Water Delivery Safety and Infrastructure Reliability: Integrating Failure Data and GIS in the Planning of Water Supply System Maintenance

Izabela Piegdoń[1*], Barbara Tchórzewska-Cieślak[2], Magdalena Stręk[3]

[1*] Department of Water Supply and Sewerage Systems, Faculty of Civil, Environmental Engineering and Architecture, Rzeszów University of Technology, Al. Powstańców Warszawy 6, 35-959 Rzeszów, Poland; piegi@prz.edu.pl; 0000-0003-1094-4569
[2] Department of Water Supply and Sewerage Systems, Faculty of Civil, Environmental Engineering and Architecture, Rzeszów University of Technology, Al. Powstańców Warszawy 6, 35-959 Rzeszów, Poland; cbarbara@prz.edu.pl; 0000-0002-7622-6749
[3] Department of Water Supply and Sewerage Systems, Faculty of Civil, Environmental Engineering and Architecture, Rzeszów University of Technology, Al. Powstańców Warszawy 6, 35-959 Rzeszów, Poland; magdas@prz.edu.pl; 0009-0008-5262-4575

https://doi.org/10.29227/IM-2025-02-02-077

Submission date: *2025-07-31* | Review date: *2025-08-24*

Abstract

In recent years, Geographical Information Systems (GIS) and their associated databases have become essential tools in the management of water supply infrastructure. Their application in water utilities extends beyond public health protection and now plays a pivotal role in network operation, maintenance planning, and risk analysis. This study focuses on the integration of GIS tools, operational data, and failure records in the risk-based management of water distribution systems, with particular attention to minimizing disruptions in water supply to consumers. A fundamental requirement for reliable operation of a water supply system is detailed knowledge of its network structure, operating conditions, technical status, and historical data on system failures. Modern GIS platforms, especially when integrated with other digital tools such as SCADA systems, hydraulic models, and monitoring software, provide a robust framework for this. One of the most valuable GIS functionalities for both water suppliers and consumers is the systematic registration of failures in the water distribution network. Failure logs, compiled over several years, offer critical insights into the causes, frequency, and seasonality of breakdowns. These datasets serve as the foundation for assessing infrastructure reliability and planning targeted maintenance interventions. This study presents an example of failure analysis conducted on a selected water supply network in Poland. The analysis highlights dominant failure causes and their temporal distribution. Using GIS-based numerical maps and failure databases, spatial distribution and intensity of pipe damage were evaluated. This facilitated the identification of high-risk areas and pipelines with elevated failure rates, which pose the greatest threat to continuous water supply. Risk mapping based on failure frequency and infrastructure condition supports decision-making in the allocation of repair resources and scheduling of rehabilitation works. This approach not only improves the effectiveness of maintenance teams but also reduces the risk of service interruptions. Moreover, the methodology is aligned with broader European policies such as the INSPIRE Directive, which promotes harmonized spatial data infrastructures as a basis for environmental and risk assessments. In an era where informatization drives operational efficiency, GIS and related information systems offer unmatched potential in the risk assessment and management of water distribution infrastructure. Their ability to process and visualize complex datasets transforms raw operational data into actionable intelligence. The outcome is a proactive maintenance strategy that enhances the resilience and security of water supply systems, ultimately ensuring uninterrupted service delivery to consumers.

Keywords: *critical infrastructure, water network, maintenance, GIS applications,*

1. Introduction

Critical infrastructure in cities encompasses systems whose functioning determines public safety, the health of residents, and the stability of economic processes. Water supply systems, in particular, are a key component of technical infrastructure, whose reliability must be maintained at the highest level [1-4]. Their disruption – for example, due to water main failures – can lead to water supply interruptions, network contamination, financial losses, and even epidemiological threats [5-13].

Water supply networks are extensive, complex, and often aging systems, making them susceptible to mechanical damage, corrosion, and hydraulic overload [14-18]. At the same time, their operational importance extends beyond simply providing drinking water – they also provide water for firefighting and industrial purposes, and serve as a support element for sewage and cooling systems. Therefore, their operation must be not only efficient but also resilient to failures and operational disruptions [7, 17-20]. The problem of water supply network failures is multifaceted – it affects the pipes themselves (diameter, age, material), soil and water conditions, installation quality, pressure changes in the system, and even seasonal temperature fluctuations. Research shows that the most common causes of failures are pipe cracks due to material aging, mechanical damage from earthworks, and electrochemical corrosion [3, 4, 6, 10, 12, 15, 20, 21]. On an urban scale, failures occur spatially – their distribution is not random but concentrated in so-called problem areas. Identifying these zones and predicting the risk of failure requires the integration of spatial and technical data.

In recent years, there has been an intensive development of digital tools supporting the management of water supply infrastructure. Geographic Information Systems (GIS), which enable the integration of spatial, operational, and diagnostic data within a single analytical environment, play a particular role [22-24]. Thanks to its capabilities of visualization, information layering, and spatial analysis, GIS is not only a tool for inventory management but is also increasingly used to predict risks and support maintenance decisions [24-31].

GIS allows for the analysis of failure rates in the context of the network's geographic location, material type, conductor age, and local operating conditions [22-24, 26, 28]. Examples of applications include, among others: These include identifying sections with an increased

number of failures, analysing the spatial seasonality of failures and integrating them with hydraulic models to assess the impact of failures on pressure parameters and supply continuity. In practice, this allows water network operators to develop risk maps, plan repairs and modernizations in advance, and optimize the allocation of technical resources [32-37].

However, in many cases, conducting a thorough risk analysis is impossible due to the lack of a complete operational database. The main reason is that searching for relevant data is time-consuming and expensive. Furthermore, there is a constant need to verify the validity of data. The European Union addressed all these requirements by establishing the INSPIRE Directive on March 14, 2007. The INSPIRE Directive aims to create a spatial data infrastructure for the European Union (EU). This will enable the exchange of spatial information on the environment between public sector organizations and facilitate public access to spatial information across Europe. The European Spatial Data Infrastructure will support policymaking across borders. Therefore, the spatial information covered by the directive is extensive and covers a wide range of thematic and technical topics. Water utilities can publish information on the geoportal about water supply failures, planned network repairs, as well as water quality or specific parameter values (physicochemical, bacteriological, and organoleptic). Such communication between water suppliers and consumers will influence their relationships and increase consumer trust.

The directive's main goal is to support Member States in environmental protection and to support activities that have a direct impact on the environment. These activities are related to:

- collecting data and storing it where it is most effective,
- the ability to seamlessly combine spatial information from various sources across Europe and make it available to multiple users,
- geographic information essential for good governance at all levels should be easily and transparently available,
- the ease of finding available geographic information, how it can be used to meet a specific need, and the conditions under which it can be obtained and used.

The purpose of this paper is to present a methodology for integrating failure data with a GIS system for water supply network management purposes. Based on data obtained from a Polish water utility, a spatial analysis of failure rates in a water supply network operating in south-eastern Poland is presented. The analysis resulted in the development of failure intensity maps and the identification of areas at increased risk of supply disruption, which provides a basis for planning repair and modernization activities in accordance with reliability engineering principles. The proposed method enables analysis of the spatial distribution of failures, identification of sections with high damage risk, prioritization of repair and modernization activities, and decision support for water supply network operators.

2. GIS and IT tools in managing water supply network maintenance in urban areas

The benefits of GIS in water infrastructure management are significant for every water company. Among its many advantages is the structured and clear communication of information, streamlining decision-making and all activities related to the recording and operation of the water supply network. Furthermore, GIS is an excellent tool for analysing data gaps and detecting potential problems that compromise water supply security [22, 24, 26, 29, 32]. Typically, over time, some information about facilities and pipelines becomes lost or unrecoverable. GIS databases enable this information to be entered into the company's computer database, enabling easy and transparent access to this data.

In water supply systems, GIS applications can be used depending on the user's needs. The application user decides which objects will be visualized and how, using attribute or spatial analyses. Object categorization includes [22, 23]:

- network objects in the technical sense (e.g., a water pumping station, a network tank, a section of a water pipe, a hydrant, a gate valve, a section of a pipe of a given diameter and made of a given material),
- objects in the technical sense (e.g., a water recipient – services, housing),
- objects in the economic sense (e.g., the price of water),
- objects in the geographical sense (e.g., a water supply area, a well location and its range).

Technical objects in GIS are most often presented as point symbols, lines, geometric symbols, and text. For proper management of a water supply network, it is crucial to precisely define and identify the objects that will be reflected in the GIS database. How the data are defined depends on the company and the goals and tasks assigned to the network operator. Ensuring the safety of water supply to consumers requires a detailed and accurate database. GIS systems allow for the recording of networks and failures, the creation of reports, assessments, and statistical analyses of the causes and effects of adverse events occurring in the network, and the determination of damage intensity indicators for specific types of pipes. Additionally, it allows for the development of repair and maintenance plans and financial analysis of the costs incurred by the company. All these factors directly impact the quality of life of water consumers, which in turn translates into their safety [7].

The main tasks of GIS to ensure the safety of water supply to consumers are [7, 35, 36, 38, 39]:

- organizing, rationalizing, and verifying inventories,
- creating a central database,
- facilitating access to information at every level of the company,
- performing analyses and assessments for decision-making purposes,
- enabling the visualization of network performance analysis results,
- enabling ongoing and continuous monitoring of water quality in the water supply network,
- improving customer service,
- streamlining the failure resolution process,
- streamlining the implementation of ongoing operational tasks and development planning,
- facilitating access to information for interested water consumers by providing access to analysis results and their visualization (water supply network failure analysis).

Despite the opportunities offered by computerization in water utilities today, the management process still relies little on IT systems. The essence of proper water infrastructure management is the proper identification of the objects that comprise it. These form the foundation of the model used in GIS programs [5]. GIS programs not only enable the conversion of data from paper maps into a digital format, but also enable full visualization of critical infrastructure components and the tracking of factors that increase the risk of water supply disruptions resulting from water supply network failures.

GIS applications in water utilities are an extremely convenient tool for risk analysis using spatial data visualization. Modern geoinformation systems sometimes constitute extensive platforms integrated with other tools used in water supply infrastructure, such as monitoring and mathematical models. The database of IT systems with which GIS applications can be integrated includes the following

systems [22, 23]:

- IT record-keeping tools, known as Electronic Document Management Systems (EDMS), which, when combined with GIS, enable quick and easy browsing of documents stored in the database. This is particularly true for spatial object documentation, where it is possible to directly link any point in the geodatabase to a text or graphical document.
- Work Management Systems (WMS). Based on spatial and cadastral data, as well as economic analyses of the water utility, a WMS allows for planning work related to the operation, modernization, and expansion of the network, while taking into account available resources for these tasks. The main tasks of a WMS include logging emergency notifications, providing decision-making support in the process of repairing and recording failures, scheduling renovation and investment work, and creating simulations and economic analyses for the maintenance and operation of both the water and sewer networks.
- Manufacturing Execution Systems (MES) enable automated production management. In particular, this involves planning, monitoring, and optimizing technological processes, for example, in terms of the quality of water supplied to customers. The system's functionality enables immediate decision-making and responding to irregularities arising during the production process (production of potable water). Data obtained from the production process allows for the analysis of key indicators affecting the production process.
- Customer Relationship Management (CRM) systems enable the management of interactions with a company's customers. Using CRM systems with GIS applications allows for the collection of information about customers who use and those who do not use the company's services. This allows the company to identify profitable customers and obtain the necessary data to improve the water supplier-recipient relationship.
- Enterprise Resource Planning (ERP) systems. In the water industry, this tool can fully inventory network assets and support resource management. Thanks to GIS application information regarding water supply network failures and condition, the ERP system facilitates planning and monitoring of investment and renovation activities. One of the system's most important tasks is the detailed recording and analysis of water production and distribution costs. It also facilitates the preparation of analyses and the definition of future goals, planning subsequent activities, and optimizing the costs associated with water delivery to consumers.

Figure 1 shows the cooperation of GIS applications with selected IT systems.

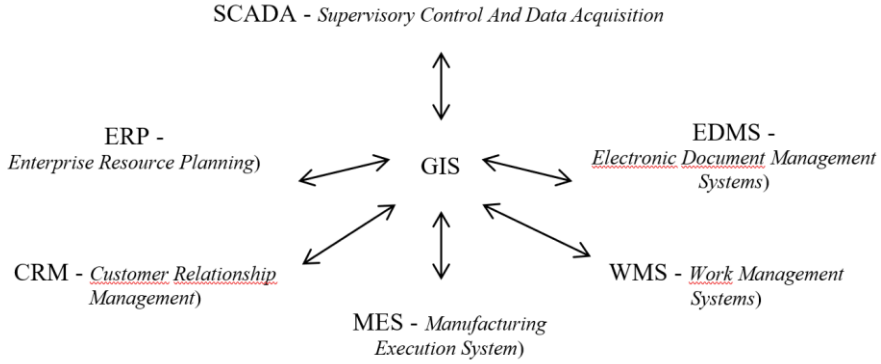

Fig. 1. GIS cooperation with selected IT systems

3. Failure water pipes recording as an element of critical infrastructure management – case study

The study site is a voivodeship capital located in south-eastern Poland. This area lies in the Sandomierz Basin, in the basin of the Wisłok River – a left-bank tributary of the San River. The hydrographic and geomorphological conditions of this region, combined with dynamic urban development, constitute significant determinants of the design, operation, and modernization of water supply infrastructure. According to data from the Central Statistical Office, the city's population in 2024 was 198,317,000 inhabitants, with a clear upward trend resulting from industrial development, internal migration, and the expansion of the city's administrative boundaries. This growth generates increased water demand and the need to modernize and expand the water supply system. The water supply network administered by the water company covers a total of 1,140.66 km (as of December 31, 2022), including: 336.07 km of water service lines, 99.11 km of main lines, and 705.48 km of distribution lines.

The dispersion of water supply infrastructure across cities and villages means that, for repair crews, the question of "where" becomes particularly important when a failure occurs. Information about the location of network sections, water connections, and fittings is particularly important for the operation process and the effective removal of the negative effects of adverse events. Equally important is data on the location of other networks (sewer, gas, etc.), which provides valuable guidance during the repair work itself. The potential of GIS in the repair planning process is enormous. However, most water utilities still do not fully utilize its capabilities due to financial constraints. Figure 2 shows the analyzed research object.

The safety of water supply also depends largely on the functioning of other critical infrastructure. Three groups of threats affecting the operation of the water supply network have been proposed. The first group comprises linear underground infrastructure, such as telecommunications lines, power cables, gas pipelines, heating pipelines, and sewer networks. For example, damage to sewer pipes (sewage leakage into the ground) or discharge of sewage directly into a river can deteriorate the quality of water drawn from surface and underground intakes. Another threat may be a power grid blackout, which could negatively impact the operation of water supply pumping stations, monitoring systems, and SCADA systems. The second group comprises streets, roads, and highways, including the transport of hazardous substances, whose leakage can cause environmental degradation and a deterioration in water quality. The third group includes external threats caused by forces of nature, such as drought, floods, and landslides. Additionally, cyber threats posed by telecommunications systems and third parties should also be considered.

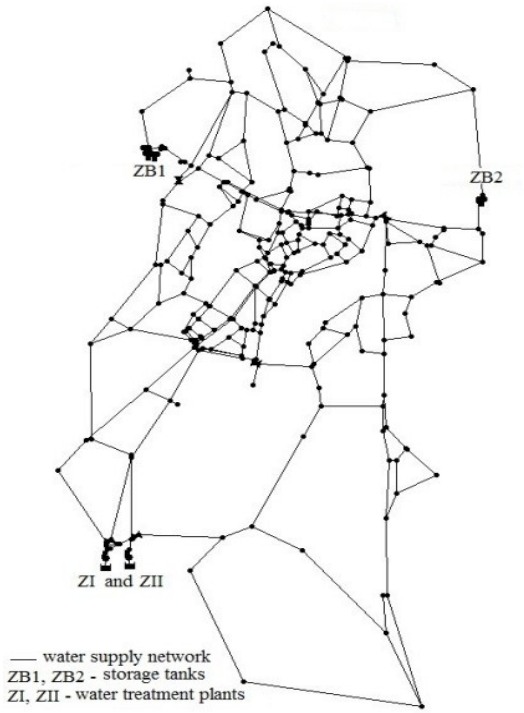

Fig. 2. The scheme of analysed water network

3.1 Recording water pipes failures

The possibilities currently offered by GIS in water infrastructure management are enormous. The use of databases in the process of delivering water to customers supports investment, modernization, and the use and operation of these systems. A significant area of application in the operational process is assessing the reliability, safety, and failure rates of water supply facilities and networks. The specific nature of water utilities operating network infrastructure requires GIS systems to not only archive and update asset data, but also provide functions and information related to power outages in sections of the water supply network undergoing repair, the location of the damage along with a description of its cause, the location and nature of the repair work being carried out, data on customers who may be deprived of water supply during the repair, and even information on the repair crew responsible for repairing the failure. [22, 23].

The dispersion of water supply infrastructure across cities and villages means that, when a failure occurs, the question of "where" becomes particularly important for repair crews. Information about the location of network sections, water connections, and fittings is particularly important for the operation process and the effective removal of the negative effects of adverse events. Data on the location of other networks (sewer, gas, etc.) is equally important, providing valuable guidance during the repair work itself. GIS is often used to establish priorities for the renewal (replacement, renovation, reconstruction) of water supply infrastructure. There are few studies on the use of GIS to assess the risk of water supply pipe failures, thus ensuring the required level of water supply security. Databases most often serve as a tool for locating failure locations. This allows for further analyses related to the operation and operation of the network, such as estimating the intensity of damage to pipes operating within the supply area or developing network renewal strategies [22, 23, 24].

GIS application users can obtain information of interest by posing simple attribute queries or complex spatial queries. Simple queries might, for example, indicate the location of a pipe failure on a map that occurred on a specific day and time, and display the attributes (parameter descriptions) specific to that object. This can be accomplished by selecting the object of interest from a created database, or by selecting its characteristic descriptive attributes, such as its identification number, diameter, etc. [22, 23, 24].

An excellent example of the effective use of GIS applications in supporting the work of water supply emergency services is the recording of failures, along with the key descriptive attributes characterizing the failures, such as pipe diameter and material. One GIS program that enables failure recording is Intergraph's G/Technology. At the general level of the numerical map, all data (networks, buildings, wells, hydrophores, etc.) is divided into point, line, and area objects. With data on the location of the failure—the exact address and technical data of the pipe—it is possible to pinpoint the location of the failed pipes on the map using the "street location" function. The end result is a visualization of each failure as a "lightning bolt" with a specific identification number. This process is crucial in failure risk analyses and assessments, which should be the basis for operational decisions.

As part of our own research conducted at a selected water utility, we created a system-based, prototype database of water supply network failures for the 2012-2014 operational years. The scope of the database entered and processed in the "failure records" module of the G/Technology program included:

- ID – the identification number of the failure event,
- Report date – the exact date the failure occurred, including the day, month, and year,
- Diagnostic report content – a description of the cause of the failure,
- Network type – the category of the water pipe that failed (main, distribution, and additional water connections),
- Cause of failure – a description of the cause of the event,
- Material – the type of material from which the emergency pipe is made,
- Diameter – the diameter of the pipe that failed.

The process of creating the database together with the “Failures” layer is shown in Fig. 3.

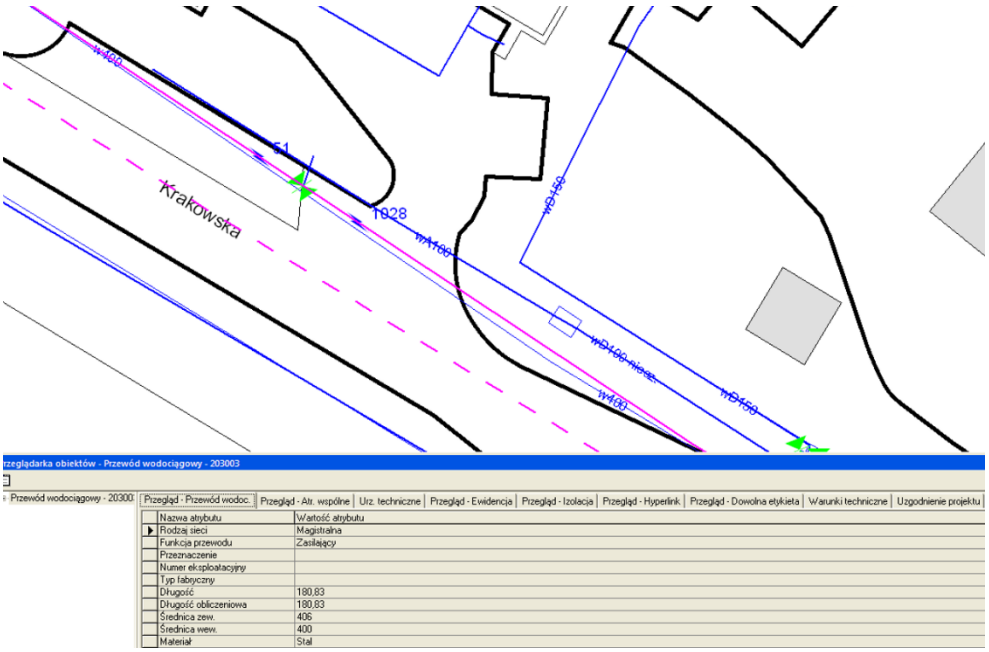

Fig. 3. A fragment of the created "Failures" layer with the structure of the attribute data of the layer - a view from the G/Technology program

The fault recording process simplifies decision-making regarding repair and maintenance plans and prioritizes which lines require repair/modernization. This approach allows for analysis of areas where failures occurred most frequently. For accurate modelling, the fault recording process should include descriptive attributes such as: the diameter of the line where the failure occurred, the line material, the cause of the damage, the line category (main, distribution, water connection), the date the report was received, the date the repair and maintenance work was completed, the consequences of the undesirable event, the time taken to repair the failure, the cost of repair, the materials and equipment used, as well as photos and descriptions enabling more detailed documentation of the event, and the length of the line where the failure occurred.

3.2 Mapping the failures of the water supply network

Given the growing challenges associated with climate change, urbanization, intensified water resource consumption, and the growing number of extreme events, an integrated approach is becoming increasingly important, combining technical reliability analysis with risk assessment of threats to the continuity and quality of water supplies. In this context, an interdisciplinary method for water supply network vulnerability mapping is being developed, enabling the identification, spatial representation, and assessment of potential threats and the vulnerability of water systems to various risk factors resulting in a lack or limitation of water supply.

Fault mapping is particularly applicable in environmental engineering, providing a tool supporting both the assessment of the vulnerability of infrastructure systems and the planning of preventive, adaptive, and crisis response measures. In the case of water supply systems, maps can integrate spatial, hydrological, demographic, and technical data, allowing for a multifaceted analysis of water supply security in the context of threats such as droughts, source contamination, critical infrastructure failures, and urbanization pressures. This approach extends traditional reliability and safety analyses, allowing for the consideration of risks not only related to the internal structure of the system, but also those arising from its environmental and socioeconomic environment.

The GeoMedia application was used as the primary tool for visualizing and spatially analysing data on water supply network failures. The system enabled the integration of tabular data on failures with the network model in the form of GIS layers containing information on pipe routes, diameters, and materials.

Thematic map layers were used to depict the locations of failures in relation to the spatial structure of the network, allowing for the identification of areas with increased failure rates. Subsequently, an analysis was conducted of the relationship between the number of failures and the technical characteristics of the pipes. Particular attention was paid to the influence of pipe type on the failure frequency. The results indicate that pipes made of grey cast iron have a significantly higher failure rate compared to modern materials such as PE or PVC, confirming field observations and previous industry publications.

Figure 4 shows the main water supply network with a visualization of the material from which it is made, while Figure 5 shows an example of a failure analysis plotted on a generated map taking into account the structure and location of the main network.

The use of GIS in network failure analysis allows not only for locating critical points in the system but also for assessing investment priorities and optimizing operating costs. Water supply network failure maps are becoming a key tool supporting the decision-making process of water network operators, planning engineers, and maintenance services. In the era of digitization of urban infrastructure, GIS solutions are conducive to the development of intelligent network management systems.

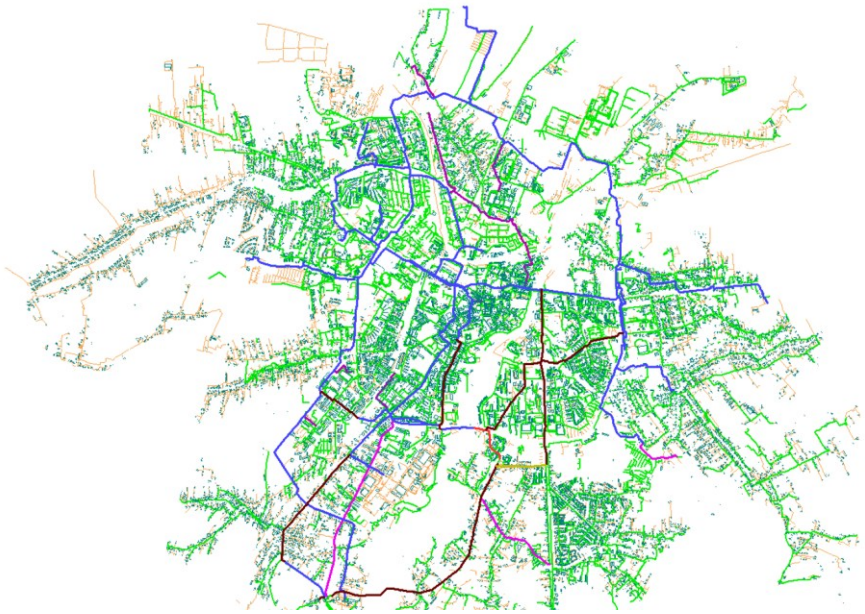

Fig. 4. Map of the main water supply network with details of the material it is made of (brown - cast iron, blue - steel, yellow, pink and red - PE and PVC)

Fig. 5. Map of water supply network failures generated based on the structure and location of the main network..

3.3 Prioritization of water supply network failure

Emergency maps generated in the GeoMedia environment can be expanded with additional analytical criteria, such as prioritizing emergency reports based on the infrastructure's importance to water supply continuity. In practice, this means that network sections can be classified according to their degree of criticality. For example, main lines supplying large urban areas or sensitive facilities (hospitals, schools, industrial plants) are assigned Priority I, requiring immediate response from technical services.

Reports concerning such sections are automatically marked as critical in the system, enabling dynamic management of operational resources – in particular, the rapid deployment of repair crews and ensuring the availability of equipment and materials. This data also forms the basis for planning infrastructure repairs and modernization for the next fiscal year, enabling the rationalization of capital expenditures based on actual operational risk.

From the perspective of network management in urban areas, this approach supports the implementation of the Smart City concept by:

- increasing the resilience of critical infrastructure to failures,
- reducing the duration of water supply interruptions to end users,
- enabling data integration with SCADA, CMMS, and notification management applications,
- creating operational risk maps to support strategic and operational decisions.

Figure 6 shows the main water supply network, along with its failure rates. Reports of failures in the main network were assigned priority I due to their crucial importance in ensuring the continuity of water supply to customers.

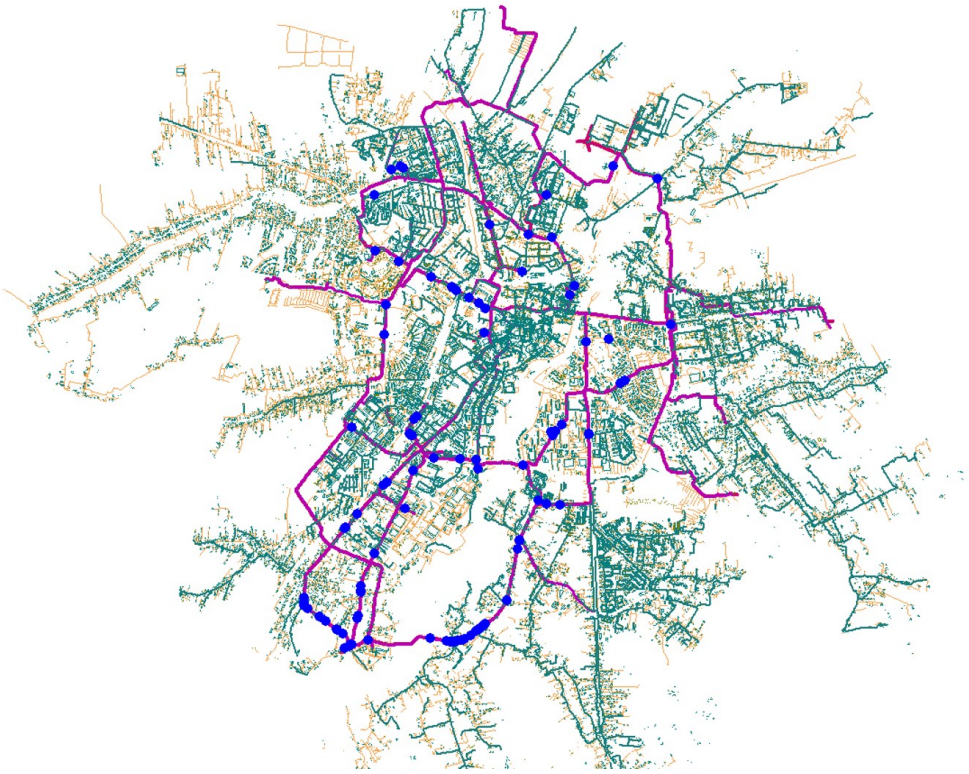

Fig. 6. Map of water supply network failures generated based on the structure and location of the main network..

In the analysed water supply system, particular attention was paid to failures occurring on the main network lines, which, due to their strategic nature, are crucial to the continuity of water supply throughout the urbanized area. For these operational incidents, the Service Priority I (the highest) was used in the notification classification system. In practice, this means that any failure report concerning a main section triggers an immediate operational response – a repair team is dispatched to the site first, bypassing lower priority reports. Maps generated in the GeoMedia application clearly highlight these incidents, allowing for their rapid location, spatial analysis, and incorporation into annual preventive and investment planning.

4. Conclusion

The analysis demonstrated that integrating emergency data with geographic information systems (GIS) is an effective tool supporting the management of water supply infrastructure from a reliability and spatial perspective. By linking failure locations with technical network parameters, such as material, diameter, and age, it was possible to identify sections most susceptible to damage and areas at high risk of water supply interruptions.

Using the GeoMedia platform enabled visualization of failure rates and prioritization of call handling, which translates into real support for operational decision-making. In particular, the use of Priority I classification for main lines allows for shorter response times and better planning of maintenance and investment activities on an annual basis. This approach improves the efficiency of maintenance teams and reduces the impact of failures on end users. At the same time, it allows the water supply operator to operate in accordance with reliability engineering principles and supports long-term management of technical resources.

In the context of the development of the Smart City concept and sustainable spatial planning, the presented methodology provides significant added value. Integrating GIS into daily operational practices enables the digitization of infrastructure knowledge, automates decision-making processes, and supports interdepartmental collaboration within municipal units. Risk maps, created based on real-world data, can be used not only by the grid operator but also by urban planners, designers, and emergency services.

However, it should be noted that the study had its limitations. It focused on a single operator in south-eastern Poland and covered a limited timeframe and dataset – without full integration with SCADA, MES, or CMMS systems. Information on real-time hydraulic parameters and groundwater conditions, which may impact failure rates, is also lacking.

Therefore, it is recommended that in the future: expand the database with additional technical, environmental, and operational parameters, integrate GIS with SCADA, CMMS, MES, and ERP systems to obtain a complete picture of the network's status and operation, implement predictive algorithms (e.g., statistical models) for failure forecasting and investment planning, introduce uniform standards for recording emergency events and regularly update data, share infrastructure and analytical data on public geoportals, enabling transparent communication with residents and planning institutions. Implementing these actions will contribute not only to improving the reliability and efficiency of the water supply system but also to the transformation of water utilities into modern, digital entities managing critical infrastructure, actively participating in the creation of smart, resilient, and sustainable cities of the future.

References

1. B. Budziło, Niezawodność wybranych systemów zaopatrzenia w wodę w południowej Polsce (Wydawnictwo Politechniki Krakowskiej, Kraków, 2010).
2. M. Kwietniewski, M. Roman and H. Kłos-Trębaczkiewicz, Niezawodność wodociągów i kanalizacji (Arkady, Warszawa, 1993).
3. J. Rak, "Selected problems of water supply safety", Environment Protection Engineering, Wroclaw University of Technology, the Department of Environmental Engineering, 35(2), 29-35 (2009).
4. B. Tchórzewska-Cieślak, Niezawodność i bezpieczeństwo systemów komunalnych na przykładzie systemu zaopatrzenia w wodę (Oficyna Wydawnicza Politechniki Rzeszowskiej, Rzeszów, 2008).
5. B. Tchórzewska-Cieślak and K. Pietrucha-Urbanik, "Water System Safety Analysis Model", Energies, 16, 2809 (2023).
6. A. Robles-Velasco, P. Cortés, J. Muñuzuri and B. De Baets, "Prediction of Pipe Failures in Water Supply Networks for Longer Time Periods through Multi-Label Classification", Expert Syst. Appl., 213, 119050 (2023).
7. B. Tchórzewska-Cieślak, J. Rak, K. Pietrucha-Urbanik, I. Piegdoń, K. Boryczko, D. Szpak and J. Żywiec, "Water Supply Safety Assessment Considering the Water Supply System Resilience", DWT, 288, 26–36 (2023).
8. J. Żywiec, D. Szpak, I. Piegdoń, K. Boryczko, K. Pietrucha-Urbanik, B. Tchórzewska-Cieślak, J. Rak, "An Approach to Assess the Water Resources Reliability and Its Management", Resources, 12, 4 (2023).
9. M. Karamouz, A. Yousefi, Z. Zahmatkesh, D. Mahmoodzadeh and M.D. Pirooz, "Simulation of Chlorine Injection in Water Distribution Networks in Response to Contaminations". Int. J. Environ. Res., 16, 6 (2021).
10. G.F. Craun, R.L. Calderon and M.F. Craun, "Outbreaks Associated with Recreational Water in the United States" Int. J. Environ. Health Res., 15, 243–262 (2005).
11. C. Calero Preciado, S. Husband, J. Boxall, G. del Olmo, V. Soria-Carrasco, S.K. Maeng, I Douterelo, "Intermittent Water Supply Impacts on Distribution System Biofilms and Water Quality", Water Res., 201, 117372 (2021).
12. D. Papciak, B. Tchórzewska-Cieslak, K. Pietrucha-Urbanik, A. Pietrzyk, "Analysis of the Biological Stability of Tap Water on the Basis of Risk Analysis and Parameters Limiting the Secondary Growth of Microorganisms in Water Distribution Systems", DWT, 117, 1–8 (2018).
13. N.A. Barton, T.S. Farewell, S.H. Hallett and T.F. Acland, "Improving Pipe Failure Predictions: Factors Affecting Pipe Failure in Drinking Water Networks", Water Res., 164, 114926 (2019).
14. E.I. Prest, F. Hammes, M.C.M. van Loosdrecht and J.S. Vrouwenvelder, "Biological Stability of Drinking Water: Controlling Factors, Methods, and Challenges", Front. Microbiol., 7, 45 (2016).
15. R. Taiwo, I.A. Shaban, and T. Zayed, "Development of Sustainable Water Infrastructure: A Proper Understanding of Water Pipe Failure", J. Clean. Prod., 398, 136653 (2023).
16. D. Młyński, T. Bergel, A. Młyńska, K. Kudlik, "A Study of the Water Supply System Failure in Terms of the Seasonality: Analysis by Statistical Approaches", AQUA—Water Infrastruct. Ecosyst. Soc., 70, 289–302 (2021).
17. Z. Yang, B. Barroca, A. Weppe, A. Bony-Dandrieux, K. Laffréchine, N. Daclin, V. November, K. Omrane, D. Kamissoko, F. Benaben; et al. "Indicator-Based Resilience Assessment for Critical Infrastructures—A Review". Saf. Sci., 160, 106049 (2023).
18. A. O. Lambert, "International report on water losses management and techniques", Water Science & Technology: Water Supply, IWA, 2(4) (2002).
19. A. Tiong and H.A. Vergara, "A Two-Stage Stochastic Multi-Objective Resilience Optimization Model for Network Expansion of Interdependent Power–Water Networks under Disruption", Int. J. Crit. Infrastruct. Prot., 40, 100588 (2023).
20. V. Marsili, F. Mazzoni, I. Marzola, S. Alvisi and M. Franchini, "Intermittent Water Supply System Rehabilitation through a Multiphase Methodology Based on Network Analysis and Hydraulic Modeling" J. Water Resour. Plan. Manag., 149, 04023048 (2023).
21. D. Zaman, M.K. Tiwari, A.K. Gupta and D. Sen, "A Review of Leakage Detection Strategies for Pressurised Pipeline in Steady-State", Eng. Fail. Anal., 109, 104264 (2020).
22. M. Kwietniewski, GIS w wodociągach i kanalizacji (Wyd. Naukowe PWN, Warszawa, 2008).
23. M. Kwietniewski, "Monitorowanie i Geograficzne Systemy Informacji w procesie współczesnej eksploatacji systemów dystrybucji wody i odprowadzania ścieków", Gaz, Woda i Technika Sanitarna, Sigma-NOT, 4, s. 9-15 (2005).
24. G. Michael and J. Zhang, "Simplified GIS for Water Pipeline Management, International Conference Pipelines: Infrastructure's Hidden Assets", American Society of Civil Engineers, San Diego, 1, s. 412-419 (2009).

References

25. I. Piegdoń and B. Tchórzewska-Cieślak, "Methods of visualizing the risk of lack of water supply", Proceedings of the European Safety and Reliability Conference, ESREL 2014, Taylor & Francis Group, s. 497-505 (2014).
26. I. Piegdoń, B. Tchórzewska-Cieślak and D. Szpak, "The use of geographical information system in the analysis of risk of failure of water supply network", Environmental Engineering V, Małgorzata Pawłowska & Lucjan Pawłowski, Editor, Taylor & Francis Group, London. p. 7-14 (2017).
27. R. Vemulapally, Development of Standard Geodatabase Model and its Applications for Municipal Water and Sewer Infrastructure (Faculty of the Virginia Polytechnic Institute and State University, Blacksburg, 2010).
28. I. Zimoch and J. Paciej, "Zastosowanie Geograficznych Systemów Informacyjnych w zarządzaniu oraz prowadzeniu kontroli jakości wody przeznaczonej do spożycia przez ludzi", INSTAL, 1, s. 38-41 (2013).
29. K. Diao, R. Sitzenfrei and W. Rauch, "The impacts of spatially variable demand patterns on water distribution system design and operation", Water, 11(3), 567 (2019).
30. M.J. de S Cordão, I.A.A. Rufino, P.B.R Alves and M.N.M.B. Filho, "Water shortage risk mapping: a GIS-MCDA approach for a medium-sized city in the Brazilian semi-arid region". Urban Water Journ, 17(7) (2020).
31. B. Tchórzewska-Cieślak, K. Pietrucha-Urbanik and I. Piegdoń, "The failure risk analysis of the water supply network". WATER, 3815, 15, 1-22 (2023).
32. K. Boryczko and B. Tchórzewska-Cieślak, "Maps of risk in water distribution subsystem". 11th International Probabilistic Safety Assessment and Management Conference and the Annual European Safety and Reliability Conference, 2012, Curran Associates, Inc.,p.5832-5841 (2012).
33. D.J. Glasbrook, Application of GIS for Maintenance in Widespread Distribution Networks (IWSA Regional Conference, Zurich, p.125-144, 1994).
34. T. Heinonen, "Use GIS at Helsinki Water". [In:] Applying GIS technologies in Water Utilities: A Challenge and a Necessity. Conference Turin. "Water Supply – A Review Journal. IWA", 18(4): 1-8 (2000).
35. M.J. Kane and A. Gough, Database to prioritize mains rehabilitation (Proc. of IWSA Spec. Conf. on New Developments in Modelling, Monitoring and Control of Water Supply Systems, Amsterdam, The Chameleon Press Ltd. London, p.195-213, 1996).
36. U.M., Shamsi, GIS applications for water, wastewater and stormwater systems (Taylor and Francis Group, Boca Raton, London-New York, 2005).
37. I. Piegdoń, "Variability of drinking water quality on the basis of analysis of qualitative monitoring from a selected water supply network located in South-Eastern Poland". WATER, 3355, 16(23), 1-25 (2024).
38. B. Reynaert, R. Horemans, and P. Vercruyssen, ArcGIS/ArcFM 8 for water distribution network management. Case study submission in response to a call for case studies distributed by the author ([In]: Shamsi U.M. for the book GIS Application for Water, Wastewater and Stormwater systems 2005).
39. M. Williams, and H. Shah, "An Integrated IT Platform for Managing Water Distribution and Sewerage Networks. Applying GIS technologies in Water Utilities: A Challenge and a Necessity". Conference Turin. "Water Supply – A Review Journal. IWA", 18(4): 31-40 (2000).