funding volumes for sewer network works, thousand UAH	%
6.4	Indices of fund utilization for sewer shaft resilience, I_{sh}	$I_{sh} = F^{sh}_{real}/F^{sh}_{plan} \cdot 100\%$, where F^{sh}_{real} is real funding volumes for sewer network works, thousand UAH; F^{sh}_{plan} is planned funding volumes for sewer network works, thousand UAH	%
6.5	Indices of fund utilization for stilling chamber resilience, I_{stch}	$I_{stch} = F^{stch}_{real}/F^{stch}_{plan} \cdot 100\%$, where F^{stch}_{real} is real funding volumes for sewer network works, thousand UAH; F^{stch}_{plan} is planned funding volumes for sewer network works, thousand UAH	%

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Indicators of the seventh category determine the effectiveness of implementing the organizational and technological control system for the stable operation of the underground engineering structures system. To determine the indicators in this category, it is necessary to calculate data over specific time intervals to account for the dynamic nature of the indicators (Table 8).

The next stage of research involves assigning a threshold value to each indicator of the effectiveness of implementing the organizational and technological control system for the stable operation of the underground engineering structures system, in accordance with its essence (Table 9).

Table 8

Group of indices in terms of the efficiency of implementing the system of the organizational and technological monitoring to ensure the stable operation of the underground utility line facilities

No.	Indices name	Formula	Unit of measurement
7.1	System implementation efficiency indices, I_{sys_impl}	$I_{sys\_impl} = F_{util}/F_{total1} \cdot 100\%$, where F_{util} is volume of utilized funds, million UAH; F_{total1} is total allocated funds, million UAH	%
7.2	System innovation implementation indices, I_{innov}	$I_{innov} = F_{Iinnov}/F_{total2} \cdot 100\%$, where F_{Iinnov} is volume of sewer network and facility rehabilitation using new technologies; F_{total2} is total volume of sewer network and facility rehabilitation	%
7.3	Domestic technology utilization indices, $I_{domestic}$	$I_{domestic} = F_{domestic}/F_{total2} \cdot 100\%$, where $F_{domestic}$ is volume of sewer network and facility rehabilitation using domestic technologies; F_{total2} is total volume of sewer network and facility rehabilitation	%

Table 9

Indices of the effectiveness of the implementation of the organizational and technological monitoring system to ensure the stable operation of the underground utility line facilities

No.	Indices Name	Indices value	
		Definition	Range of values
1	2	3	4
1.1	Urban sewer network availability level, U_{s1}	unsatisfactory	0–2
		satisfactory	>2–3
		sufficient	>3–10
1.2	Urban collector availability level, U_{c2}	unsatisfactory	0–2
		satisfactory	>2–3
		sufficient	>3–10
1.3	Urban sewer tunnel availability level, U_{st}	unsatisfactory	0–2
		satisfactory	>2–3
		sufficient	>3–10
1.4	Urban sewer shaft availability level, U_{sh}	unsatisfactory	0–2
		satisfactory	>2–3
		sufficient	>3–10
1.5	Urban stilling chamber availability level, U_{stch}	unsatisfactory	0–2
		satisfactory	>2–3
		sufficient	>3–10
2.1	Share of municipal budget funding, U_b	insufficient	0–20
		moderate	>20–80
		sufficient	>80–100
2.2	Share of operating company funding, U_{comp}	insufficient	0–20
		moderate	>20–80
		sufficient	>80–100
2.3	Share of European Bank for Reconstruction and Development (EBRD) funding, U_{EBRD}	insufficient	0–20
		moderate	>20–80
		sufficient	>80–100
2.4	Share of construction organizations' co-funding, $U_{co\text{-}constr}$	insufficient	0–20
		moderate	>20–80
		sufficient	>80–100
3.1	Performance indices for sewer network rehabilitation work, $I^{s1}_{perform}$	critical	0–20
		satisfactory	>20–80
		moderate	>80–100
3.2	Performance indices for collector rehabilitation work, $I^{c2}_{perform}$	critical	0–20
		satisfactory	>20–80
		moderate	>80–100
3.3	Performance indices for sewer tunnel rehabilitation work, $I^{st}_{perform}$	critical	0–20
		satisfactory	>20–80
		moderate	>80–100

Continuation of Table 9

1	2	3	4
3.4	Performance indices for sewer shaft rehabilitation work, $I_{perform}^{sh}$	critical	0–20
		satisfactory	>20–80
		moderate	>80–100
3.5	Performance indices for stilling chamber rehabilitation work, $I_{perform}^{stch}$	critical	0–20
		satisfactory	>20–80
		moderate	>80–100
4.1	Performance indices for emergency sewer network repairs $I_{perf\_damage}^{s1}$	critical	0–20
		satisfactory	>20–80
		moderate	>80–100
4.2	Performance in indices for emergency collector repairs, $I_{perf\_damage}^{c2}$	critical	0–20
		satisfactory	>20–80
		moderate	>80–100
4.3	Performance indices for emergency sewer tunnel repairs, $I_{perf\_damage}^{st}$	critical	0–20
		satisfactory	>20–80
		moderate	>80–100
4.4	Performance indices for emergency sewer shaft repairs, $I_{perf\_damage}^{sh}$	critical	0–20
		satisfactory	>20–80
		moderate	>80–100
4.5	Performance indices for emergency stilling chamber repairs, $I_{perf\_damage}^{stch}$	critical	0–20
		satisfactory	>20–80
		moderate	>80–100
5.1	Environmental risk indices for sewer network operation, I_{env}^{s1}	critical	0–20
		satisfactory	>20–80
		moderate	>80–100
5.2	Environmental risk indices for collector operation, I_{env}^{c1}	critical	0–20
		satisfactory	>20–80
		moderate	>80–100
5.3	Environmental risk indices for sewer tunnel operation, I_{env}^{st}	critical	0–20
		satisfactory	>20–80
		moderate	>80–100
5.4	Environmental risk indices for sewer shaft operation, I_{env}^{sh}	critical	0–20
		satisfactory	>20–80
		moderate	>80–100
5.5	Environmental risk indices for stilling chamber operation, I_{env}^{stch}	critical	0–20
		satisfactory	>20–80
		moderate	>80–100
6.1	Coefficient of fund utilization for sewer network resilience, C_{s1}	unsatisfactory	0–30
		satisfactory	>30–70
		sufficient	>70–100
6.2	Indices of fund utilization for collector resilience, I_{c2}	unsatisfactory	0–30
		satisfactory	>30–70
		sufficient	>70–100
6.3	Indices of fund utilization for sewer tunnel resilience, I_{st}	unsatisfactory	0–30
		satisfactory	>30–70
		sufficient	>70–100
6.4	Indices of fund utilization for sewer shaft resilience, I_{sh}	unsatisfactory	0–30
		satisfactory	>30–70
		sufficient	>70–100
6.5	Indices of fund utilization for stilling chamber resilience, I_{stch}	unsatisfactory	0–30
		satisfactory	>30–70
		sufficient	>70–100
7.1	System implementation efficiency indices, I_{sys_impl}	unsatisfactory	0–20
		moderate	>20–80
		high	>80–100
7.2	System innovation implementation indices, I_{innov}	unsatisfactory	0–20
		moderate	>20–80
		high	>80–100
7.3	Domestic technology utilization indices, $I_{domestic}$	unsatisfactory	0–20
		moderate	>20–80
		high	>80–100

The threshold values of performance indicators used to implement the organizational and technological monitoring system are designed to ensure the stable operation of underground infrastructure facilities.

In practical terms, the proposed methodology provides managers of urban utilities with practical tools to make informed decisions in the field of urban infrastructure management, ensuring the efficient provision of services and reducing the risks associated with aging utility networks. On the other hand, this research has several limitations. Since the researchers used statistical data from their region to develop the indicator system and determine its numerical limits, at least the latter needs to be corrected for another area. In addition, during the research the authors mainly relied on data on sewage infrastructure, so the extension of the results to underground communication networks for other purposes needs additional development.

In the future, the results are planned to be used in the development of an intelligent expert system for estimating the stability of underground sewer networks and structures. To be able to organize work in conditions of uncertainty, the authors are going to apply fuzzy logic when building the system. The results, presented in the article, give grounds to argue about the possibility of their implementation in a real industrial process.

4. Conclusions

1. As a result of research was developed a methodological basis to form a hierarchy of indicators for monitoring of the stable work of underground sewer networks and facilities. The hierarchy includes seven logically structured groups of indicators that cover technical, financial, environmental, and organizational feathers of the system's stability. The received result completely complies with the research goal, as it serves basis to conduct an integral estimation of the condition of the sewer infrastructure and can be a basis for monitoring. The developed system of indicators contains both fixed and dynamic parameters and allows estimating both the current state of the system and its adaptive characteristics.

2. The seven clusters of indicators (three to five per cluster) provide a multidimensional estimation of system resistance. In contrast to existing fragmented decision, the hierarchical organization of indicators creates a logically coherent and methodologically unified system. This approach permit identifying and eliminating bottlenecks in the infrastructure, making operational failures and investment gaps visible, and helps determine a list of restoration priorities. Combining operational, financial, and environmental indicators gives noticeably higher sensitivity to early marks of letdown in the utility networks compared to only one category metric. That why the proposed solution is so good for long run.

3. The effect of each indicator on the sustainability of underground sewer networks was assessed by establishing quantitative ranges of variability and determining thresholds of sensitivity. The results show that the indicators related to the effectiveness of emergency response and reconstruction outcomes have the strongest direct impact on the sustainability of the sewer system, while financial and environmental indicators are medium-term modulators of sustainability. This quantitative assessment allows critical, moderate, and insignificant factors to be identified, thus providing decision-makers with a tool for prioritizing measures and allocating funds more effectively. This result is particularly valuable because of its practical applicability: it allows adaptive monitoring thresholds to be established and facilitates the transition from reactive to preventive maintenance strategies.

Conflict of interest

The author declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Manuscript has no associated data.

Use of artificial intelligence

The authors declare the use of AI tools, namely:
– ChatGPT model GPT-5.1;
– used in section 1 of the article and in the initial list of sources;
– studied in detail the sources found using AI using keywords and filters (full-text scientific articles published in the last 5 years and referenced in international databases); each item in the reference list was checked personally;
– following the link provided by AI, the authors carefully studied the material and drew their own conclusions;
– use of AI accelerated the process of finding sources, but did not affect the results of the study.

Authors' contributions

Olha Starkova: Conceptualization, Supervision; ***Olena Shapovalova***: Project administration, Writing – original draft; ***Alevtyna Aleinikova***: Methodology; ***Ganna Solodovnyk***: Investigation; ***Petro Liubynskyi***: Formal analysis.

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Olha Starkova, *Doctor of Technical Sciences, Professor, Head of Department of Cybersecurity and Information Technologies, Simon Kuznets Kharkiv National University of Economics, Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0002-9034-8830*

✉***Olena Shapovalova,*** *PhD, Associate Professor, Department of Cybersecurity and Information Technologies, Simon Kuznets Kharkiv National University of Economics, Kharkiv, Ukraine, e-mail: olena.shapovalova@hneu.net, ORCID: https://orcid.org/0000-0003-4566-6634*

Alevtyna Aleinikova, *Doctor of Technical Sciences, Associate Professor, Department of Construction Technology and Organization, O. M. Beketov National University of Urban Economy in Kharkiv, Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0002-2486-4263*

Ganna Solodovnyk, *PhD, Associate Professor, Department of Cybersecurity and Information Technologies, Simon Kuznets Kharkiv National University of Economics, Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0001-6323-5083*

Petro Liubynskyi, *PhD Student, Department of Cybersecurity and Information Technologies, Simon Kuznets Kharkiv National University of Economics, Kharkiv, Ukraine, ORCID: https://orcid.org/0009-0004-3471-2206*

✉*Corresponding author*