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Modeling of Water Age in Distribution Systems- Case Study

Raber Hasan[1], and Mehmet Ishak YUCE[2]

[1,2] Department of Civil Engineering, Gaziantep University, Gaziantep, Turkey

Correspondence should be addressed to Raber Hasan; eng.raber@gmail.com

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ABSTRACT- Ensuring water quality in water distribution systems (WDS) is crucial for public health. Water authorities aim to provide consumers with an adequate supply of high-quality water at optimal pressure. This study focuses on a segment of Erbil City's WDS to analyze hydraulic parameters and water quality, particularly water age, using observed and documented data. The primary objective is to determine the age of water as it travels within the distribution system. The research utilizes EPANET 2.2 for a comprehensive case study, with digital loggers monitoring pressure and ultrasonic flow meters measuring discharges. The findings are expected to help develop new water projects and improve existing infrastructure, contributing to responsible water management and public well-being. Access to clean drinking water significantly impacts society, the economy, health, and the environment.

KEYWORDS- Water Distribution System, Water Quality, Water Age, Erbil City, EPANET

I. INTRODUCTION

Water Distribution Systems (WDS) are crucial for delivering safe, high-quality drinking water in adequate quantities to various consumers. These systems vary in design and complexity depending on local factors, but their primary function remains the same: to ensure a reliable supply of potable water. In transmission systems, large mains or tunnels transport raw water to Water Treatment Plants (WTPs), which undergo treatment processes such as coagulation, sedimentation, filtration, and disinfection. Treated water is then conveyed to storage facilities before distribution mains deliver it locally. Distribution mains distribute water through a network that may be branched or looped, with individual buildings connected via service pipes. Local utilities typically manage the external distribution network, while in-house systems are the responsibility of property owners [12].

Pumping stations are often required to maintain adequate pressure, particularly in areas where gravity alone is insufficient. Conversely, Pressure Reducing Valves (PRVs) are used in regions with excessive pressure. The system includes numerous manholes and valves for access and control and storage basins to balance pressure, manage demand fluctuations, provide reserves for firefighting, and ensure emergency supplies [12].

The pipe materials selection depends on pressure conditions, diameter, and corrosion risk. Historically, cast iron (CI) and ductile iron (DI) pipes have been prevalent, but plastic pipes like polyvinyl chloride (PVC) and polyethylene (PE) are also common. However, plastic pipes can introduce chemicals and support microbial growth [5].

Looped networks offer advantages over branched ones by providing alternative supply routes and improving water quality through better circulation. However, they may risk water discoloration due to sediment resuspension and may not self-clean as effectively as branched systems [3].

Ensuring a continuous supply of high-quality drinking water requires the proper design, operation, and maintenance of WTPs and WDS. Effective management practices, regular monitoring, and adherence to regulatory standards are imperative to safeguard public health and meet consumer expectations [15].

Water age, defined as the time a parcel of water spends in the system from source to consumption, is a crucial parameter for assessing water quality in WDS [6]. Operators aim to minimize water age to comply with regulations, maintain system pressure, and ensure customer satisfaction. In the U.S., the average water age typically ranges from one to three days [10]. High water age can lead to Disinfection By-Products (DBPs) and microbial contamination, which increase as disinfectant levels decrease over time [9].

Factors affecting water age include pipe size, network configuration, demand fluctuations, and external water sources [6]. Extended water age can result in sediment formation, chlorine consumption, microbial growth, and DBP formation [16].

Hydraulic models analyze water age, assessing the cumulative time water spends in the system. These models help evaluate water quality impacts, such as storage tank turnover, disinfectant residual loss, and DBP formation[17]. Unlike constituent analysis, water age analysis does not require additional calibration, making it a straightforward method based on hydraulic data [17].

Digital modeling simplifies real-world systems into mathematical forms, facilitating their study [14][18]. Simulations predict system responses under various conditions, aiding in safe and cost-effective analysis and planning[18]. Calibration and validation ensure model accuracy and credibility [11].

Detailed network models replicate actual WDS components closely, while skeletonized models offer simplified representations [1][2]. Tracer studies can empirically determine water age, but modeling tools like EPANET 2.2 provide efficient alternatives for simulating water age[4].

Developed by the EPA, EPANET models WDS and supports steady-state and extended-period simulations. It offers tools for analyzing WDS and optimizing system modifications to reduce water age [6][7].

High water age can be identified through aesthetic indicators such as poor taste, odor, and discoloration or monitoring indicators like depressed disinfectant residuals and elevated DBP levels (AWWA, 2002). Strategies to reduce water age include valve throttling, system configuration optimization, continuous tapping, and improved storage basin operation [13] (AWWA, 2002).

Effective water-age management involves proactive monitoring, strategic design, and operational practices[16]. Identifying areas of high water age, optimizing infrastructure, and implementing operational strategies are essential for maintaining water quality and system reliability.

II. ERBIL CITY WATER DISTRIBUTION SYSTEM

This case study evaluates a segment of Erbil City's water WDS using EPANET 2.2 software to model water age and improve hydraulic and water quality characteristics, aiming to support future planning and enhance system reliability. Erbil, also known as Hewlêr, is the Kurdistan Regional Government's (KRG) capital and one of the world's oldest cities, with over 6000 years of history (UNESCO World Heritage Centre, n.d.). Located in northern Iraq, Erbil covers 14,471 km² and has a population of 1,431,580. It lies at 36°12'22.6548" N and 44°0'31.932" E, with an elevation of 412 meters. The city's economy includes agriculture, animal breeding, industries, and tourism, supported by stable security. Erbil experiences a Mediterranean climate with cold, wet winters and hot, dry summers, receiving over 400 mm of annual rainfall, primarily between mid-October and late May.

The Erbil Water and Sewerage Directorate (EWSD) manages the water distribution system, which includes treatment plants, well operations, distribution lines, and network management. The Ifraz water treatment plants are critical in providing clean and safe water to residents.

The study area, located east and northeast of Erbil City, includes a network of ductile iron pipelines transporting water from a concrete reservoir to eighteen neighborhoods, serving approximately 20% of the city's population, as illustrated in below figure 1.

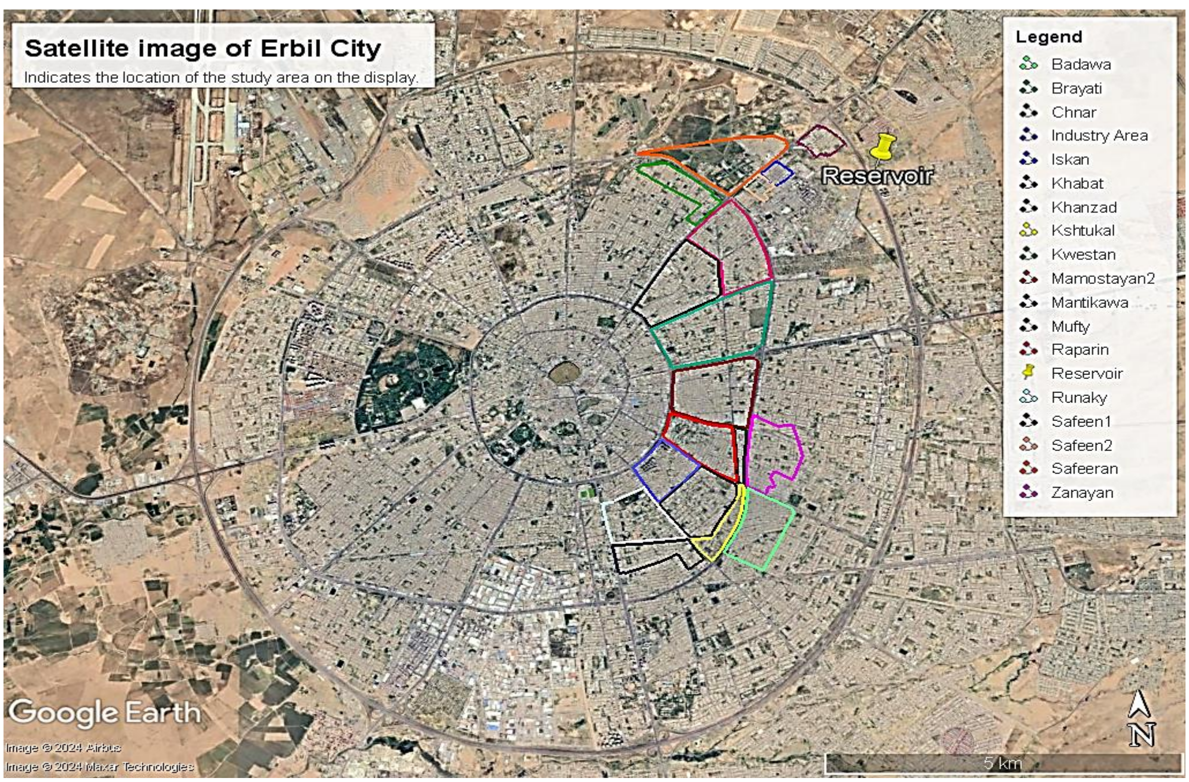

Figure 1: The location of the study area in Erbil city using a satellite image

The primary water source is the Ifraz 3 Water Treatment Plant (WTP). Water is conveyed through a glass-reinforced plastic (GRP) transmission pipeline, which is 1500 mm in diameter and 20,137 meters long, delivering 7,590 m³/hr to the Maroda pumping station reservoir. From Maroda, water is transferred to the Dawajin reservoir via similar pipelines at a flow rate of 7,992 m³/hr over 11,142 meters. The Dawajin reservoir, at 490 meters above mean sea level (MSL), has a capacity of 20,000 cubic meters and dimensions of 50 x 50 x 8 meters. Water flows by gravity from the Dawajin reservoir into the distribution network through ductile iron pipes, 800 mm and 1200 mm in diameter, totaling 11,302.81 meters.

The network's sub-main pipes include plastic, cast iron, high-density polyethylene (HDPE), PVC, and DI. Site inspections confirmed that all valves were fully open and properly maintained, ensuring no adverse effects on hydraulic simulations regarding head loss and pressure drop. The below figure 2, elaborates on the case study distribution system model, developed in CIVIL3D, which incorporates the Great Zab River (GZR), Ifraz 3 WTP, Maroda Intermediate Pump Station (MIPS), Dawajin reservoir, transmission main, and distribution main pipes.

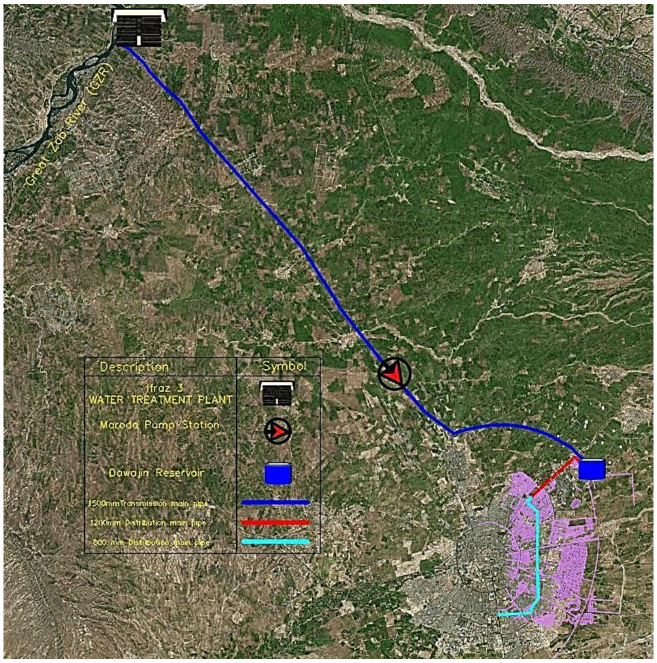

Figure 2: The Water Distribution Network model in the CIVIL 3D program

Ifraz 3 WTP and MIPS house seven high-service pumps, three of which are on standby. Each pump discharges 2,000 m³/hr and has a head of 115 meters. These pumps move treated water through the GRP transmission main pipeline to MIPS and then to the Dawajin reservoir.

The study area includes over 35,000 documented legal house connections and additional undocumented illegal connections. It encompasses residential, commercial, government offices, schools, hospitals, and a limited industrial zone focused on car repairs. Several wells connect directly to the network, with minimal impact on water quality. Elevated tanks and pipelines enhance water distribution, especially where groundwater does not reach the main pipelines.

III. METHODOLOGY

This study systematically developed, analyzed, and calibrated a hydraulic and water quality model for the Erbil City water distribution network segment using EPANET 2.2 software. The data collection process encompassed documented files, site investigations, and field tests to ensure model accuracy. Primary data sources included records from the EWSD detailing pipe characteristics, valve locations, and pump capacities, supplemented by field measurements for verification. The hydraulic model covered main and sub-main pipes with diameters ranging from 110 mm to 1200 mm, representing the network supplied by the Ifraz 3 WTP. Each network component received a unique identifier, including nodes (junctions, tanks, reservoirs) and links (pipes, pumps, valves). Essential parameters such as pipe diameter, length, roughness coefficient, valve specifications, node elevations, water demand, tank capacities, pump specifications, control rules, initial water quality, and calibration data were meticulously recorded and integrated into the model.

Field testing involved inspecting and cleaning manholes, verifying node elevations with GPS devices, and installing flow meters and pressure loggers as necessary. Discrepancies between documented data and on-site measurements were addressed to ensure precision. Water demand analysis calculated the total volume of water conveyed from the Dawajin reservoir to the distribution network, distributing this demand across nodes based on population density and consumption patterns. A consistent flow fluctuation pattern was applied to all nodes in EPANET 2.2 to ensure uniform demand representation.

Initial model calibration under steady-state conditions matched measured pressure values at various locations, accurately representing real-world hydraulic conditions. Extended Period Simulation (EPS) calibration captured dynamic changes in water demand and system behavior over time, aligning model-predicted demand patterns with observed fluctuations in consumption and accurately predicting tank water levels, flow rates at system meters, and energy consumption to optimize operational strategies and enhance system sustainability (Walski et al., 2003). Model accuracy was further refined by incorporating detailed field data and recalibrating parameters such as the Hazen-Williams head loss coefficient (C-factor).

The hydraulic model development incorporated comprehensive data collection, including junction positions, pipe characteristics, demand, elevation, and initial Hazen-Williams head loss coefficient (C-factor) assumptions. Based on the Ductile Iron Pipe Research Association (2016), a C-factor of 135 was deemed appropriate for long-term operations in ductile iron pipes. While the model operated smoothly under normal conditions, introducing the calculated C-factor using the Hazen-Williams head loss formula into EPANET 2.2 caused operational issues, such as model failures and negative pressure zones. Solutions included introducing additional pumps or booster stations, upgrading pipes, or adding parallel pipelines to enhance flow capacity and reduce resistance, particularly at high-demand junctions.

A pump station was installed downstream of the reservoir outlet, including booster pumps, to increase energy for water delivery, transitioning the system from gravity-based to a pumping system. Three pumps were installed downstream of the reservoir outlet to increase the flow rate to 1600 m³/hr and maintain a constant head of 20 meters, significantly increasing system pressure and achieving higher pressures at all junctions compared to the existing model and field observations. Calibration involved fine-tuning the model's pressure profile to match observed field data, achieving a mean error of 22.635 and a correlation coefficient (R) of 0.998, indicating a strong correlation between observed and computed pressures.

Water age simulation, conducted using EPANET, tracked water age at various nodes over 72 hours, demonstrating improvements after system enhancements, such as additional pumps and upgraded pipes. These improvements reduced the average water age across all nodes, indicating fresher water and potential improvements in water quality and system efficiency. The proposed system reinforcement strategy was thoroughly analyzed and designed for feasibility and effectiveness. Simulating various operational scenarios over 72 hours helped identify potential issues, and the feasibility of implementing the proposed model was assessed for cost efficiency and practicality, representing a low-cost, long-term solution.

IV. RESULT AND DISCUSSION

The study analyzed the hydraulic parameters and water quality, specifically water age, of Erbil City's WDS using EPANET 2.2. The initial model, which served as the baseline, displayed an average water age of 13 hours and 40 minutes. The highest water age was recorded at node 63, with 15 hours and 55 minutes, while the lowest was at node 20, with 12 hours and 17 minutes.

Improvements to the model included adding extra pumps downstream of the reservoir outlet and upgrading pipes to enhance flow capacity and reduce resistance. These modifications reduced the average water age to 12 hours and 45 minutes, with node 63 showing a water age of 14 hours and 59 minutes and node 20 showing 11 hours and 22 minutes. Table 1 summarizes these findings.

Table 1: Comparison of water age between existing and improved models at selected nodes

Node	Existing model water age (hour)	Improved model water age (hour)
n_{20}	12:17	11:22
n_{26}	12:25	11:31
n_{41}	13:36	12:42
n_{50}	14:05	13:10
n_{63}	15:55	14:59
Average	13:40	12:45

The hydraulic analysis showed increased pressures in the improved model due to the additional pump head. This resulted in higher and more stable pressure readings across various nodes compared to the existing model (see Table 2).

Table 2: Pressure Comparison between the existing and improved models

	Existing model	**Improved model**		**Existing model**	**Improved model**
Node ID	Pressure (m)	Pressure (m)	Node ID	Pressure (m)	Pressure (m)
Junc 12	38.19	59.84	Junc 52	53.44	75.1
Junc 13	38.15	59.81	Junc 53	52.25	74.95
Junc 14	22.77	58.25	Junc 54	53.22	74.88
Junc 15	34.96	58.93	Junc 55	49.95	73.98
Junc 16	46.53	68.19	Junc 56	52.84	74.5
Junc 17	43.41	67.79	Junc 57	34.08	74.07
Junc 18	52.87	74.52	Junc 58	50.88	72.54
Junc 19	52.74	74.39	Junc 59	50.47	72.03
Junc 20	52.6	74.25	Junc 60	49.71	71.08
Junc 21	52.68	74.34	Junc 61	47.93	69.58
Junc 22	58.03	79.68	Junc 62	45.44	69.27
Junc 24	52.64	74.28	Junc 63	49.61	71.27
Junc 25	48.12	72.53	Junc 64	48.95	71.19
Junc 26	55.87	77.52	Junc 65	53.24	73.77
Junc 27	52.51	74.16	Junc 66	52.75	73.06
Junc 28	51.72	73.83	Junc 67	52.51	73.51
Junc 29	49.6	71.26	Junc 68	58.33	78.32
Junc 30	33.38	70.31	Junc 69	59.13	79.07
Junc 31	51.93	73.59	Junc 70	53.65	78
Junc 32	51.99	73.65	Junc 71	53.21	78.67
Junc 33	50.78	73.11	Junc 72	63.45	83.31
Junc 34	48.73	73.19	Junc 73	63.28	83.47
Junc 35	51.43	73.08	Junc 74	62.96	83.33
Junc 36	2.87	72.13	Junc 75	54.57	76.22
Junc 37	50.33	71.99	Junc 76	46.93	75.78
Junc 38	50.25	71.9	Junc 8	-1.3	42.25
Junc 39	41.93	71.42	Junc 9	21.95	43.6
Junc 40	47.06	71.22			
Junc 41	49.8	71.46			
Junc 42	49.7	71.36			
Junc 43	48.79	70.98			
Junc 44	49.65	71.31			
Junc 45	46.05	70.8			
Junc 46	49.58	71.24			
Junc 47	47.86	70.52			
Junc 48	48.89	70.55			

Junc 49	43.39	70.18			
Junc 50	51.99	73.65			
Junc 51	28.53	72.79			

The comparative analysis of the existing and improved WDS models using EPANET 2.2 highlighted significant enhancements in hydraulic performance and water quality. The reduced water age across the network indicates a more efficient turnover, resulting in fresher water delivery to consumers. The improved model's lower water age implies better water quality, reduced potential for contamination, and higher customer satisfaction.

Moreover, the enhanced pressures observed in the improved model suggest a more reliable water supply, particularly during peak demand periods. These improvements can mitigate issues related to negative pressure zones, which are critical for maintaining system integrity and preventing contamination.

The study underscores the importance of continuously monitoring and upgrading WDS infrastructure to ensure optimal performance. The findings provide valuable insights for water authorities in Erbil City and other regions facing similar challenges, guiding future water project implementations and infrastructure enhancements. Ultimately, these improvements contribute to better public health outcomes and more sustainable water management practices.

V. CONCLUSION

This study successfully developed, analyzed, and calibrated a hydraulic and water quality model for a segment of Erbil City's water distribution network (WDN) using EPANET 2.2, aimed at enhancing system credibility and supporting future planning, particularly in assessing water age. Key findings include:

- Hydraulic Model Calibration: The calibration process indicated a significant reduction in the C-factor for the 800mm distribution main pipelines from standard 140 to 83.3, highlighting issues related to pipe age and non-economic velocities contributing to increased unit head loss.
- System Improvements: The addition of booster pumps and pipeline upgrades effectively addressed negative pressure zones, ensuring consistent water delivery to high-demand areas and improving system performance and reliability.
- Enhanced Performance: Improvements in hydraulic and water quality models resulted in better pressure management, economic velocities, increased discharge rates, reduced unit head loss, and decreased water age, thereby addressing deficiencies in the existing model.
- Impact of Modifications: The modifications significantly reduced water age across the network, validating the proposed changes' effectiveness and providing a basis for further WDN optimization.
- Model Reliability: The improved models are reliable for long-term application under various conditions, ensuring stable performance and adaptability to different scenarios, free from operational disruptions.
- Future Challenges: While the current model meets present demands, it may face challenges due to aging infrastructure and rapid population growth. Continuous monitoring and periodic reassessment are necessary to maintain the model's effectiveness and address emerging challenges.
- This study confirms the effectiveness of the improvements made to Erbil City's WDN, offering a reliable and efficient framework for urban water supply and serving as a valuable reference for future optimization and sustainability efforts.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest between them and with any third party.

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