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Towards the Evaluation of Hydraulic Performance of Water Distribution Network by GIS and Hydraulic Model

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***Abstract*—The hydraulic performance of the water distribution network system is crucial for ensuring efficient and reliable water supply. In response to increasing environmental and economic factors, there are various international standards and methods to evaluate the performance of water networks. On this basis, 70 types of research published internationally were reviewed to determine the best standards and methods for evaluating the hydraulic performance of Water Distribution Network (WDN). In the present study, the literature survey is divided into two main groups: methods and criteria. There has been a growing interest in evaluating and designing water networks, especially using integrated software simulators such as Geographic Information System (GIS) and EPAENT software, as well as GIS and WaterCAD. As a result, the study found that the most commonly used integrated software was GIS and EPAENT, with a usage percentage of 37.1%, and the least used was GIS and Micro-Electro-Mechanical Systems (MEMS) at 1.4%.**

Keywords— Hydraulic simulations, methods, criterion, water distribution Network

I. Introduction

One of the most crucial infrastructures that directly impacts both the sustainability of water resources and the standard of living for the general public is the water distribution network. These networks' performance needs to be routinely observed and examined in order to guarantee that they run smoothly. The assessment of water network performance is a multifaceted undertaking that necessitates the examination of various elements such as infrastructure integrity, water flow, and pressure [1].

The increasing population, urbanization, economic growth, and changes in urban lifestyles have heightened the demand for water, both in terms of quantity and quality [2]. Climate change and environmental pollution have amplified this pressure by impacting the accessibility of water resources to meet the growing demand. As a result, water sources worldwide are becoming depleted and polluted [3]. The water demand and hydraulic performance were assessed using WaterCAD software. This software allows users to input data and create pipes in the system through a graphical interface. It then presents the results based on the entered data [4].

In recent years, water supply pipe network accidents have become increasingly common due to ageing pipes, changes in pipeline environments, and human factors. These incidents not only result in the wastage of valuable freshwater resources but also have a significant impact on human life, as well as social and economic development [5]. There are several effective methods for reducing leakage, including asset management, pressure control, active leakage control measures, pipe rehabilitation, and the installation of District Metered Areas (DMAs) [6]. However, in pressurized pipe networks, EPANET simulates the behavior of water movement and quality over an extended period of time [7].

In modern infrastructure management and urban planning, the use of Geographic Information Systems (GIS) alongside specialized hydraulic modeling tools such as EPANET and WaterCAD is crucial for optimizing water distribution systems [8], [9]. The integration of GIS with either EPANET or WaterCAD enables a comprehensive method for managing water distribution systems. GIS provides spatial context and data visualization capabilities, while EPANET and WaterCAD offer advanced simulation and analysis tools. By merging these technologies, professionals can develop detailed models of water networks, analyze their performance under different conditions, and use data-driven decisions to enhance system efficiency and resilience [10].

The engineering design and operation of both new and existing water supply and distribution networks depend heavily on efficient water distribution and supply [11]. Artificial intelligence techniques such as artificial neural networks (ANNs) using different algorithms like Levenberg-Marquardt (LM), Bayesian Regularization (BR), and Scaled Conjugate Gradient (SCG), as well as the Adaptive Neuro-Fuzzy Inference System (ANFIS), have been utilized to design water networks for predicting velocity and pressure [12]. Establishing hydraulic adequacy is essential in the engineering design of water supply and distribution schemes, whether for supplying treated and potable water or for moving water in pressure conduit pipes for irrigation or potable water distribution and supply [13].

The objective of this study was to analyze data collected from multiple sources over the past two decades. Seventy research studies have been collected and analyzed from scientific journals, published books, and reports from international organizations. There has been increasing interest in the evaluation of water networks, particularly using integrated software simulators like GIS and EPAENT, as well as GIS and WaterCAD. The summary is divided into two main groups: methods and criteria.

II. METHODS AND MATERIEL

Geographic Information Systems (GIS) and hydraulic simulators are frequently integrated nowadays. Geographically referenced data can be collected, managed, analyzed, and displayed using a GIS system [14]. Certain analytical techniques and project management for large data volumes can benefit from this type of system. Importing model results into GIS for hydraulic simulation work provides better result display and more analysis opportunities [15]. As a result, this tool can be utilized as a source for decision support and data modeling, helping to reduce costs, save time, and enhance efficiency [16].

"Combining GIS with a hydraulic simulator often offers the following advantages: (i) automatic calculation of pipe lengths; (ii) a more detailed, flexible, and scale-dependent map presentation; (iii) sophisticated editing features; (iv) elevation data interpolation; and (v) demand calculation." In GIS, pumps and valves are usually represented as points (or nodes) rather than as links, in contrast to some hydraulic simulators, which require a different approach [17].

III. METHODS OF HYDRAULIC SIMULATIONS

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A. Maintaining the Integrity of the Specifications

SCADA stands for "Supervisory Control and Data Acquisition System." The term "supervisory" indicates that there is personal oversight of the system's operation. Field instruments, communication networks, remote stations, and central monitoring stations, together with the supervisor, compile data about the system's operation and allow for the control of some elements of the network in a SCADA system [18]. During a typical day, the existing SCADA system gave measurements of pressure and flow downstream of the pumping stations, as well as accessible water level data in some of the system's tanks [19]. SCADA offers real-time information and enables control of numerous parameters within the water network. However, this extensive data does not automatically result in operational, planning, or service improvements for water utilities [20].

EPANET is a water distribution system modeling software package developed by the United States Environmental Protection Agency's (EPA) Water Supply and Water Resources Division. EPANET is in the public domain (free) [21], [22]. The Environmental Protection Agency (EPA) in the United States provides hydraulic modeling software, which offers a wide range of capabilities to help with decisions related to the management, planning, operation, and growth of a water distribution system[23]. The hydraulic behavior of water inside pressurized water network pipes is simulated by the application. The software monitors the water flow through the pipes and determines the pressure at each intersection [24]. EPANET 2.0 utilizes stochastic simulation to conduct a dependability analysis of water distribution systems, accounting for hydraulic factors such as pressure, head, and velocity [25], [26]. EPANET typically functions under the "demand-driven" assumption, which states that pipe flows and nodal pressures must be shown to be hydraulically consistent with the nodal demands. Nodal demands are assigned preset values. For this, the Hazen-Williams formula is used to determine the head loss inside the pipes [26], [27]. For WDS ESR-E9A, the result is computed using EPANET software. There is also a comparison of the error between the pressure calculated with EPANET software and, furthermore, the pressure that is actually measured [28]. The EPANET program involves three stages [29]:

Represent the water network using the drawing tools available on the program toolbar.

Easily entering network data for each part of the system.

Accessing the program results in a smooth, easy, and simple manner.

However, by allowing files in metafile format to be inserted into the EPANET model, pipe networks in AutoCAD format can be loaded directly into the model, increasing efficiency. It also works on the same principle within the ArcEngine environment [30].

Remote Sensing (RS) is the measurement and observation of untouchable things [31]. The collection of information about something that is not immediately related is also referred to as RS. Sensors are used to do this; the body is not in direct contact with them [32].

Micro-Electro-Mechanical Systems (MEMS) is a technology that accurately and affordably determines the location of damage on a large scale to a water system by measuring acceleration, which changes on the surface of the pipe [33].

Water GEMS is one of the advanced hydraulic programs used to analyze and design water distribution networks [34]. The calibration of the hydraulic model was accomplished by contrasting the simulated and measured values in the field [35]. Hydraulic models are frequently employed to verify the water distribution system's design. [36]. The model is a representation of the real world, and computer models forecast and explain physical phenomena through the use of mathematical formulas. Water distribution system modeling enables the determination of system pressure and flow rate under a range of conditions without the need for on-site physical monitoring [37]. Water GEMS is a hydraulic modeling application with improved interoperability, GIS model construction, optimization, and asset management features specifically designed for water distribution systems. Engineers can investigate, design, and optimize water distribution systems with ease using Water GEMS. evaluations of power usage, component concentration, and fire flow [38], [39]. Using WaterGEMSV8i allowed for a more thorough grasp of network operation and the pressure regime, demand, velocity, head loss, and general systematic studding. However, WaterGEMS is used as a tool that engineers and utilities can use to assess, plan, and enhance water distribution systems. Its features include discharge, pressure head, constituent concentration analysis, pump simulation, and other features [40]. WaterGEMS was used to conduct a hydraulic performance study over a prolonged period of time. A location map in GIS displays the town's reservoirs, boost, and water sources [41].

WaterCAD was selected to model the current subsystems water supply network because of its relative capacity to imitate the behavior of a real or proposed system under different operating conditions and demand loading, which is essential for making decisions [42]. Extended period and steady-state simulations are the two types of simulations that WaterCAD can execute by running the model at the current year's daily average at demand peaking and temporal variation under various scenarios. The existing systems' model has been analyzed [43]. A near-world hydraulic model with pipes, pumps, and fire hydrants was made using WaterCAD [44].

Considering that the compacts units are operating at full design capacity in terms of pressure and flow, and the program analyzed the network, and it was found through the analysis that the areas of scarcity are few and confined to the edges of the area where the pressures range from (0.71–2.2) bar and the velocity was (0.04–1.91) m/s as shown in Figure 1. [13].

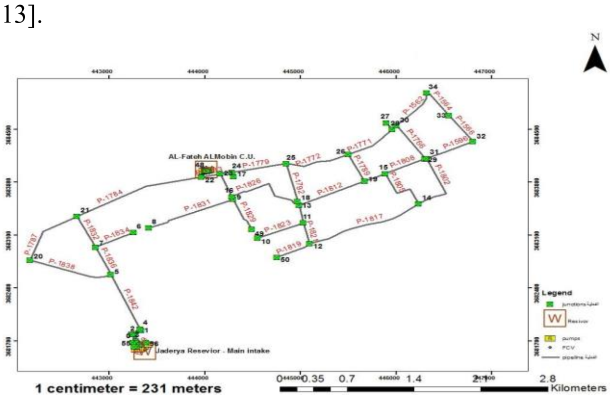

Figure 1 Case Study of AL-Karada – Iraq [13].

WaterGEMS and WaterCAD have a powerful design algorithm that ensures accurate water distribution network designs by regulating water flow, velocity, and pressure. The software uses a genetic algorithm to obtain solutions and includes advanced genetic algorithm optimization engines for automated calibration, design, rehabilitation, and pump operations [45].

Decision Support System (DSS) is an interactive computer-based information system, meaning it possesses the same attributes as information systems in general. The phrase "interactive" suggests that the user and the system are communicating with one another [46].

Bayesian Belief Network (BBN) is a graphical model that allows for probabilistic relationships between a group of variables [47].

Topological model: There were topological simplifications used. These reductions were required in order to operate the hydraulic model efficiently and without using a lot of computer power. These techniques could involve dividing into consumption zones and using the arithmetic mean method [48].

Kypipe: At the University of Kentucky, LL KYPIPE (USA) created a program. A petroleum network can be created using the KYPIPE program, which is also used for transient and hydraulic network analysis [49].

District Metered Areas (DMA): It is the process of breaking up a big network into smaller, more isolated networks. District Measured Areas (DMAs) are what these are known as for efficient water management. Observe it to efficiently keep an eye on the amount and quality of water. There are minor variations in the characteristics of water quality and quantity [50].

MATLAB: MATLAB program was used to enable hydraulic simulation by applying the digital assistant method [51].

Deep Neural Network, Artificial Neural Networks (DNN, ANN): an artificial neural network (ANN) with multiple hidden layers between the input and output layers is called a deep neural network (DNN). Thousands of distinct neural network types have been developed by researchers that modify or adapt the current models. A range of deep learning theoretical frameworks exist, including multi-layered convolutions, recurrent neural networks (RNNs), and feed-forward neural networks (FFNNs) [52].

Digitalization: Digital Using satellite images, new urban settlements have been identified that were not registered in physical or digital plans and currently have water networks installed and running [53].

Kettler and Coulter linear model is an equation that defines the linear model that Kettler and Goulter dreamed of. $\lambda = k_0 * E$ Shamir and Howard exponential model Howard and Shamir's exponential model. The following equation defines the exponential model that Shamir and Howard suggested. $\lambda(t) = \lambda(t_0) * e^{A(t-t_0)}$ [54].

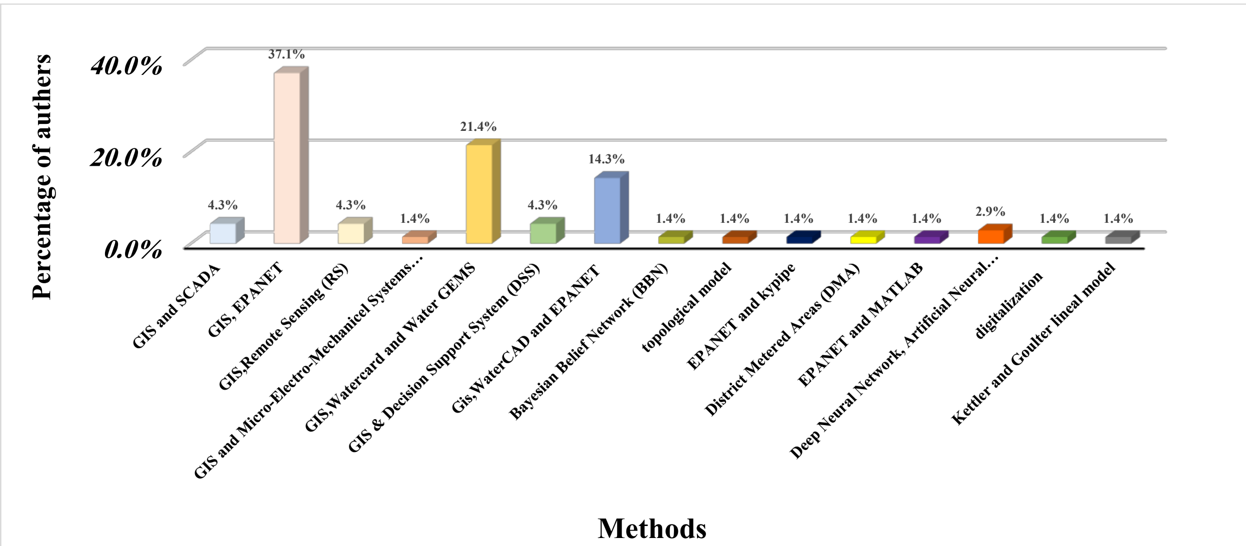

Figure 2 Percentage of Authors per methods

B. Criterion

Network design: the water supply network's simplification yielded pipe links and nodes, which are then encoded to create the pipe network calculation diagram. The actual water supply pipe's diameter in the study area is large, depending on the pipe's direction. It is complex and has various lengths; thus, it needs to be made simpler by removing the little pipes [30]. Model skeletonization is achieved by removing parallel pipes and replacing them with similar pipes at the consumer end. A pipe with an equivalent diameter connects the artificial reservoir to the network for intermittent simulation. The diameter of the equivalent pipe is correctly selected, and its length and C-factor are the same as those of the dominating pipe [55]. The findings of the network analysis carried out on the three distinct WDNs are presented. The values of pertinent metrics that were calculated to compare the WDNs' resilience, vulnerability, and structural characteristics are reported [56]. The flow rates and water pressure recorded at the PSA's entrance during the calibration period are shown here [57]. was selected based on the pressure and velocity distribution. Supply networks in EPANET are defined by components like nodes, pipelines, valves, and tanks [58]. production of precise geographic digital data, including pressure gradients, pipe properties, network layout, connection, network routing, and network allocation, as input into data for the network design optimization model [59]. The observed data collected from the site at these specific pressure points is used to calibrate the simulated pressure computed by the EPANET software [6].

The head loss in a pipe is affected by factors such as flow velocity, pipe diameter, length, roughness coefficient, and Reynolds number. Head loss, which is unavoidable, refers to the reduction in the total energy of water as it moves through the system. The relationship between head loss and velocity is direct. Water GEMS utilizes the Hazen-Williams formula to calculate head loss. [60]. Water utilities face several challenges, including the significant loss of water in distribution networks. It becomes difficult to meet the needs of the user community when a large portion of the supplied water is lost. The velocity of water flow in a pipe is an important factor in assessing the hydraulic performance of a water supply and distribution system. Flow rates below 0.6 m/s can lead to water stagnation, sediment buildup, and bacterial growth in the pipe. Conversely, flow rates above 2 m/s can result in head loss and water hammer[61]. The most important factor influencing the risk of leaks is the material of the pipes, followed by the density of leakage points, the age of the pipes, the density of the pipe network, the pressure in the pipe network, and the loads on the road. It is well-established that the risk of failure and damage is higher in water supply systems where the pipe material is weak and the pipes are old [62]. Pipeline failures are generally known to be caused by physical and operating reasons, such as high pipe age, decreasing pressure resistance, high system operating pressure, severe pressure change, and persistent water interruption [63]. In the event of an unexpected pipe failure or the need for firefighting water flow, a demand-driven analysis may result in lower than required or even negative nodal pressures. This situation is known as pressure deficiency and means that the designed water demands will not be met in the actual network. These operational emergencies are called Pressure-Deficient Conditions [64].

Beneficiaries: Population census criteria are considered important criteria for determining the extent of water network coverage. One of the most predominant factors affecting the performance of an existing network is the increase in population and its associated demand requirements, which may call for complete reticulation or rehabilitation of the existing system [65]. Employees of the Algerian water company say that over 50% of their workforce is mobilizing for this goal when asked about the quality of the welcome provided to subscribers; subscribers, on the other hand, think that just 27% of their personnel is doing this. Administrators must enhance staff training in order to handle complaints from clients in a more professional manner. The vast majority of subscribers believed that their complaints were not being sufficiently handled. To raise the caliber of its management, the organization must also respond to subscriber complaints faster [66]. During the research of the municipality-Hungarian, there was no discernible change in the municipality's housing stock. In the total housing stock, one-room dwellings made up 18%, two-room dwellings (including one room and a box room) made up 46%, three-room dwellings (including two rooms and a box room) made up 26%, and even dwellings with four or more rooms (including three rooms and a box room) made up 10%. Single-story detached homes define the neighborhood [48]. Customer satisfaction with drinking water sources was examined in relation to water quality, distance (the distance to be fetched), and time (the time it took to fetch and return). With 97.6% (5% on-premise, 24.8% within 5 minutes, and 67.8% on 5–30 minutes), Kebele-01 reported the highest levels of satisfaction, whereas Kebele–02 scored 56.85% satisfaction with 5–30 minutes and 43.2% discontent (with 30 minutes). Services in the Kebele-Chiri area reported the highest levels of dissatisfaction with the total amount of time (30 min) required to collect water from their source (round trip) [67]. At present, 96% of urban dwellers worldwide have access to improved sources of drinking water, while only 84% of rural residents do. However, 663 million people, which accounts for 4% of the global population, still lack access to clean drinking water sources [68]. These findings demonstrate that the four primary pillars for assessing network performance are water pressure, hydraulic characteristics, population, and flow velocity. The pressure criterion's supremacy suggests that the most crucial element in guaranteeing customer pleasure and network effectiveness is pressure stability. The necessity of investing in infrastructure improvement and routine pipe maintenance is also reflected in the significance of hydraulic characteristics and flow velocity. Lastly, the population criteria highlight the significance of integrating demographic data into operational procedures by demonstrating how demographic issues affect network planning.

Globally, the efficiency of water distribution systems depends largely on the hydraulic performance and projected water demand of water distribution networks. [69]. The entire amount of water needed to meet the needs of different sectors, such as household, agricultural, industrial, and environmental applications, is referred to as water demand. It is necessary to comprehend and regulate the demand for water in order to ensure a sustainable supply of this vital resource. The water demand explanation of the HSTU Campus in Dinajpur, Bangladesh, is as follows: Areas 1 and 2 have daily total water demands of 435.24 and 633.55 cubic meters, respectively. The total amount of water that needed to be provided daily to the networks was 1068.79 cubic meters. The hydraulic simulation's reporting start time was set for 1 PM or 13:00 hours because that was when the greatest water demand occurred [70].

Soil: The corrosion process of various pipe materials is greatly influenced by soil corrosivity (SC). The external erosion of water mains is mostly caused by many soil variables, including soil resistivity, pH, redox potential, sulfide content, and moisture content. A soil's resistance to the passage of electric current is measured by its soil resistivity (SR). The acidity or alkalinity of the soil is determined by its pH [47].

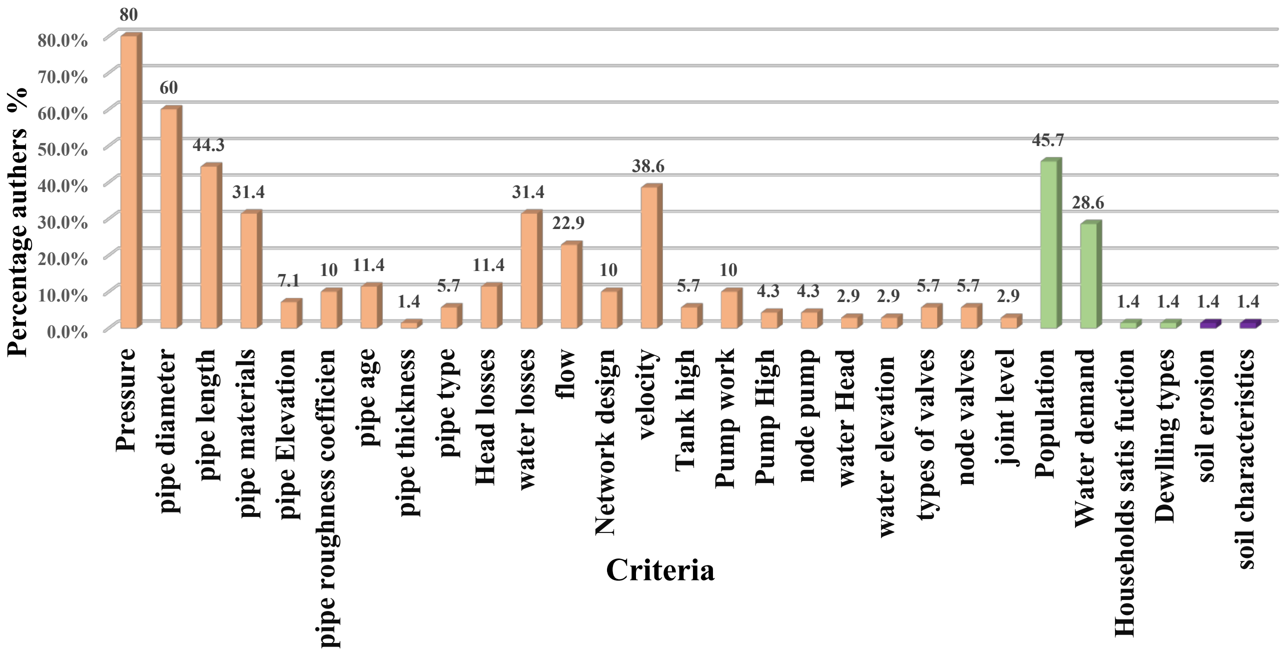

Figure 3 Percentage of Authors per design parameters

IV. DISCUSSION AND CONCLUSIONS

The primary goal of this research is to comprehensively study and analyze the existing literature on water distribution systems. A total of 70 research works have been collected and thoroughly examined. The review has been carefully categorized into main groups, focusing on the methods utilized to evaluate water distribution systems and the specific criteria involved in their evaluation.

In Figure 2, bar charts are presented, illustrating the percentage of each method, specifically hydraulic simulator software, as derived from the literature survey. Fig.2 highlights that the combined use of GIS with the EPANET hydraulic simulator constitutes the highest percentage at 37%. Additionally, the integration of GIS with WaterCAD and WaterGEMS accounts for 21.4% of the methods used. Conversely, the lowest percentage, at 1.4%, is attributed to a diverse range of methods, including MEMS, DSS, BBN, the topological model, EPANET with Kypipe, DMA, EPANET/MATLAB, digitalization, and the Kettler/Goulter lineal model.

Figure 3 illustrates the percentage of criteria (parameters) that authors studied in their papers. A wide range of criteria have been previously studied. The most commonly repeated parameter in the literature is pressure, at a percentage of 80%. Additionally, other parameters such as pipe diameter, population, pipe length, velocity, and water losses show relatively high percentages at 58.6%, 45.7%, 44.3%, 38.6%, and 31.4%, respectively. On the other hand, Fig. 3 shows the lowest percentage of 1.4% attributed to soil erosion, soil characteristics, households' satisfaction, and dwelling types. Stable water pressure is essential to ensuring equitable and sufficient water distribution for all users, as evidenced by the maximum impact rate of 80%.

Second place went to the diameter of pipes, with 60%, as the analyses verified the importance of pipe design and material quality in enhancing network efficiency and lowering water loss.

The effect rate of 45% for the population indicates that when constructing networks to satisfy growing demand, population density must be taken into consideration as shown in Fig.3

Future networks will be designed with high density and rural places in mind, using updated population census data.

directing more funds into urban growth regions in order to guarantee sustainable distribution.

In conclusion, the combination of EPANET hydraulic simulation software with GIS is the most commonly used method for studying water distribution systems. However, other software such as GIS and Micro-Electro-Mechanical Systems (MEMS), EPANET with Kypipe, etc., have not received enough attention from authors. Additionally, while many parameters such as pressure, pipe diameter, and velocity have been frequently studied in the literature, there are still many other parameters that must be focused on.

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