# Resilience and Efficiency-Based Comparative Hydraulic Analysis of Looped and Branched Water Distribution Networks using water Gems

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**ABSTRACT -** *Water distribution networks (WDNs) are essential infrastructure systems responsible for supplying potable water to communities, and their performance is highly dependent on network configuration. This study presents a comparative hydraulic assessment of looped and branched water distribution systems with emphasis on efficiency, pressure regulation, and resilience. Hydraulic simulations were performed using Bentley WaterGEMS to evaluate system behavior under normal demand, peak demand, and pipe failure conditions. Key performance parameters, including nodal pressure distribution, pipe flow characteristics, energy consumption, and resilience indices, were analyzed for both configurations. The results show that looped networks maintain more uniform pressure and higher service reliability due to the availability of multiple flow paths, allowing continued water supply during pipe outages. In contrast, branched networks offer simpler design and lower construction costs but are more vulnerable to pressure losses and service interruptions under failure scenarios. Sensitivity analyses considering variations in demand, pipe diameter, and network topology further demonstrate the superior robustness of looped systems. Overall, the study highlights that while branched networks may be suitable for low-demand or cost-sensitive applications, looped networks provide enhanced operational performance and resilience. The findings support informed decision-making for sustainable and reliable water distribution system planning using advanced hydraulic modeling tools.*

***Key Words***: **Water Distribution Network, Looped Network, Branched Network, Hydraulic Analysis, Resilience Index, WaterGEMS**

## 1. INTRODUCTION

Water distribution networks (WDNs) are a fundamental component of municipal infrastructure, responsible for supplying treated water to residential, commercial, industrial, and public consumers. The performance of these systems directly affects public health, economic activities, and sustainable urban growth. Therefore, efficient planning, operation, and maintenance of WDNs are essential to ensure reliable supply, minimize water losses, and optimize energy use.

Based on their layout, WDNs are commonly classified as branched or looped networks. Branched systems follow a tree-like structure with a single flow path to each demand node, making them simple and cost-effective to construct. However, their lack of redundancy makes them vulnerable to service interruptions during pipe failures. In contrast, looped networks consist of interconnected pipes that provide multiple flow paths, improving pressure balance, operational flexibility, and reliability during failures or maintenance, though at higher initial cost and complexity.

Rapid urbanization, population increase, and variable demand patterns further challenge WDN operation. Advanced hydraulic modelling tools such as Bentley WaterGEMS enable detailed evaluation of pressure, flow behaviour, energy consumption, and system reliability. This study presents a comparative hydraulic analysis of looped and branched WDNs using WaterGEMS to support informed and sustainable network design decisions.

## 2. LITERATURE REVIEW

Reviewing existing research is essential to understand advancements in water distribution network (WDN) design, particularly in hydraulic performance, resilience, and modeling approaches. Earlier studies mainly emphasized cost-effective and simple network layouts. Recent research, however, focuses on improving reliability, resilience, and energy efficiency due to urban growth, changing demand patterns, and aging infrastructure. This review summarizes previous work under four themes: network configurations, hydraulic performance, resilience and efficiency, and the role of simulation tools in WDN analysis.

### 2.1 Water Distribution Network Configurations

WDNs are generally classified as branched or looped systems. Branched networks have a tree-like structure with a single flow path, making them simple and economical to construct but highly vulnerable to failures. A pipe break can interrupt supply to downstream areas. Looped networks use interconnected pipelines that provide multiple flow paths, improving pressure balance and reliability during failures. Although looped systems require higher initial investment and complex design, studies show they are more suitable for urban areas with high reliability requirements.

## 2.2 Hydraulic Performance Analysis

Hydraulic performance analysis ensures that water demands are met under varying operating conditions. Parameters such as nodal pressure, flow velocity, and pipe capacity are commonly evaluated. Modern modeling tools like EPANET and WaterGEMS allow simulation of normal and stressed conditions, including peak demand and pipe failures. Literature indicates that looped networks generally maintain more uniform pressure and stable flows, while branched systems may experience pressure deficiencies at terminal nodes during high-demand or failure scenarios.

## 2.3 Resilience and Efficiency in WDNs

Resilience refers to a network's ability to continue supplying water during disruptions such as pipe bursts or demand fluctuations. Various indicators are used to assess network robustness and reliability. Operational efficiency focuses on minimizing energy consumption, pressure losses, and hydraulic inefficiencies. Integrating resilience and efficiency assessments helps in designing networks that are both reliable and cost-effective. Recent studies emphasize multi-objective optimization to balance system robustness with long-term operational efficiency.

## 2.4 Role of Simulation Software in WDN Analysis

Simulation software plays a vital role in modern WDN design and management. Tools such as Bentley WaterGEMS enable scenario-based analysis of demand variations, network layouts, and failure conditions. These platforms provide detailed insights into pressure distribution, energy usage, and system resilience. Studies using WaterGEMS show that looped networks maintain better service continuity during failures compared to branched systems. Sensitivity analysis further helps in understanding the impact of design and operational changes on network performance.

## 3. METHODOLOGY

This study follows a structured methodology to compare the hydraulic performance, resilience, and efficiency of looped and branched water distribution networks using Bentley WaterGEMS. The approach includes network selection and data collection, hydraulic modeling, performance metric evaluation, and comparative analysis. Both network configurations are developed using identical demand patterns and design parameters to ensure a fair and reliable comparison.

## 3.1 Network Selection and Data Collection

A representative water distribution network is selected to develop looped and branched configurations with comparable size, pipe length, and demand distribution. Network data are obtained from municipal records, standard datasets, and published case studies. Collected information includes pipe dimensions, material properties, roughness coefficients, nodal demands, elevations, and operational parameters such as peak demand factors and minimum pressure requirements. This dataset ensures realistic and consistent simulation conditions.

## 3.2 Hydraulic Modeling Using WaterGEMS

The collected data are incorporated into Bentley WaterGEMS to define the network topology. Junctions represent demand nodes, while pipes, pumps, and valves form the hydraulic links. Reservoirs and tanks are assigned appropriate elevations and capacities. The models are calibrated using baseline demand and pressure data to ensure accurate representation of real-world operating conditions.

### 3.2.1 Simulation Scenarios

Hydraulic simulations are carried out under three operating scenarios: normal demand conditions, peak demand conditions, and pipe failure scenarios. Normal operation establishes baseline performance, peak demand evaluates system capacity, and pipe failure simulations assess network resilience and redundancy. These scenarios enable evaluation of network behavior under both routine and stressed conditions.

### 3.2.2 Output Parameters

Key hydraulic outputs obtained from WaterGEMS include nodal pressure values, pressure deficits, pipe flow rates, flow velocities, pump energy consumption, and hydraulic grade line profiles. These parameters are extracted for each simulation scenario to assess network performance, efficiency, and reliability.

## 3.3 Performance Metrics

Network performance is evaluated using resilience and efficiency indicators. Resilience metrics include pressure deficit analysis, service continuity index, and network redundancy index. Efficiency is assessed through total energy consumption, hydraulic grade uniformity, and pipe utilization factor. These indicators provide a quantitative basis for comparing looped and branched networks.

## 3.4 Comparative and Sensitivity Analysis

Results from both network configurations are compared using numerical indices and graphical analysis. Sensitivity studies are conducted by varying pipe diameter, demand levels, and network layout to examine their influence on hydraulic performance and energy consumption. Based on the analysis, recommendations are developed for optimal network configuration, pipe sizing, and operational strategies to improve resilience and efficiency.

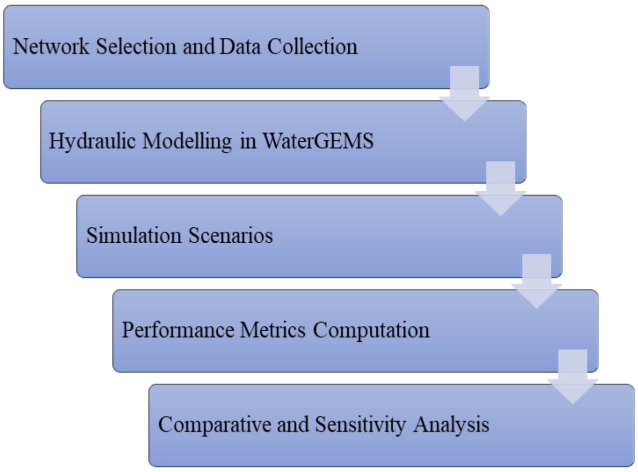

**Figure -1:** Methodology Flowchart

The proposed methodology provides a comprehensive framework for evaluating WDN performance, facilitating informed decision-making in both the design and operational phases.

## 4. RESULT AND DISCUSSION

This chapter presents and interprets the results obtained from the hydraulic, resilience, and energy-efficiency evaluation of looped and branched water distribution network configurations. The analysis combines structural assessment, hydraulic simulation, failure-based resilience testing, demand variability analysis, and energy performance comparison. Results are discussed to highlight the influence of network topology on hydraulic behavior, reliability, and operational efficiency, enabling a comprehensive comparison of the two configurations.

### 4.1 Structural Characteristics of the Networks

The looped network consists of interconnected pipelines forming multiple closed circuits, providing alternative flow paths between nodes. This structure increases redundancy and operational flexibility. In contrast, the branched network follows a tree-like layout with a single flow path to each demand node, resulting in lower pipe length and simpler construction. While the branched configuration reduces initial infrastructure requirements, the looped network demonstrates greater structural robustness due to its interconnected topology.

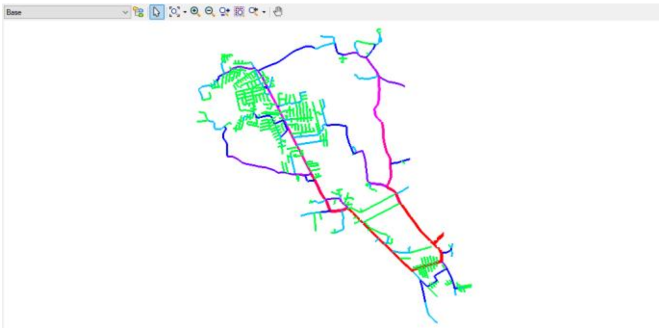

**Figure -2:** Looped Network

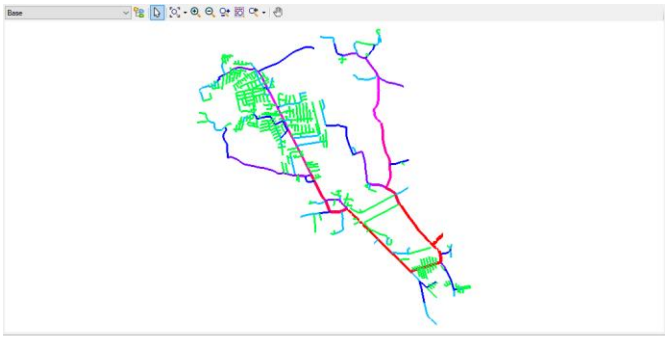

**Figure -3:** Branched Network

### 4.2 Hydraulic Performance Analysis

Hydraulic simulation results indicate that the looped network maintains more uniform pressure distribution across demand nodes under both normal and peak demand conditions. Flow redistribution through alternative paths reduces pressure losses and extreme velocity variations. The branched network exhibits noticeable pressure drops at terminal nodes, particularly during peak demand. These results confirm that network interconnectivity plays a significant role in improving hydraulic stability and service reliability.

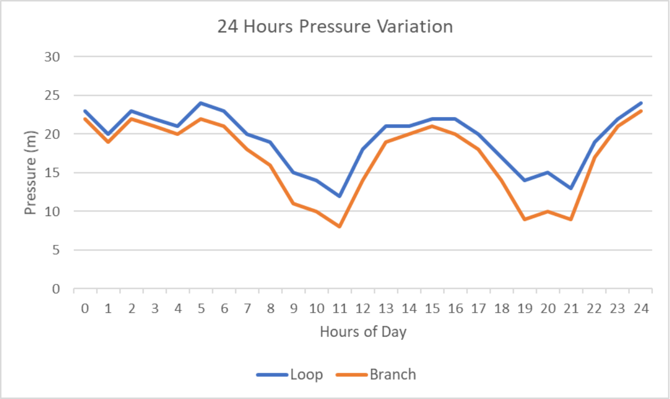

**Figure -4:** 24 Hours pressure Variation

### 4.3 Resilience Assessment under Failure Conditions

Pipe failure simulations reveal that the looped network sustains water supply to most nodes by rerouting flow through adjacent links. Service disruption remains localized, demonstrating high resilience. Conversely, failures in the branched network result in complete supply interruption to downstream areas due to the absence of alternate paths. Resilience indices clearly indicate superior performance of the looped configuration under outage scenarios.

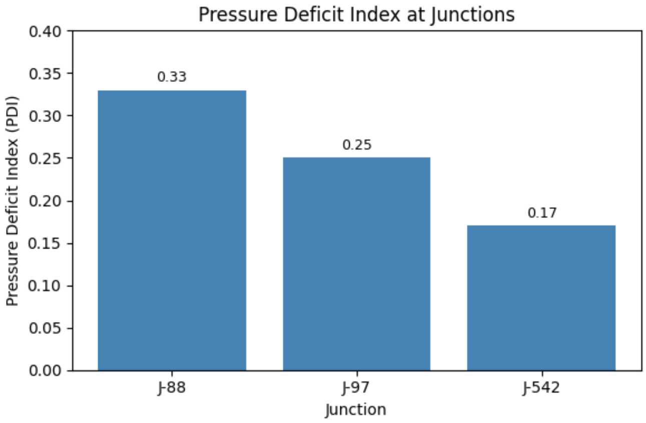

**Figure –5: PDI Distribution across Nodes in branch network**

### 4.4 Discussion

The results establish a strong relationship between network topology and system performance. Looped networks provide enhanced hydraulic stability, higher resilience, and improved energy efficiency, making them suitable for urban and high-demand applications. Branched networks, while economical and easy to implement, are more appropriate for low-demand or rural systems where reliability requirements are less stringent.

## 5. CONCLUSIONS AND RECOMMENDATIONS

### 5.1 Conclusion

This study presented a comparative evaluation of branched and looped water distribution networks using hydraulic simulation, structural assessment, and resilience indicators. Although both networks were modeled with identical physical parameters, their performance differed significantly due to network topology and redundancy. The branched system exhibited pressure deficiencies, higher head losses, and limited ability to meet peak demand because of its single-path flow and dead-end nodes. In contrast, the looped network demonstrated stable pressure distribution, smoother hydraulic grade lines, and improved flow redistribution. Resilience indices further confirmed that looped networks possess greater robustness, reduced vulnerability, and superior service reliability, highlighting the importance of connectivity and redundancy in modern WDN design.

### 5.2 Recommendations and Future Scope

Based on the findings, looped, or partially looped configurations are strongly recommended for urban and expanding water distribution systems due to their enhanced reliability and resilience. Even minor loop closures in branched areas can significantly improve pressure stability. Critical pipes and nodes identified as bottlenecks should be prioritized for upgrades. Water utilities are encouraged to adopt hydraulic simulation tools such as WaterGEMS for routine planning, failure assessment, and resilience monitoring. Future research may integrate real-time SCADA data, pump optimization, and energy analysis to further enhance operational efficiency. Additional studies on leak behavior, transient analysis, water quality modeling, and multi-objective optimization can support more resilient and sustainable WDN planning.

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