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Hydraulic Modeling and Spatial Data Integration in Urban Water Supply Networks: Methodological Advances and Practical Applications

Péter Orgoványi[1]
[1]*Faculty of Water Science, Ludovika University of Public Service, 6500 Baja, Hungary*

ABSTRACT
The hydraulic modeling of public water supply systems has undergone significant technological and methodological advancements over the past decades. The integration of computer simulations, geographic information systems (GIS), and machine learning-based predictive algorithms has opened new possibilities for understanding network behavior, optimizing operations, and forecasting water quality. This study reviews the historical development of hydraulic modeling, highlights the role of modern data-driven approaches, and provides a detailed analysis of methodologies for spatial distribution of consumption data. Special attention is given to zoning and address-based geocoding as tools for improving modeling accuracy, with a particular focus on Hungarian implementation practices. The novelty of this research lies in demonstrating the integration of geocoded consumption point identification into hydraulic network modeling, enabling the automatic alignment of consumer address data with GIS platforms. This approach significantly enhances the spatial resolution of consumption data, reduces manual labor requirements, and supports more accurate representation of real consumption patterns. Through practical examples, the paper illustrates how these methods contribute to reducing water loss, accelerating fault diagnostics, and developing sustainable and intelligent water supply systems.
Keywords: *hydraulic modeling, GIS, geocoding, EPANET, sustainable operation*

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I. INTRODUCTION

Public water supply systems are fundamental components of modern urban infrastructure, exerting a direct influence on residents' quality of life, public health, and both economic and environmental sustainability. Water, as a resource, is not only essential but increasingly regarded as a strategic asset in the face of global challenges such as climate change, urbanization, and the quantitative and qualitative limitations of natural resources. Rising water demand, aging infrastructure, and increasing uncertainty in environmental and climatic conditions all underscore the need for a deeper understanding and more efficient management of water supply systems.

The analysis and development of water supply networks increasingly rely on mathematical and computer-based modeling tools. Modern models enable the prediction of hydraulic behavior, the optimization of operations, the assessment of system reliability, and the comparison of various development scenarios. The methodological foundations of modeling began to take shape in the 1960s, and with the advancement of computing technology, the simulation of complex, large-scale systems became feasible. Today, modeling practices are based on the numerical solution of hydraulic equations, the management of large databases, and the integration of optimization and decision-support systems.

Although public utility services are often taken for granted, it is essential to understand the technical, environmental, and organizational factors that influence the condition and operation of these networks. Detailed knowledge of the structure of water supply and sewerage networks, as well as the physical and chemical processes occurring within them, is crucial for ensuring long-term, sustainable operation. The accurate determination of flow phenomena in gravity and pressurized pipelines is achieved through modern hydraulic network modeling techniques, which play a role not only in planning water quantity and pressure but also in designing quality parameters such as material transport.

Public water supply and sewerage systems are complex infrastructures where engineering, natural science, and social factors interact closely. The reliability of a given system depends not only on the condition of physical components—such as pipes, pumps, and reservoirs—but also on operational strategies, energy use, changing consumer demands, and environmental challenges. Climate change, urban population growth, and the limitations of water resources all place increasing pressure on these systems, making comprehensive evaluation and long-term planning essential for sustainable operation.

Modeling approaches in this field are of paramount importance, as they enable the numerical description and simulation of real-world processes. A modern model not only predicts hydraulic behavior but also contributes to the analysis of water quality dynamics, the minimization of operational disruptions, and the scientific foundation of network development decisions. Through scenario analysis, researchers and planners can assess the consequences of alternative interventions, thereby optimizing both strategic and operational aspects of system management.

However, the effectiveness of modeling is significantly influenced by the availability and quality of data. The integration of data stored in various, often incompatible IT systems used by service providers presents a major challenge for professionals and frequently requires substantial manual effort. In light of these factors, the statistical and hydraulic evaluation of water supply systems is not merely a technical task but a strategically important activity that supports the protection of critical infrastructure and the achievement of sustainable urban development goals.

II. THE EVOLUTION AND CURRENT APPROACHES OF WATER SUPPLY NETWORK MODELING

The factors and methods mentioned can only be fully understood by reviewing the scientific findings and engineering applications that have shaped the modeling of water supply and sewerage networks over the past decades. Various approaches in the literature place differing emphasis on solving hydraulic equations, supporting network development strategies, or applying data-driven, predictive methods.

In recent decades, the hydraulic modeling of urban water supply networks has undergone significant development, closely linked to the rapid advancement of computer technologies and the gradual transformation of engineering perspectives. While early models relied on manual calculations and basic assumptions about flow and pressure, their accuracy was highly limited, making them suitable primarily for basic design and estimation tasks. With the spread of computing, it became possible to simulate large-scale, dynamic, multi-node networks in detail, opening new dimensions for engineering analysis and practical applications. Today, sophisticated algorithms and real-time data analysis solutions are employed to significantly improve network performance forecasting, as well as the optimization of operations and development planning. [1].

The development of hydraulic modeling can be divided into several clearly distinguishable phases. Prior to 1980, the design and analysis of water supply systems were primarily supported by manual calculations, empirical formulas, and simplified hydraulic assumptions. In practice, these calculations were mainly based on hydrostatic principles, simplified forms of the Bernoulli equation, and basic flow formulas. The 1980s and 1990s marked a turning point, as computer-aided design (CAD) became widespread, complemented by simulation software such as the early versions of EPANET. These programs revolutionized the field by enabling more realistic analysis of pressure conditions and flow distributions, as well as the evaluation of complex system interactions.

From the 2000s onward, the modern era has been characterized by the integration of geographic information systems (GIS), real-time data collection, the proliferation of sensor networks, and the development of optimization algorithms based on these technologies. Additionally, machine learning has gained increasing importance, as it enables the use of large volumes of measured and modeled data to predict system behavior and identify potential sources of failure [2].

Today, hydraulic modeling focuses on several interrelated key areas. In the development of smart water networks, Internet of Things (IoT) devices, sensors embedded in pipelines, and remote monitoring solutions are integrated to enable real-time data collection on flow and pressure conditions. This provides more accurate decision support for operators, especially in critical situations such as leak detection or peak demand periods [3]. The rise of data-driven approaches is particularly important, as machine learning and predictive models are capable of forecasting the expected evolution of network conditions, identifying unusual behavioral patterns, and proactively signaling potential issues before they lead to major failures.

Sustainable and resilient planning is of key importance today, as models must not only reflect average operational conditions but also account for extreme hydrometeorological events. These include increasingly frequent drought periods caused by climate change, as well as hydraulic loads associated with intense rainfall. The goal of modern models is to incorporate flexibility in order to manage factors that threaten the continuity of supply and to provide appropriate decision support in emergency situations.

In addition, water quality modeling has also undergone significant development in recent years. Research efforts are increasingly focused on accurately predicting the movement and interactions of reactive and non-reactive substances stored or flowing within pipelines, as well as the chemical and biological processes that influence water quality [4].

One of the most serious and still pressing issues in water supply networks is water loss, which holds significant importance from economic, environmental, and supply security perspectives. Various methods are used to detect leaks and hidden faults: acoustic sensors and pressure detectors assist in the early identification of localized, minor failures [5], while statistical data analysis techniques and machine learning algorithms can identify leakage-related patterns through long-term analysis of flow data. Remote sensing technologies are playing an increasingly important role, including satellite and drone-based surveys, which are capable of detecting anomalies on a large scale in extensive networks—especially in areas where traditional on-site inspections are difficult or costly to carry out. [6].

Fault diagnostics is also a key area of research and practice, as the rapid detection and management of failures can significantly reduce the severity of disruptions in water supply. Continuous monitoring of pressure and flow enables the identification of abnormal behavior indicative of system malfunctions [7]. Hydraulic simulations also assist in predicting the most likely failure points by taking into account past experiences and current network parameters. This approach is often complemented by on-site instrumental measurements and inspections, which enable precise localization and targeted repair of faults. Forecasts generated by models are frequently combined with engineering expert knowledge, allowing for the planning of rapid and effective interventions in practice [8].

Numerous international studies address the discretization of hydraulic network models, which is one of the most critical and often most sensitive steps in the modeling process. During discretization, continuous processes that represent real hydraulic phenomena are necessarily broken down into spatial and temporal units, meaning that large and complex systems are divided into smaller, computable elements. The accuracy of input data fundamentally determines the reliability of output results, making the preparation, validation, and refinement of input parameters essential for successful application. With sufficient experience and professional knowledge, the correct selection of topology and other input parameters can help achieve modeling goals while minimizing labor and computational resource requirements—thereby increasing efficiency and operational cost-effectiveness. This is especially important in large-scale systems, where excessive model complexity can lead to unjustified costs and longer computation times, while under-parameterized models may distort decision-support processes through inaccurate predictions.

Several approaches have emerged in the international literature for modeling low-pressure or intermittently pressurized networks. Ingeduld and colleagues (2006) applied a unique method by modifying the EPANET source code to enable accurate representation of systems operating under such special conditions. Although these types of problems are relatively rare in Hungary—where public utility networks typically operate under constant pressure—extreme situations such as emergency events, prolonged power outages, or exceptional hydrological conditions may create scenarios in which modified modeling solutions become highly relevant. Ingeduld and his team tested the developed EPANET variant in the Indian city of Shillong and in Dhaka, the capital of Bangladesh, where complex and often non-continuous water supply networks posed significant challenges. The insights gained contributed to the reconstruction of these systems and the establishment of conditions for continuous and safe water supply [9].

The integration of GIS technologies into the process of building hydraulic network models has ushered in a new era of extensive data management. The use of geographic information systems enables the organized handling of large-scale and complex spatial data in a digital environment, making raw data more accessible and usable for modeling purposes. Through GIS platforms, various data sources—such as consumer connection points, pipeline geometries, and field survey results—can be linked within a unified system, thereby alleviating previous challenges in data management.

Geospatial systems gain true significance in advanced operational strategies when they are connected and integrated with sensor and monitoring systems that provide real-time data. These sensors are capable of measuring pressure, flow velocity, water quality parameters, and other quantities that determine hydraulic balance. When such data is directly transmitted to GIS-based hydraulic models, input parameters become available in near real-time, representing a major breakthrough compared to earlier static modeling applications.

From an operational and management perspective, this real-time connection enables faster responses to emerging issues, such as leaks, sudden pressure drops, or capacity shortages. For decision-makers, dynamic data flow offers not only speed but also enhanced supply security, as interventions can be scheduled in a timely manner and decisions regarding system status can be based on more accurate information. It is anticipated that in the future, further integration of GIS, hydraulic modeling, and sensor-based data collection will lead to unified intelligent operational platforms capable of simultaneously managing network stability, changing supply demands, and sustainability considerations.

III. MODELING PRACTICE

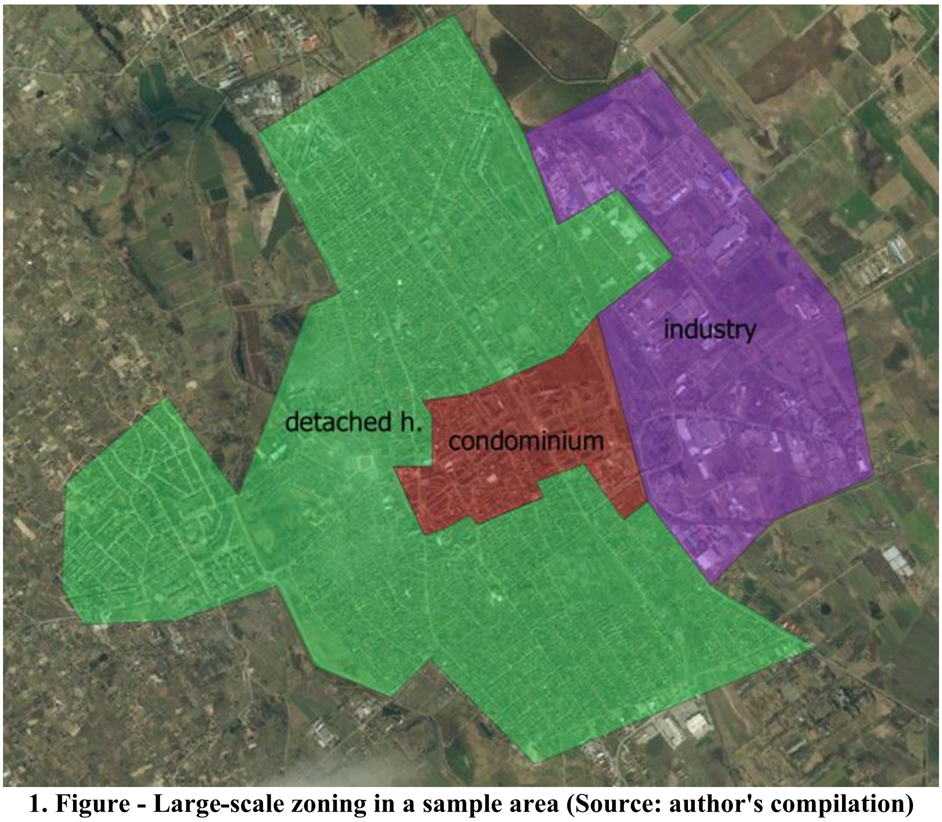
In Hungary, the majority of design guidelines related to public water supply systems were written in the 1970s, a time when the structure of settlements and water usage habits differed significantly from today's conditions. These manuals provided detailed analyses of consumption characteristics of the era and offered recommendations for various generalized life situations regarding the quantitative norms to be used in design processes. One of their main objectives was to provide a reference framework for estimating residential, industrial, and institutional water consumption, allowing designers to align their calculations with confidence. Although these descriptions are now considered partially outdated, they can still serve as useful reference points if applied with appropriate caution and updated context.

In current design practice, the creation of entirely new water supply systems in previously undeveloped areas is rare. The focus is much more on expanding, reconstructing, and modernizing existing systems, or on connecting new residential or industrial zones. In such cases, data from older design guidelines may be used as supplements to urban planning documents or for establishing weighting factors, but they must always be adapted to the specific characteristics of the area, taking into account local consumption patterns and more recent measurement data.

Today, water utility coverage in Hungary is practically complete, rendering many of the previously used methodologies obsolete. A prime example is the categorization of housing types based on water supply levels—a widely applied approach in the 1970s—which no longer provides a suitable basis for design. The earlier practice distinguished four types: public standpipe service, fully equipped service, semi-equipped service, and modern buildings with continuous hot water supply or district heating. Since the vast majority of homes now fall into the latter category, this classification is no longer effective for differentiating consumption characteristics in a meaningful way.

Traditionally, investigations at the settlement level have relied on building typologies. In determining water demand, a distinction was made between continuous (attached) and detached building structures, which could be further detailed based on the degree of development. However, it is advisable to return to the classical methodology for determining water demand, which is based on the number of people to be served and the specific water consumption per capita. This logical framework remains valid today, even though the available databases are now richer and more accurate than in previous decades. This is due to the widespread use of modern billing systems and consumer metering devices, which provide relatively detailed water consumption data for individual properties and areas.

From the perspective of network hydraulic modeling, one of the greatest challenges is no longer the determination of total water consumption volumes, but rather the accurate mapping of their spatial distribution. Due to current data recording practices, this is often difficult to determine with sufficient precision, as micro-level data from individual consumers are not always integrated into geographic information systems. Therefore, during modeling tasks, it is essential to logically delineate consumer groups spatially, one of the most common methods of which is districting. Districting allows for the distribution of loads to be divided based on the actual settlement structure and building typologies, thus making the model more representative of the network's actual operation.



1. Figure - Large-scale zoning in a sample area (Source: author's compilation)

The delineation of consumption zones can be based on various criteria, typically including settlement structure, building typology, and the separation of residential and industrial areas. In practice, a well-established approach is to represent districting graphically on a map, as this not only enhances clarity but also facilitates integration into the modeling process (Figure 1). The consumption zones thus created contribute to a more accurate depiction of spatial water demand distribution in the models and provide a solid foundation for hydraulic analyses and development decisions.

The essence of the districting method lies in treating consumers within the same zone of a settlement as a unified group, allowing consumption values to be considered evenly distributed. From this point on, the spatial distribution is primarily determined by the street layout and the arrangement of water pipelines running through public areas. Accordingly, consumption values assigned to individual pipeline segments can be distributed in two ways: based on the size of the area unit associated with the segment, or based on the length of the pipeline itself. These two approaches ensure proportional distribution while flexibly adapting to the morphological characteristics of the settlement.

Before the widespread adoption of IT systems, hydraulic network assessments were largely performed manually. Engineers would highlight larger-diameter pipes during analysis, assign specific area units to them, and estimate characteristic consumption values using weighting factors. This simplified representation of the network enabled relatively quick estimations of key hydraulic parameters—even on paper—which was considered an efficient solution given the technical limitations of the time. Although digital simulations have now replaced this method, the underlying logic of manual calculations remains useful in certain planning scenarios.

One major advantage of districting is its ability to support long-term modeling of water consumption changes in settlements. By utilizing statistical data, analyzing urban planning strategies and development plans, and aligning these elements, it is possible to define current and future consumption zones based on anticipated settlement structures. This approach is particularly suitable when the modeling objective is to forecast future demand loads or to support decisions related to capacity expansion or infrastructure reconstruction. However, it is important to emphasize that districting inherently results in a form of spatial discretization, which may reduce the resolution of spatial data. In other words, while the model becomes simpler, the fine details of local variations may be less visible.

Naturally, other methods can also be used to distribute consumption values spatially. The choice among them depends largely on the purpose of the analysis, the accuracy of available data, and computational capacity constraints. A common principle, however, is that large consumers—such as industrial facilities, institutions, or major public buildings—should always be treated separately from residential consumers. This separation significantly improves the accuracy of model results, as the water usage patterns of large consumers often differ in both timing and volume from residential trends, and would otherwise distort calculations based on uniform distribution.

IV. A NEW APPROACH TO MODELING PRACTICE

The first and most crucial step in model construction is determining the logic by which consumer-defined nodes are assigned to the network. Two fundamental options are available: either consumption points are directly linked to the network's topological branches—that is, to the nodes—or, if sufficient data is available, they are matched to actual consumption locations, such as residential properties, industrial units, or institutions. In practice, the first method is most commonly used, as data limitations and the separation between technical records and billing systems make direct integration of the two databases difficult. The methodology presented in the next chapter offers a solution to this issue.

If the network's base topology allows consumption assignment at the node level, several distribution approaches can be applied. The simplest method, in the absence of districting, is to divide the total residential consumption by the number of nodes and assign the resulting value to each node. This large-scale simplification is applicable in settlement structures where development is regular and homogeneous, making the consumption distribution approximately uniform. A more accurate approach distributes consumption values proportionally to the length of pipeline segments. Since each pipeline segment has a start and end point, half of the segment's length is assigned to each node as a weighting factor. This method provides a more refined picture but still does not account for spatial variations in building density and property usage. When designing the topology, it is advisable to ensure that segment division follows the logic of the settlement structure, which improves accuracy to some extent, though it does not eliminate the method's limitations entirely.

Clearly, the most accurate way to model consumers would be to assign them to their actual consumption locations, as this would most realistically reflect the network's operation. However, the structure of current databases generally does not allow this, since matching records between billing and technical registries would be extremely time-consuming. In smaller settlements, it is theoretically possible to manually assign consumption values to streets, but in larger towns—where hundreds or even thousands of streets exist—this would impose an unrealistically large workload.

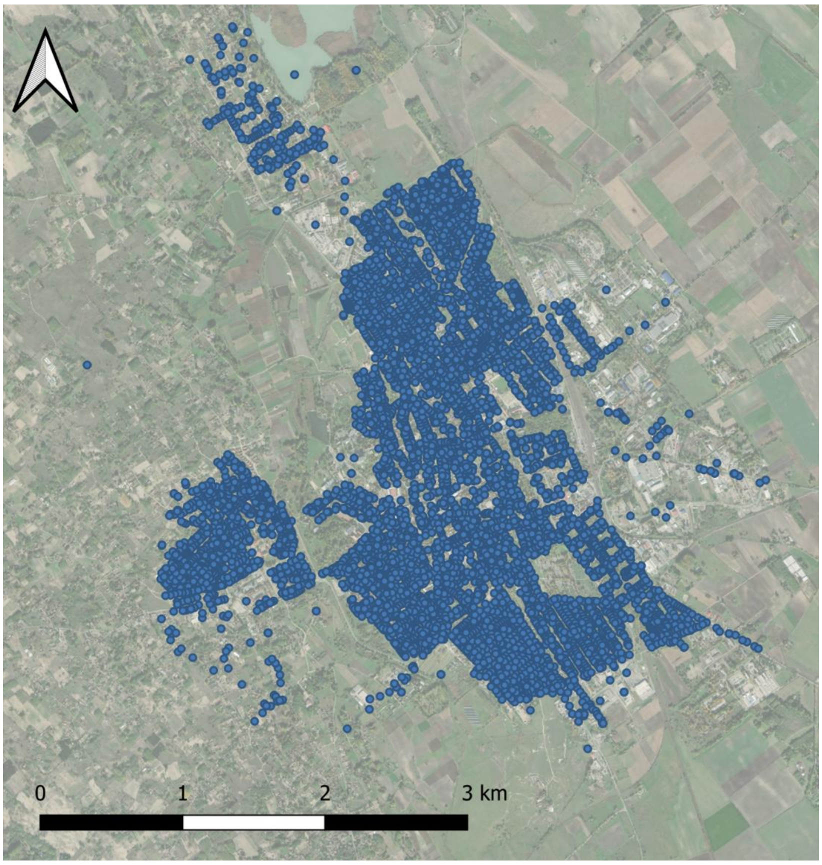
International literature presents several alternative approaches that can assist in determining consumption distribution. These include, for example, the use of active pressure and flow meters installed at multiple points in the network, which can indirectly identify consumption patterns across different areas by analyzing the network's hydraulic response. The advantage of such methods is that they do not require manual processing of household-level data, but instead provide information through the measurement of actual operational processes. This is particularly beneficial in large cities, where the consumer structure is much more heterogeneous and integrating data stored in separate systems is challenging.

It can be concluded that although assigning consumption directly to actual consumption locations would yield the highest accuracy, current practices in Hungary face database-related limitations. Therefore, hydraulic network models continue to rely primarily on node-based or pipeline-length-proportional distribution methods, which may be supplemented by pressure-based or other indirect techniques when necessary. One important direction for future development is the creation of integrated systems capable of managing billing data, technical records, and real-time measurement information simultaneously, thereby enabling more accurate modeling based on actual consumption locations.

The most precise results can be achieved when consumption is directly assigned to the actual consumption location, as this best reflects real network behavior. Thanks to technological advancements in recent years, it is now possible for water utility providers to enrich billing databases with spatial data. One of the most straightforward tools for this is the use of Google's address directory and associated geocoding solutions, which allow consumer addresses to be integrated into geographic information systems. This enables the geographic location of consumers to be managed on a shared platform with network records, creating the opportunity for more accurate modeling of consumption data.

Previous investigations show that, with proper data preparation, Google's address lookup service can identify and geolocate consumer address data with over 90% accuracy. This applies both to the number of successful matches and to the quantitative precision of the results. Figure 2 illustrates the results of an address lookup performed for a sample settlement, demonstrating the practical applicability of the method.

It is important to emphasize that the quality of the method is fundamentally determined by the geocoding application used, as its search algorithm and error-handling mechanisms directly affect the reliability of the results. While around 2020 these systems still exhibited significant inaccuracies, by 2025 the match rate has improved considerably. Based on our experience, the system is now less sensitive to character accuracy and can reliably return correct results even in cases of common typos or abbreviations.



2. Figure - Address-based determination of consumption points (Source: author's compilation)

Geocoding of address data enables the precise spatial placement of residential, institutional, and industrial consumers, thereby allowing water demand estimation to be aligned with technical databases and hydraulic network models. However, a significant quantitative factor is network water loss, which can be approximated using the methods described in previous chapters. If the service provider maintains a database of past repairs, pipeline age, and network condition, these can be used experimentally to distribute water loss across districts. This type of estimation can contribute to a more accurate understanding of the spatial patterns of water loss, especially when combined with other data sources.

The geocoding process, however, involves several limiting factors. Since the system can only perform spatial localization based on street name and house number, records containing only parcel numbers cannot be automatically processed using Google's address lookup. Such data must be supplemented with precise address values or, if available, coordinates at the beginning of the process. Another issue arises from additional address details within properties—such as floor and door numbers—which must be simplified for successful lookup. In practice, these cases are assigned to a single point and are considered one consumption location from a geospatial perspective.

Preparing address databases requires particular attention, as exports from billing systems often contain unnecessary spaces, tabs, or other characters that interfere with the search process. Therefore, one of the key prerequisites for successful geocoding is the cleaning and standardization of the input database. At the end of the preparation phase, a format must be created that Google's address lookup can properly interpret. In subsequent stages of the work, linking different databases is best done using the consumer ID, so it is recommended to include this identifier in the search records as well.

V. SUMMARY

This study provides a comprehensive overview of the evolution, current methodological approaches, and practical applications of hydraulic modeling in municipal water supply systems. Today, the accurate understanding and optimization of water networks increasingly rely on data-driven solutions based on geographic information systems (GIS) and machine learning, which enable the prediction of system behavior, monitoring of water quality, and rapid diagnosis of failures.

The study presents the historical phases of hydraulic modeling in detail, the role of EPANET and GIS technologies, and the possibilities for developing smart water networks. Special attention is given to the spatial distribution of consumption data, with a focus on districting and address-based geocoding methodologies, which significantly enhance the accuracy and applicability of modeling.

Considering the specific characteristics of Hungarian practice, the study highlights that traditional design guides and categorization methods have become partially outdated, yet with proper updates, they can still serve as useful reference points. Through practical examples, the document illustrates how consumption zones can be logically delineated and how network topology can be adapted to modeling objectives.

One of the key findings of the research is that the precise spatial identification of consumption locations—especially through address-based geocoding—represents a major advancement in hydraulic network modeling. Google-based address lookup can identify consumer locations with over 90% accuracy, enabling the integration of billing and technical databases and thus allowing for a more accurate representation of real consumption patterns.

The study also points out that one of the keys to future development lies in the creation of integrated data management systems that combine real-time sensor data, geographic information, and consumer records. This not only improves modeling accuracy but also contributes to the realization of sustainable, intelligent water supply systems capable of adapting to changing environmental and societal challenges.

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