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CIVIL ENGINEERING FOR MITIGATION OF RISK FROM NATURAL HAZARDS

Improving EPANET Reliability: Resolving Emitter Backflow and Nodal Reporting Issues Under FAVAD Formulation

Master's Degree Thesis

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ABSTRACT

Durable access to clean water relies on the precise management of Water Distribution Networks (WDNs), yet accurately modeling leakage and nodal behavior remains a significant technical challenge. This thesis addresses two critical limitations within the EPANET hydraulic engine: the unphysical occurrence of backflow through emitters during negative pressure scenarios and the lack of transparency in reporting nodal demands.

To resolve these issues, an automated pipeline was created with the aid of Docker. This kind of development environment helped in the process of rapid iterative running and testing of the C-based source code. The core logic of engine modified with track-back analysis of hydraulic solver. With change of many modules in the engine code finally emitter backflow problem solved, and total nodal outflow separated to components: delivered, Leak-1 (Power Law leakage), and Leak-2 (FAVAD leakage).

For validation of final version, four tests designed to run in the Fossolo WDN benchmark, a network with 58 pipes and 37 nodes. Numerical results confirm that the modified version successfully eliminates emitter backflow under negative pressure and separated total nodal outflow to their components correctly. Crucially, comparative analysis (Test-4) demonstrated that neglecting leak area variability in FAVAD approach modeling of leakage can lead to a significant underestimation of leakage rates. In the normal scenario, the model reported a leakage flow of 48.728 L/s (59% of total outflow) using FAVAD parameters, compared to only 18.299 L/s when area variability was ignored. These findings highlight the necessity of the FAVAD approach modeling leakage, especially for WDNs with high pipe elasticity. The resulting version provides more reliable, transparent, and physically accurate tool for the advanced modeling and management of leakage in hydraulic infrastructures for engineers and researchers.

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Introduction

1.1 Background

Durable access to clean water is essential for any activities. Throughout history, one can observe that most great civilizations were established along the rivers. The enumerated infrastructures play a key role in the proper functioning of agriculture, industry, and public health, among other sectors.

Water Distribution Networks are one of many kinds of hydraulic infrastructures. They ensure the continuous and reliable supply of water from sources to end users. WDNs are one of the most important and technically challenging types of hydraulic infrastructures. These systems face many challenges during the process of ensuring reliable water supply like leakage and maintaining water quality (Zeidan, Li, & Ostfeld, 2018). For a better understanding of these systems, simulation tools are widely used these days and are seen to be an effective approach to analyze and predict WDN behavior under different conditions.

Leakage in WDNs is a global unavoidable issue which can cause significant economic and energy loss (Perez, et al., 2014). Leaks also can damage infrastructures and increase health risk (Perez, et al., 2014). This loss could happen through pipes or joints because of damage and poor installation and can exist in tanks and reservoirs (Righetti, Bort, Bottazzi, Menapace, & Zanfei, 2019). Despite all technical progress in the domain, accurately localization leaks is still a challenging problem (Fan & Yu, 2022) and how leakage actually affect the hydraulic of network is still not completely understood (Zaman, Uddameri, Tiwari, & Sen, 2022).

Leakage is one of the major challenges in managing and modeling water distribution networks. One of the main factors of efficient management of WDNs is minimizing water losses (Zaman, Uddameri, Tiwari, & Sen, 2022). Detecting and managing leakage is a fundamental aspect of hydraulic network analysis, maintenance and decision-making processes in WDNs. Added to field measurements of pipeline leakage and experimental tests for leak detection and localization, numerical models via hydraulic solvers play a crucial role in leakage prediction towards proper management of hydraulic systems.

1.2 Motivation

EPANET is a widely used open-source software for modeling of WDNs over extended periods (Rossman, 2010). It allows tracking water flow rates in pipes, pressures in nodes, tank levels, and chemical concentration through the network (Saminu, Abubakar, & Sagir, 2013). Two main approaches can be followed up for a WDN analysis via EPANET. The Demand Driven Analysis (DDA) assumes that demands in nodes are fully satisfied regardless of the pressure level (Muranho, Sousa, Gomes, & Marques, 2020). EPANET has become a standard tool in both academia and industry. However, the Pressure Driven Analysis (PDA) relates nodal demands to the pressure level in each node of the network via a head-flow relationship (Wagner, Shamir, & Marks, 1988).

Considering its popularity among researchers and hydraulicians, EPANET has become a standard tool in both academia and industry. Nevertheless, EPANET still has some limitations. One of the issues that drive the effort in this work was the backflow that may take place when modeling a leakage through the emitter function in EPANET 2.2, the last officially released version of EPANET from United States Environmental Protection Agency EPA(Agency, 2026). The latter issue is mainly encountered when a leaking node shows a negative pressure head. A backflow in a leaking node means that water is sucked in the network from the outside leading to a non-realistic condition that should not be encountered in practice. Another aspect of EPANET that can be considered also a limitation, mainly when the hydraulic model involves leakage and emitter functions, is the form of nodal results reporting. Current EPANET versions provide in the modeling report the results of the nodal demand in a condensed form. In fact, when leakage or emitter functions take place in the model, the user needs to consider that the obtained nodal demand is a cumulative demand involving the leakage and the emitter outflows added to the actually delivered flow to the consumer. Then, splitting the nodal demands in the EPANET report to consider different forms of outflows (leakage, emitter, delivered, etc.) would make the software more user-friendly and would enhance the interpretability of the hydraulic results. The motivation of this work comes mainly from these two issues and handling these limitations is the principal objective of this thesis.

1.3 Objectives

The main objectives of this thesis are to address the above limitations in EPANET codebase.

The first objective is to fix the backflow problem caused in negative pressure in nodes. By modifying the source code, the emitter model is going to be adjusted so that flows reflect realistic network behavior under negative pressure in nides, preventing unphysical water intrusion.

The second objective is to separate the nodal outflow into its components to provide more details about leakage and actual delivered water in the WDNs. The revised code will be able to split "demand" in old version (which is normally the total outflow of nodes) into **delivered**, **leak-1** (emitter leak), and other **leak-2** (Leakage leak). This provides more detailed and accurate information for network analysis and modeling, enabling engineers and researchers to better assess the performance and reliability of water distribution networks, especially in case of leakage.

1.4 Thesis Structure Overview

- **Introduction:** Overview of the background, motivation, and objectives of the thesis.
- **Chapter 1 – Literature Review:** Review of the state of the art on Water Distribution Networks (WDNs) and EPANET.
- **Chapter 2 – Methodology:** Description of the methodology and the processes through which the research was conducted.
- **Chapter 3 – Results and Discussion:** Presentation and discussion of the results obtained after modifying the codebase.
- **Conclusions and Future Work:** Evaluation of whether the results met the expectations and discussion of potential directions for future research.
- **Bibliography**
- **Appendix**

1. Literature Review

1.1 Hydraulic Infrastructure

The importance of access to sufficient, high-quality water is crucial for several kinds of activities(Meinzen-Dick & Rosegrant, 2001). Throughout history, one can observe that most great civilizations were established along the rivers. The latter is due to the obvious fact that without water for drinking and to cultivating crops no society can last (Postel, 2013). Nowadays, it is common to find societies built far from rivers and water sources, as large-scale water transportation systems have undergone outstanding advancement. Nevertheless, it is still challenging to provide enough high-quality water for end-users continuously. Hence, systems that deal with transportation, availability, and quality of water are also as important as water itself. Dams, hydropower plants, water supply systems, sewerage networks, stormwater drainage system, irrigation systems, and treatment plants are some examples of hydraulic infrastructures(Grigg, 2019). The enumerated infrastructures play a key role in the proper functioning of agriculture, industry, and public health, among other sectors. They are not only essential for starting and continuous activities of any kind but also, they provide protection to communities from many risks like flooding, environmental degradation and waterborne diseases (Muller, Biswas, Martin-Hurtado, & Tortajada, 2015). Among all hydraulic infrastructures, the combination of elements that are necessary for supply water from sources to users refers to us as water distribution networks.

1.2 Water Distribution Networks (WDNs)

Water Distribution Networks are one of many kinds of hydraulic infrastructures. They ensure the continuous and reliable supply of water from sources to end users. End users include households, industries, and public services, for example schools and hospitals. The WDNs performance can directly affect the public health, economic development and sustainability of natural resources(Shuang, Liu, & Porse, 2019). Complexity is one of the key characteristics of modern WDNs due to their large scale, nonlinear hydraulic behavior, and changing operation conditions(Izquierdo, Montalvo, Perez-Garcia, & Matias, 2012). Moreover, the growth of population and the impact of climate change add further complexity. Based on the above, WDNs are one of the most important and technically challenging types of hydraulic infrastructures.

Modern WDNs are complex pressurized systems with many physical components, including pipes, valves, storage, pumps, etc. (Sana, Haroon, & Guangji, 2019). Their main goal is to supply water to end users from sources such as reservoirs or treatment plants. These systems face many challenges during the process of ensuring reliable water supply like leakage and maintaining water quality (Zeidan, Li, & Ostfeld, 2018). For a better understanding of these systems, simulation tools are widely used these days and are seen to be an effective approach to analyze and predict WDN behavior under different conditions.

A proper simulation of a WDN requires prior knowledge of its topology which is generally composed of two main elements: Nodes (e.g., junctions, reservoirs, tanks etc.) and Links (e.g., pipes, pumps, valves etc.) (Giudicianni, et al., 2018). Known variables are diameter, and roughness for links and nodal demand and source head for nodes. Combining mass and momentum conservation equations, a system of equations is obtained and then numerically solved to find out the main unknowns which are the pressure head in nodes and the flow rate along links. For a WDN, the outcome of the simulation can help understanding, managing and maintaining the functioning of the water system under its design conditions as well as in case of sudden disruption (pump failure, pipe burst, etc.).

1.3 Leakage in WDNs

Leakage in WDNs is a global unavoidable issue which can cause significant economic and energy loss (Perez, et al., 2014). Leaks also can damage infrastructures and increase health risk (Perez, et al., 2014). In a general definition leakage is loss of water from system, but this waste is also means waste of money and energy which invested collecting, transporting, and treating this water without reaching the end users (Chan, Chin, & Zhong, 2018) and (Righetti, Bort, Bottazzi, Menapace, & Zanfei, 2019). This loss could happen through pipes or joints because of damage and poor installation and can exist in tanks and reservoirs (Righetti, Bort, Bottazzi, Menapace, & Zanfei, 2019). These damages can happen because of ground movement, high pressure, excavation, pipe aging, low temperature, pipe defects, and material low quality (Righetti, Bort, Bottazzi, Menapace, & Zanfei, 2019).

One of the main factors of efficient management of WDNs is minimizing water losses (Zaman, Uddameri, Tiwari, & Sen, 2022). Detecting and managing leakage is a fundamental aspect of hydraulic network analysis, maintenance and decision-making processes in WDNs. The operation of detecting water leakage usually is an extensive and expensive field work (Righetti, Bort, Bottazzi, Menapace, & Zanfei, 2019). Despite all technical progress in the domain, accurately localization leaks is still a challenging problem (Fan & Yu, 2022) and how leakage actually affect the hydraulic of network is still not completely understood (Zaman, Uddameri, Tiwari, & Sen, 2022). Despite all methods and approaches for detecting and managing leakage, it is essential to be able to include leakage in models and solvers.

1.4 Hydraulic Network Analysis

Hydraulic network analysis refers to the process of determining the flow rates in pipes and pressure heads at nodes in a WDN according to its operation conditions. The process of simulation of WDNs is based on solving a system of equations derived from two fundamental physical conservation laws: the mass and the momentum conservations. Head loss is a nonlinear function of flow rate, pipe diameter, pipe length and pipe roughness. The relationship between flow rate and head loss can be described with one of many empirical equations such as Darcy-Weisbach, Hazen-Williams or Manning equations. Due to this nonlinear relation, solving the governing equation is not a straightforward process and many methods have been proposed in literature to address this complex problem.

Wood and Charles (1972) introduced a linearized approach with fast convergence for open and closed loop systems. Nahavandi Catanzaro (1973) developed a new matrix-based method for steady-state and also transient to solve for nodal pressure and mass flow rates in branches. Hall (1976) attempted to formulate the problem as a convex program by using geometric programming and claimed that under specific conditions the solution is unique. Gupta (2006) provide an innovative theoretical framework for generalized network models under steady state or transient flow conditions. These methods are not applicable for water networks but also useful in other related fields.

Over the years, several algorithms have been developed for hydraulic analysis. Among these, the Global Gradient Algorithm (GGA) has become a standard for hydraulic analysis of WDNs because of its stability and efficiency (Todini, 2006). GGA solves the system of nonlinear equations using topological spare matrix for converging and numerical stability and this algorithm performs well even for large and complex networks (Todini, 2006). It is widely used in many hydraulic modeling software applications such as EPANET, which will be discussed in a later section. Traditional approaches assume that nodal demand is equal to nodal outflow (demand driven) but real network may in low-pressure does not be able to satisfy the base demand, in such case, the outflow would be lower than demand based on the pressure in that node (Gupta & Abdy Sayyed, 2013). To address this problem some researchers like Gupta (2013) have proposed pressure-dependent demand (PDD) approaches which consider nodal outflow based on nodal demand and pressure head in node. Such an approach allows us to simulate network performance more accurately even under deficient conditions such as pipe bursts or pump failures (Liu, Yu, & Savic, 2011). Researchers extended modeling packages such as EPANET to enable the implement PDD formulation.

1.5 Leakage in EPANET: different models and basic formulations

While detecting leakage in the field is physically demanding, accurately representing it in hydraulic models is critical for predicting network behavior and planning interventions. In EPANET, there are three possible ways to model leakage exit:

i. Leakage as a Demand Multiplier
ii. The Emitter (Power Law)
iii. The FAVAD (Fixed And Variable Area Discharge) approach

The second and third methods are standard approaches for simulating leakage, but with the first method it is also possible to model leakage in a very simplified way. In the coming subsections, each of these methods will be briefly described.

i. Leakage as a Demand Multiplier

The simplest approach to modeling leakage is the Demand Multiplier method, often referred to as the "accounting" approach. In this scenario, leakage is treated identically to consumer consumption. The engineer calculates the total volume of water loss (e.g., 20% of the system total) and distributes that across the network by artificially increasing the base demand at junctions. This can be done by creating a specific "leakage pattern" or by using a global multiplier in the hydraulic options. The advantage of this method is its simplicity; it ensures the total mass balance of the system (Water In = Water Out) without complex calibration of coefficients. However, its major drawback is that it relies on and limited to Demand Driven Analysis (DDA).

In this method assumption is that the leakage volume is fixed regardless of the system's pressure. With this said, this method cannot be used for pressure management studies.

ii. The Emitter (Power Law)

To account for the physical relationship between pressure and flow, EPANET provides the Emitter property at junction nodes. This method utilizes the standard orifice flow equation where leakage flow depends on the pressure at the node. In standard practice, the pressure exponent is set to 0.5. This approach represents a significant improvement in over demand multipliers because it introduces Pressure Driven Approach (PDA) behavior: if pressure drops, the leakage rate drops accordingly. The exponent of 0.5 physically represents a "rigid" hole, such as a corrosion puncture in a steel or cast-iron pipe where the area of the hole remains constant regardless of pressure. While this is the native and most common method in EPANET, it may underestimate leakage in networks where pipe materials are flexible, as it assumes the hole geometry never changes.

Leakage differs from normal consumer consumption because it is pressure dependent. As pressure in a pipe increases, the rate of water loss through a crack or hole increases.

- **DDA**: Assumes a fixed volume is consumed regardless of pressure (e.g., a user filling a bathtub). Only the leakage outflow depends on the pressure.
- **PDA**: Both user demand and the leakage outflow are pressure dependent (e.g., leaks are highest when pressure is high).

EPANET for models this physical relationship uses the Emitter property at junction nodes. An emitter allows water to outflow from the network to the atmosphere just with the help of pressure at that specific node.

The software uses a power-law equation derived from the orifice flow equation:

$$Q = Cp^{\gamma} \qquad \text{Equation 1-1}$$

where:

Q = leakage flow rate,
p = pressure head,
C = leakage coefficient and
γ = pressure exponent.

iii. The FAVAD approach for leakage modeling

The FAVAD concept is more appropriate for modeling leakage as it considers the leakage area variability. Unlike the standard emitter, FAVAD recognizes that leakage area in materials exhibiting higher elastic behavior (PVC, polyethylene) may expand as pressure increases. As the pressure inside the pipe rises, cracks open wider, allowing water to escape at a rate much faster than standard orifice theory predicts. To implement this in EPANET, engineers still use the Emitter function but adjust the global pressure exponent to a value higher than the default 0.5, typically ranging from 1.5 to 2.5 (Cassa & van Zyl, 2013). The advantages of this method are that it offers higher level of accuracy since generally they are built on a calibration of field data. The downside is the difficulty of calibration; determining the exact exponent requires extensive field data, and incorrectly estimating this value can lead to significant errors in the model's predictions. The leakage through an orifice is generally described by the Tucciarelli formula (Tucciarelli, Criminisi, & Termini, 1999).

$$Q = C_d A \sqrt{2gh}$$ Equation 1-2

where:

Q = leakage flow rate,
C_d = discharge coefficient, usually taken = 0.6
A = leak area,
g = acceleration due to gravity and
h = pressure head.

The relationship between leakage and area with pressure is described with the equation below that was obtained after an extensive series of experimental tests (Cassa & van Zyl, 2013).

$$A = A_0 + mh$$ Equation 1-3

where:

A = leak area at head h,
A_0 = initial leak area (area of leak under zero pressure conditions) and
m = head-area slope (potential of pipe to increase leak size under pressure).

In the case of a longitudinal crack an empirical formula for *m* was derived by (Cassa & van Zyl, 2013):

$$m = \frac{2.93157 d^{0.3379} Lc^{4.8} 10^{0.5997(logLc)^2} \rho g}{E t^{1.746}}$$ Equation 1-4

Where:

d = pipe diameter
Lc = length of the crack
E = Young modulus of elasticity
t = pipe wall thickness

Combining equations (2.2) and (2.3), the implementation of the FAVAD approach in the very last release of EPANET (EPANET 2.3) is made through defining two parameters for each of the leaking pipes of the WDN referring to the leak area and the leak exponent.

Considering a leaking pipe with a longitudinal crack distributed along its length. Denoting A_0 the initial leak area per one meter of pipe length, the parameter C1 is written

$$C1 = \frac{A_0[mm2] * 100}{L[ft]} = \frac{A_0[mm2] * 100}{L[m] * 3.28084} \qquad \text{Equation 1-5}$$

where:

A_0 = initial leak area (area of leak under zero pressure conditions) and
L=Total pipe length.

Similarly, and by considering equation 2.4, the leak expansion rate is defined through the parameter C2 written as

$$C2 = \frac{m[\frac{mm^2}{m}] * 100}{L[m] * 3.28084} \qquad \text{Equation 1-6}$$

2. Methodology

2.1 Interacting with Code: Implementation Challenges

The initial stage of this research required modifying the core EPANET hydraulic engine. To interact with the codebase outside of the standard GUI, the original C code must be compiled into executable machine code which is a process involving complex software engineering requirements (Analytics, n.d.).

Furthermore, being able to see and test results after any changes of code in real-time added another layer of complexity. Considering long trial-and-error required, the process is nearly impossible using the manual method.

This section outlines the methods for interacting with the EPANET source code and explains why these manual standard approaches were insufficient due to iterative needs of this research and the description of the automated pipeline which made this process fast, durable, and fully reproducible

2.1.1 Manual Compilation and Execution Methods

Typically, a C-based program like EPANET is transformed from human-readable source code into a machine-executable file through a sequence of compilation commands. It is good to notice that all this process is essential to be done for every single and simple run (just give input and take output) of the engine. According to the official EPANET documentation, the standard workflow utilizes CMake, a cross-platform build system, to manage the compilation process. Under normal conditions, a researcher would interact with the code through one of two primary methods:

Command Line Interface (CLI): Utilizing a compiler such as **GCC** (on Linux) or **Clang** (on macOS). The process involves manually creating a "build" directory, running **cmake** to generate the makefiles and finally executing the make command to produce the binary.

Integrated Development Environments (IDEs): Using software like **Microsoft Visual Studio** or **Xcode**. Although these tools have a graphical interface for compiling but still, they rely on the underlying CMake configurations to link the various modules.

2.1.2 Limitations of Manual Methods

While the methods are effective for general software use, they present significant hurdles in a research environment where the code is subject to constant modification. The standard approaches proved inadequate for this study for the following reasons:

- **Environmental Dependency**: EPANET relies on specific mathematical libraries and **C-standards**. Compiling directly on a **host machine** (e.g., a personal laptop) limited the research results to that specific hardware and compiler version for the operating system. This makes the study difficult to reproduce on other machines with another OS because it needs to set all steps manually again.
- **Manual Iteration Bottleneck**: For solving the problem based on multi-modularity of codespace "trial-and-error" is a must. Each time the source code is adjusted, the researcher must manually re-trigger the compilation and re-locate the resulting executable. This manual intervention is time-consuming and creates a disconnect between development and testing.
- **Modular Complexity**: EPANET is not a single script; it is a system of modular dependencies. Furthermore, most of the modules are long and complex Managing the linking of these modules manually for every test run increases the probability of human error.
- **Complex Error Identification & Debugging**: Without an automated pipeline, the researcher faces a "black box" debugging cycle. Finding the root cause of a logic error requires executing heavy, manual command-line tasks for every minor change.

2.1.3 Transition to an Automated Pipeline

The complexity of the EPANET codespace combined with the need to instantly see the results of code changes in successful run and see error in the unsuccessful run across multiple input scenarios pushed research to move toward automation.

To resolve these challenges, the study replaces the manual interaction with an **Automated Pipeline**. By using Docker and Docker Compose, the entire sequence of configuring the environment, giving input and getting output, compiling the source code, and executing the simulation is abstracted into a single, repeatable process which just triggered with a single command line. This ensures that every result is generated from a clean, identical environment, completely independent from the host machine and operating system.

2.2 Development Environment: Containerized Build System

To overcome the complexities of manual compilation and environmental dependencies, a unified development environment was architected using containerization. By isolating the EPANET engine from the host operating system, the research achieves a "disposable" yet "durable" workflow where the compilation environment remains identical across every iteration, regardless of the researcher's local machine configuration.

2.2.1 Containerized Architecture

The environment is built upon a Debian Bullseye Linux distribution, chosen because it is lightweight, stable and compatible with C-based engineering software. This container acts as a box that houses the entire development tool chain.

The components of this box are:

- **Containerization (Docker):** To encapsulate the OS, libraries, and binaries, ensuring the "durability" mentioned in the previous section.
- **Version Control (Git):** Embedded within the environment to track structural changes to the engine throughout the research lifecycle.
- **Build Automation (CMake):** For managing the build process in a compiler-independent manner.
- **Compiler Suite (build-essential):** Utilizing GCC/G++ to transform C source code into machine-executable binaries.

2.2.2 Automated Compilation Pipeline

The development environment is defined by a blueprint that automates the entire lifecycle of the engine. Upon initiation, the system performs an autonomous multi-stage sequence:

- **Environment Provisioning**: The system pulls the base Linux image and injects the required compilers and dependencies.
- **Source Injection**: The EPANET source code is mapped into the container's internal file system.
- **Autonomous Build**: The system automatically creates a directory for build, then generates the necessary Makefiles via CMake, and compiles the final “**runepanet**” executable.

2.2.3 Data Synchronization via Volume Mapping

A critical hurdle in using containerized engines is the isolation of the file system. To resolve this, the development environment utilizes Bidirectional Volume Mapping. This creates a persistent, real-time link between the researcher's local project directory and the container's internal working directory.

This synchronization is the "engine room" of the iterative process, solving the manual data transfer problem:

- **Zero-Latency Data Exchange**: Instead of manually copying input (*.inp file) files into the container, the container "sees" the local project folder as its own. Any change made to a network file on the host is immediately available to the EPANET engine inside the container. This process called "Hot Reloading" in computer science.
- **Persistent Results**: Because the output directory is mapped to the host, the simulation results (*.rpt file) after written in container copied directly to the local machine. They remain on the researcher's computer even after the container finishes its task and shuts down.

2.2.4 Centralized Error Handling and Debugging

Another major advantage of this containerized approach is simplifying error handling. In traditional manual workflows, errors are often fragmented—compiler errors appear in one terminal, linker warnings in another, and runtime hydraulic crashes might be hidden in system logs or silent output files.

By running the entire process within a single containerized pipeline:

- **Unified Logging**: All stages of the process—from the initial C-compilation and linking to the actual hydraulic execution—are piped into a single output stream.
- **Real-Time Troubleshooting**: If a code modification causes a syntax error or a logical crash during simulation, the error is reported instantly in one central location. This is significantly helpful in the trial-and-error phase.

2.2.5 Execution Logic

To ensure the environment is durable and efficient, the system is configured with a specific Execution. Upon launch, the container automatically calls the compiled runepanet executable, targeting specific files (such as **input.inp** and **output.rpt**) within the mapped volume.

This transformation turns a complex, multi-step manual compilation into an automated pipeline, providing the high-speed, durable framework necessary for deep modifications to the hydraulic engine.

2.3 Detection: Trace-Back Analysis of the Hydraulic Engine

To identify the source of the emitter backflow problem, the trace-back methodology was employed. Rather than analyzing the engine from the initial input phase, the detection of problem began at the final output (the function is writing the result in the output file) stage and moved upstream through the functional call stack of the C-source code.

2.3.1 Starting point: Reporting Layer

The detection process initiated with the functions responsible for writing the final simulation results in the final output. Specifically, the investigation targeted the reporting modules (e.g., report.c) that extract calculated hydraulic data and write them to the *.rpt output file. By analyzing the variables passed to these output functions, it was possible to identify which data structures were carrying the incorrect backflow values.

2.3.2 Functional Call-Stack Reversal

After identifying the wrong output variables, the research followed the chain of function calls backward. Because EPANET utilizes a modular architecture based on complex data types and pointers, the investigation required tracing how these pointers were passed between the modules and the reporting tool.

For example, “writenodetable” is a function which is responsible for writing nodal result in the final report. This function called in the “writeresults” function which is called in the “writereport” function in the “EN_report” function in the “epanet.c” module.

2.4 Engine Modifications

Following the isolation of the logic failure, the EPANET 2.3 source code was modified across several functional layers. This ensured that the new emitter backflow logic was not only mathematically sound within the solver but also properly integrated into the project's data structures and reporting protocols.

2.4.1 Definition of Data Structures and Enums

To accommodate the new hydraulic state, the engine's foundational definitions were expanded. Modifications of **types.h** and **epanet2_enums.h** is to introduce new variables and enumeration constants that represent emitter-specific backflow statuses. These changes allowed the engine to distinguish between demand, emitter flow (leake-1), and leakage flow (leake-2).

2.4.2 Solver Logic and Hydraulic Calculation

The core of the modification resides in **hydraul.c** and **hydsolver.c**. The hydraulic iteration loop was updated to include a conditional check for negative pressure at nodes equipped with emitters.

Logic Adjustment: Modification of solver was in a way to prevent the default behavior of treating emitters as simple head-dependent demands that prevent the emitter from being negative under negative pressure.

Mathematical Implementation: By adjusting the linearized equations within the Global Gradient Algorithm (GGA) implementation in **hydsolver.c**, the engine was forced to recognize reverse flow as a physical possibility, updating the nodal heads and link flows accordingly.

2.4.3 Data Flow and Input/Output Integration

Input Handling (input1.c, project.c): The project initialization and input parsing were refined to ensure that emitter parameters to correctly mapped to the new data structures during the setup phase.

Result Processing (output.c, report.c): The reporting functions were modified to retrieve the new backflow status from the solver. This ensures that when the simulation completes, the output (*.rpt) files accurately reflect negative flow values.

2.4.4 Rules and Global Logic

Finally, the control logic in **rules.c** and the top-level execution calls in **epanet.c** were reviewed and adjusted. This ensured that operational rules (such as tank levels or valve statuses) interact correctly with nodes experiencing backflow, maintaining the overall stability of the simulation across all time steps.

2.4.5 Disaggregation of Nodal Results

A critical component of the engine modification was the separation of emitter flow from standard nodal demand in the reporting phase because the original EPANET 2.3 logic, emitter discharge is often bundled into total nodal outflow, making it difficult to isolate backflow events during analysis.

Modifying reporting logic by changing **report.c** and **output.c** to:

Distinct Categorization: Isolate emitter flow as a separate column or status within the nodal output tables.

Directional Visibility: Ensure that negative values representing backflow into the system are explicitly preserved rather than being rounded to zero or treated as undefined.

Status Flags: Update the text reporting (via **text.h** and **enumstxt.h**) to flag nodes where backflow is occurring, providing a clear diagnostic indicator for the researcher.

This separation is crucial for the Verification, as it allows for a direct comparison between the theoretical backflow predicted by the modified equations and the actual values recorded in the simulation reports.

3. Results and Discussion

3.1 Overview

This chapter is dedicated to presenting the main results of this thesis. To this end, a real WDN was considered as a benchmark for conducting various numerical tests on EPANET software. Firstly, the objectives of thesis are shortly reviewed. Then, the benchmark Fossolo WDN is described. Afterward, outcomes of the various conducted tests are presented and thoroughly discussed to shed light on main differences between the old and the new versions of EPANET and to introduce the improvements we have made through this work to make EPANET more user-friendly. We qualify by "old" all parameters that are obtained via the original EPANET code and by "new" the parameters obtained by the modified code.

Finally, to point out the importance of considering the FAVAD approach for leakage modeling in WDNs, a comparative analysis was made between the emitter function (the power law) used in EPANET2.2 and the FAVAD formulation as introduced in EPANET 2.3 in terms of leakage outflow evaluation.

3.1.1 Objectives

The main objectives of this work are:

i. **A more realistic representation of leakage in EPANET***:* to reach this objective, the focus was made into dealing with the backflow issue encountered when modeling leakage using the emitter function under a negative nodal pressure. Also, it was pointed out the importance of considering FAVAD formulation rather than the power law if modeling leakage in highly elastic pipeline that are susceptible to radially expand due to the pressure effect.

ii. **A more user-friendly representation of results in EPANET***:* to reach this objective, the EPANET output file was expanded to include extra fields in which obtained nodal outflows are dissociated for the user to distinguish between the actually delivered and the leakage outflows.

To illustrate the main changes made to EPANET source code to reach these objectives, a set of numerical tests are conducted on the WDN Fossolo. Additionally, through these numerical tests the difference between old (EPANET 2.2) and new (EPANET 2.3) versions of EPANET is highlighted.

3.1.2 Fossolo WDN

The Fossolo system is based on the water distribution system for the Fossolo neighborhood in Bologna, Italy. The system has an average demand of 3,000 CMD. The network was first presented by Bragalli et al. (2008) as part of a design study. A general schematic of the system is shown in Figure 3-1. The system has one reservoir and 8.4 kilometers of pipe.

The Fossolo network is composed of 58 pipes and 37 nodes, which include 36 junctions and one reservoir. The total pipe length of the system is approximately 8.4 kilometers, with diameters ranging from 16 mm to 229.2 mm. Although originally developed using mixed-integer nonlinear programming (Bragalli, D'Ambrosio, Lee, Lodi, & Toth, 2012), the network has since been used in various research works (Hafsi, Giudicianni, & Creaco, 2026) and optimization studies, including those using multi-objective hybrid approaches and genetic algorithms(Creaco & Franchini, 2014) and (Bi, Dandy, & Maier, 2015).

The network classified in "looped" classification based on pipe loops exist in the network. In a classification analysis by Hoagland et al. (2015) shows that the network contains 16 loops which most of them are 5-pipe loops. In another study using graph-theory-metrics categorizes this network as a "Transmission Dense-Loop" system. Another study mentioned that in the network average node-degree of 3.1 and a meshed connectedness of 0.3 (Hwang & Lansey, 2017).

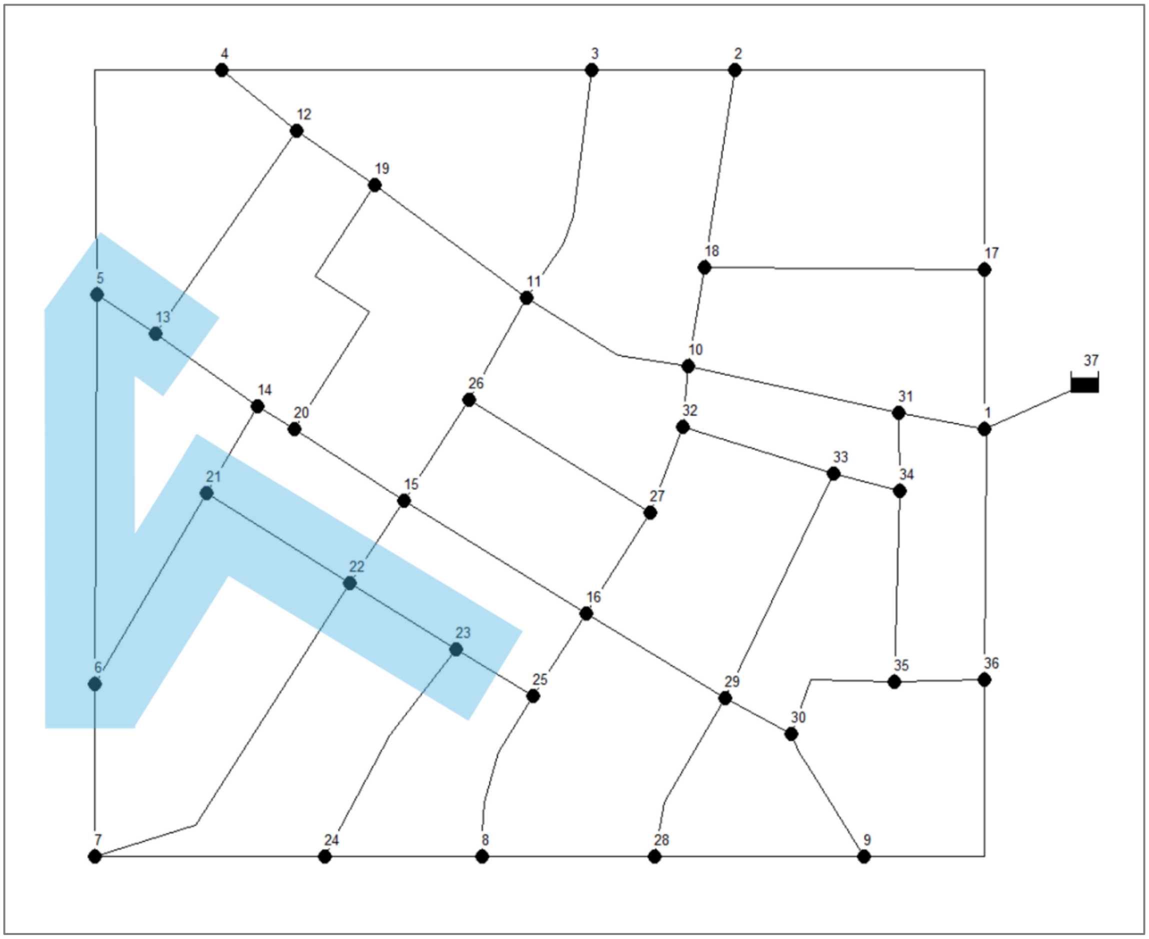


Figure 3-1 Fossolo WDN (pipes of interest are highlighted)

3.2 Tests Lists

Table 3-1 summarizes the set of numerical tests along with their main objectives. The results of these tests are detailed and discussed in the following subsections.

Table 3-1 List of numerical tests

Test ID	Objective	Category
Test-0	Analysis of Fossolo WDN in its intact state (without leakage).	Improving the Reliability of EPANET
Test-1	Dealing with the emitter backflow issue in EPANET 2.2.	
Test-2	Improving the readability of the EPANET output file: Separation of the total outflow into delivered and leakage outflows.	
Test-3	Comparing FAVAD formulation to the power law: defining the cases using FAVAD is necessary for leakage modeling.	FAVAD vs. Power Law
Test-4	Comparing FAVAD formulation to the power law: defining a realistic probable case of leakage in the whole network	

3.2.1 Issues in EPANET 2.2: Illustrative examples

Firstly, consider Fossolo WDN, illustrative example to emphasize the two main issues dealt with in this work, i.e. the emitter backflow and the node demand output are presented.

Setting up a demand driven analysis (DDA) in which base demands must be satisfied in any condition even under negative pressure values in the leaking nodes. Based on sign of the pressure and the amount of leakage, three possible cases may arise in a node:

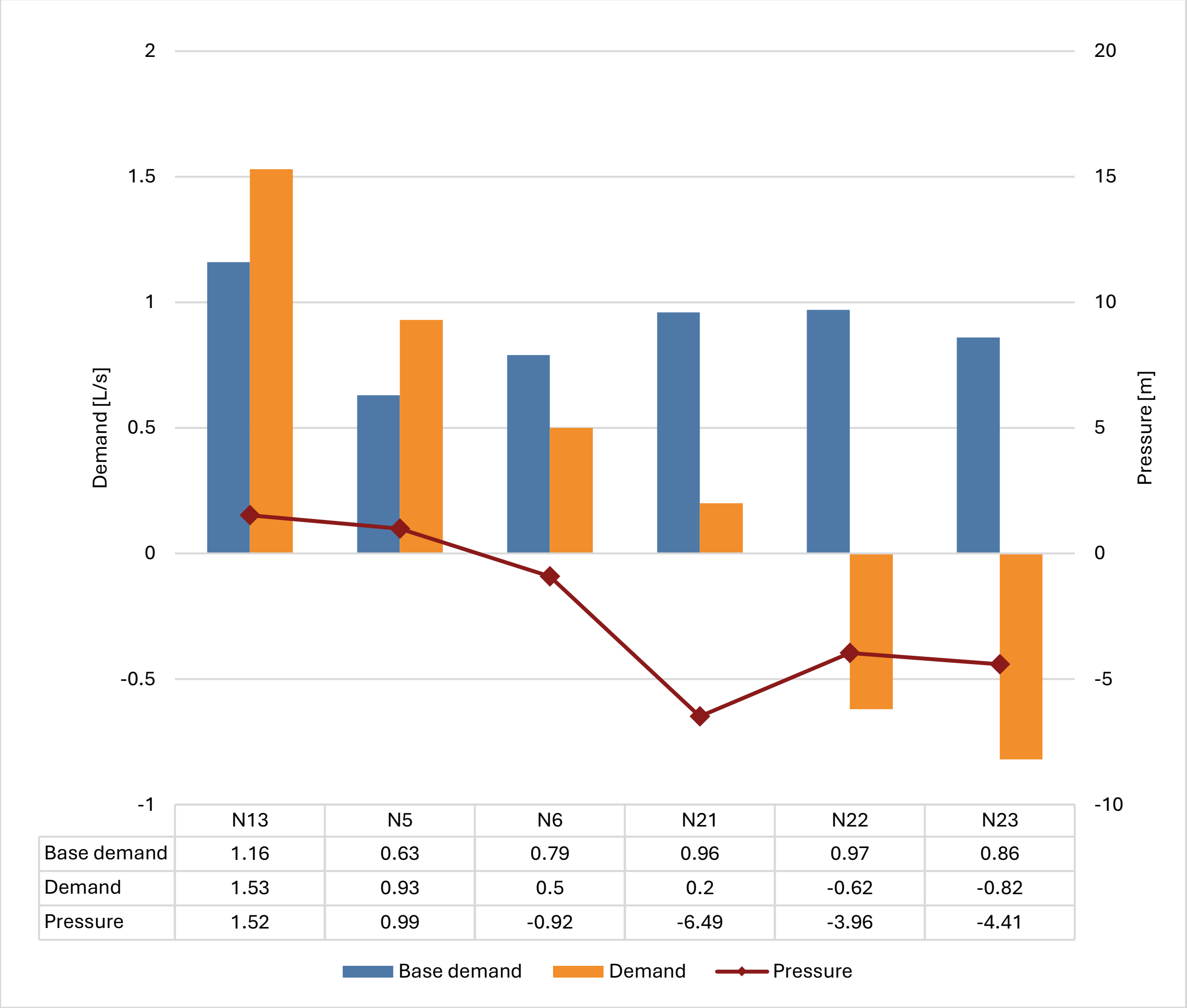
i. Positive pressure value: in this situation the node outflow is equal to the base demand if the node does not show a leakage and it is greater than the base demand if the node is leaking.
ii. Negative pressure value with a leakage rate smaller than the base demand: the node outflow, although being less than the base demand, is positive.
iii. Negative pressure value with a leakage rate greater than the base demand: a negative value of the node outflow will be reported in the EPANET output file.

To highlight these main issues the settings of test-1 are considered with some changes in head of source and elevation of some node as shown in the Table 3-2. Figure 3-2 illustrates these issues.

Table 3-2 Primary changes to the elevations of some nodes in Fossolo network

	ID	Original	Set	Difference
Reservoirs	37	121.00	72.00	-49.00
Junctions	5	61.24	51.24	-10.00
	13	61.90	58.90	-3.00
	21	62.80	74.80	+12.00
	22	63.90	73.90	+10.00
	23	64.20	74.20	+10.00

It is obvious that if absolute value of leakage is less than base demand, nodal demand would be positive and leak value would be hidden. This negative value would be hidden like in nodes N6 and N21. But if the absolute value of leakage is greater than base demand nodal demand value would be negative, and it is indicatable like in nodes N5 and N6.



	N13	N5	N6	N21	N22	N23
Base demand	1.16	0.63	0.79	0.96	0.97	0.86
Demand	1.53	0.93	0.5	0.2	-0.62	-0.82
Pressure	1.52	0.99	-0.92	-6.49	-3.96	-4.41

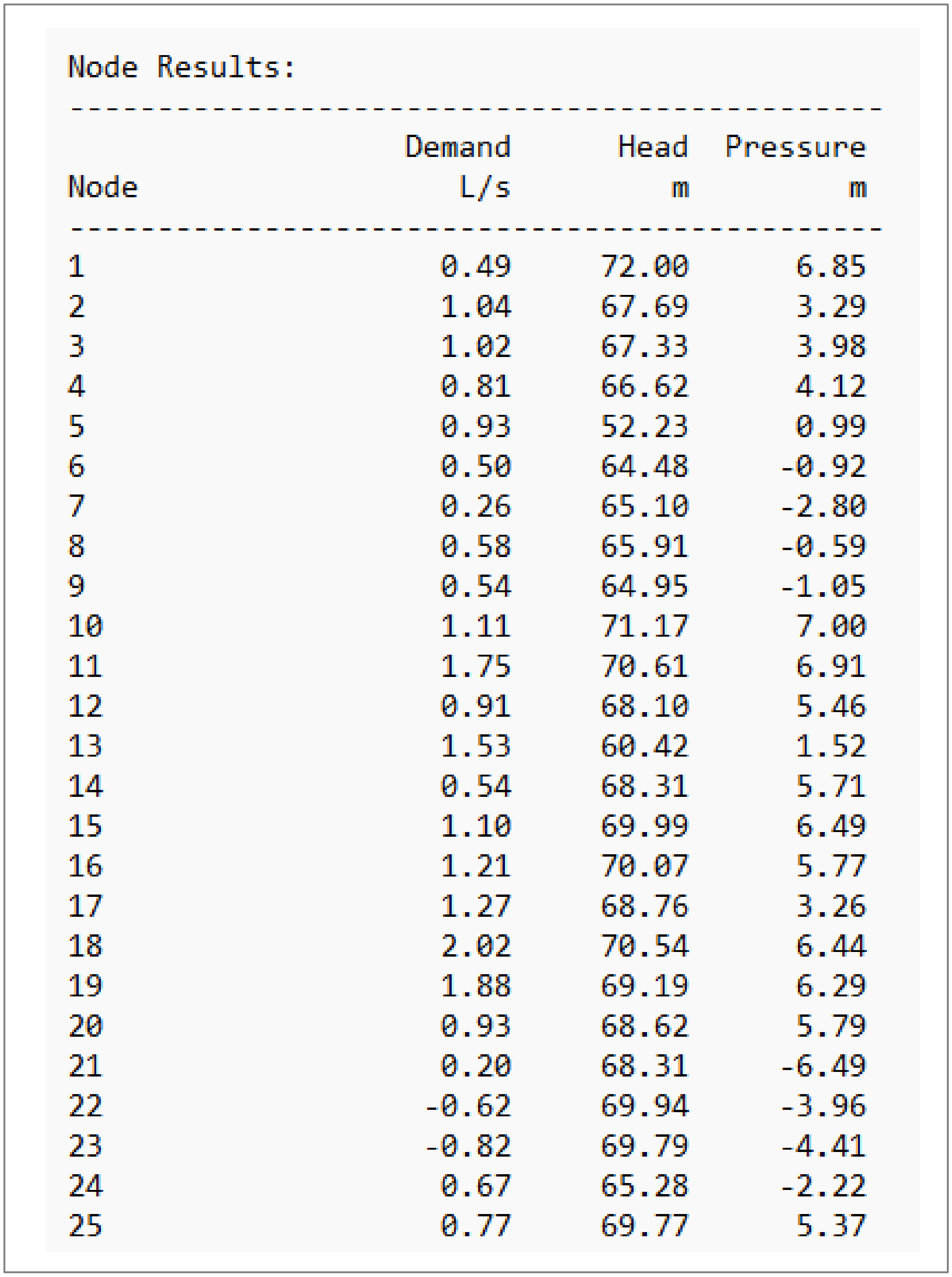
Figure 3-2 EPANET outcomes (Test-1 with change of elevations)

As mentioned in DDA base demand must be satisfied in any condition. Three probable conditions can be seen in **Error! Reference source not found.** and in this figure result of EPANET which is only demand (total outflow) calculated to indicate what is happening. From left to right first 2 nodes have positive pressure the second two nodes have negative pressure, but leak value is less than base demand and in the third two nodes have negative pressure with leak greater than base demand. Now problem is obvious and it can be seen visually in this figure and EPANET would not give us such information which is the second motivation of this thesis.

	N13		N5		N6		N21		N22		N23	
Leak		0.37		0.3		-0.29		-0.76		-1.59		-1.68
Delivered		1.16		0.63		0.79		0.96		0.97		0.8
Demand	1.53		0.93		0.5		0.2		-0.62		-0.82	
Pr	1.52	1.52	0.99	0.99	-0.92	-0.92	-6.49	-6.49	-3.96	-3.96	-4.41	-4.41

Figure 3-3 Detailed representation of EPANET outcomes (Test-1 with change of elevations)

With running EPANET it gives results in text format like shown in the Figure 3-3. It is seen that there is no information about the amount of leak or delivered or total outflow. It reports all these values under the demand title. Everything gets more complicated if 2 types of leaks are modeled by EPANET. In the recent version of EPANET beside emitter it is possible to model leak in another way. First type of leak can be modelled in nodes with help of emitter but there is another type of leak modelling in recent version which is possible to model leak with help of leakage title in input text in pipes. In this thesis we called them **leak1** and **leak2** and there will be more description about them in the next sections.



```
Node Results:
----------------------------------------------
                      Demand      Head  Pressure
Node                     L/s         m         m
----------------------------------------------
1                       0.49     72.00      6.85
2                       1.04     67.69      3.29
3                       1.02     67.33      3.98
4                       0.81     66.62      4.12
5                       0.93     52.23      0.99
6                       0.50     64.48     -0.92
7                       0.26     65.10     -2.80
8                       0.58     65.91     -0.59
9                       0.54     64.95     -1.05
10                      1.11     71.17      7.00
11                      1.75     70.61      6.91
12                      0.91     68.10      5.46
13                      1.53     60.42      1.52
14                      0.54     68.31      5.71
15                      1.10     69.99      6.49
16                      1.21     70.07      5.77
17                      1.27     68.76      3.26
18                      2.02     70.54      6.44
19                      1.88     69.19      6.29
20                      0.93     68.62      5.79
21                      0.20     68.31     -6.49
22                     -0.62     69.94     -3.96
23                     -0.82     69.79     -4.41
24                      0.67     65.28     -2.22
25                      0.77     69.77      5.37
```

Figure 3-4 EPANET actual results in text format

**** It is also important to mention that this result was obtained from the Test-1 configuration, which will be described in the following chapters.***

3.3 Improving the Reliability of EPANET

This section describes the first series of tests, including Test-0, Test-1, and Test-2. These tests are designed to evaluate and improve how the software handles network data and output results. Test-0 involves the analysis of the Fossolo WDN in its intact state (without leakage) to establish a baseline for the network. Test-1 focuses on dealing with the emitter backflow issue in EPANET 2.2, which is an important step in making the hydraulic modeling more realistic.

Furthermore, this section covers the results of improvements which have been made to the software's results through Test-0 to Test-2. By focusing on these three tests, this section demonstrates how the reliability and user-friendliness of the EPANET software have been achieved.

3.3.1 Test-0 Intact State

- Objective of Test-0

The objective of Test-0 is to analyze the Fossolo WDN in its intact state, which means the network is modeled without any leakage. In this test, no change is made to the network parameters or settings. It is used to establish a baseline for the system's hydraulic behavior under normal demand conditions. By evaluating the network in this state, we can ensure that the initial data is correct before any modifications are introduced.

- Settings in Test-0

Setting of the Fossolo network can be seen in the Table 3-3 which there are no leaks in system and source head is unchanged.

Table 3-3 Setting of the Fossolo network for Test-0

Source Head (m)	121					
Nodes	N13	N5	N6	N21	N22	N23
Base Demand (L/s)	1.16	0.63	0.79	0.96	0.97	0.86
Elevations (m)	61.90	61.24	65.40	62.80	63.90	64.20
Heads (m)	112.20	107.30	108.01	113.60	116.65	115.55
Pressures (m)	50.30	46.06	42.61	50.80	52.75	51.35
Demand (L/s)	1.16	0.63	0.79	0.96	0.97	0.86
Delivered (L/s)	1.16	0.63	0.79	0.96	0.97	0.86
Emitter Coeff	0.00	0.00	0.00	0.00	0.00	0.00
Leak-1 (L/s)	0.00	0.00	0.00	0.00	0.00	0.00
C1 (m)	0.00	0.00	0.00	0.00	0.00	0.00
C2 (-)	0.00	0.00	0.00	0.00	0.00	0.00
Leak-2 (L/s)	0.00	0.00	0.00	0.00	0.00	0.00

- Results of Test-0

A summary of the important information regarding the results of Test-0 is shown in Figure 3-5. The chart shows the result of model in initial condition for six selected nodes: N13, N5, N6, N21, N22, and N23. The data does not show any difference in the results (demand and pressure) between the old version and the new version of the software. Also, the pressure remains the same in both the old and new versions across all nodes. This confirms that the baseline hydraulic behavior of the network in new engine is the same as old version when no leakage is present.

	N13	N5	N6	N21	N22	N23
Base Demand	1.16	0.63	0.79	0.96	0.97	0.86
Demand Old	1.16	0.63	0.79	0.96	0.97	0.86
Demand New	1.16	0.63	0.79	0.96	0.97	0.86
Pressure Old	50.3	46.06	42.61	50.8	52.75	51.35
Pressure New	50.3	46.06	42.61	50.8	52.75	51.35

Figure 3-5 Initial condition (Old vs. New)

3.3.2 Test-1 (More realistic representation of leakage in EPANET)

- Objective of Test-1

This test is designed to show the output of the old and changed versions of the EPANET model simultaneously. It focuses on three probable situations that may happen in the network regarding the base demand set at the nodes. The characteristics of the Fossolo network were modified (as described in the previous section) to create these three situations in the six chosen nodes, with each situation applied to two nodes.

This test does not focus on the separation of results; instead, its purpose is to show that the negative leakage problem is solved. The leak in this test is identified as Leak-1, which is modeled using the Emitter function in the nodes.

The objective of Test-1 is to show the improvement of reliability of modeling by dealing with the emitter backflow issue in EPANET 2.2. In previous versions, modeling leakage using the emitter function could cause errors when pressure in nodes became negative. This test focuses on showing this specific issue is fixed to ensure the software handles these physical conditions correctly.

- Settings in Test-1

Table 3-4 and Table 3-5show the settings used for Test-1. It should also be mentioned that values for Leak-1 is not directly given by model; instead, it is calculated inversely based on DDA.

Table 3-4 Setting of the Fossolo network for Test-1 old version

Source Head (m)	72					
Nodes	N13	N5	N6	N21	N22	N23
Base Demand (L/s)	1.16	0.63	0.79	0.96	0.97	0.86
Elevations (m)	58.90	51.24	65.40	74.80	73.90	74.20
Heads (m)	60.42	52.23	64.48	68.31	69.94	69.79
Pressures (m)	1.52	0.99	-0.92	-6.49	-3.96	-4.41
Demand (L/s)	1.53	0.93	0.50	0.20	-0.62	-0.82
Delivered (L/s)	1.16	0.63	0.79	0.96	0.97	0.86
Emitter Coeff	0.30	0.30	0.30	0.30	0.30	0.30
Leak-1 (L/s)	0.37	0.30	-0.29	-0.76	-1.59	-1.68
C1 (m)	0.00	0.00	0.00	0.00	0.00	0.00
C2 (-)	0.00	0.00	0.00	0.00	0.00	0.00
Leak-2 (L/s)	0.00	0.00	0.00	0.00	0.00	0.00

Table 3-5 Setting of the Fossolo network for Test-1 new version

Source Head (m)	72					
Nodes	N13	N5	N6	N21	N22	N23
Base Demand (L/s)	1.16	0.63	0.79	0.96	0.97	0.86
Elevations (m)	58.90	51.24	65.40	74.80	73.90	74.20
Heads (m)	60.04	51.93	57.93	64.24	67.48	66.47
Pressures (m)	1.14	0.69	-7.47	-10.56	-6.42	-7.73
Demand (L/s)	1.48	0.88	0.79	0.96	0.97	0.86
Delivered (L/s)	1.16	0.63	0.79	0.96	0.97	0.86
Emitter Coeff	0.30	0.30	0.30	0.30	0.30	0.30
Leak-1 (L/s)	0.32	0.25	0.00	0.00	0.00	0.00
C1 (m)	0.00	0.00	0.00	0.00	0.00	0.00
C2 (-)	0.00	0.00	0.00	0.00	0.00	0.00
Leak-2 (L/s)	0.00	0.00	0.00	0.00	0.00	0.00

- Results of Test-1

The results for Test-1 demonstrate how the changed version of EPANET handles the emitter backflow issue compared to the old version across six nodes (N13, N5, N6, N21, N22, and N23). Figure 3-6 shows the demand and pressure values for both versions. In nodes where the pressure becomes negative (N6, N21, N22, and N23), the old version of EPANET produces "Demand Old" values that are lower than the base demand, even falling into negative values for nodes N22 and N23. In contrast, the "Demand New" values in the changed version remain equal to the base demand, proving that the negative leakage problem has been solved.

	N13	N5	N6	N21	N22	N23
Base Demand	1.16	0.63	0.79	0.96	0.97	0.86
Demand Old	1.53	0.93	0.5	0.2	-0.62	-0.82
Demand New	1.48	0.88	0.79	0.96	0.97	0.86
Pressure Old	1.52	0.99	-0.92	-6.49	-3.96	-4.41
Pressure New	1.14	0.69	-7.47	-10.56	-6.42	-7.73

Figure 3-6 Old demand vs. new demand

Figure 3-7further explains these results by showing the "Old demand Separation." In the old version of the software, the leak and delivered components are not separated, which causes the total demand to drop incorrectly when pressures are negative. For example, at nodes N22 and N23, the old model shows negative total demand because it incorrectly treats the emitter as a source of water (backflow) during negative pressure. The changed version fixes this by ensuring the leakage becomes zero when pressure is negative, keeping the delivered demand protected and accurate.

	13		5		6		21		22		23	
	Old	Sep	Old	Sep	Old	Sep	Old	Sep	Old	Sep	Old	Sep
Leak	0	0.37	0	0.3	0	-0.29	0	-0.76	0	-1.59	0	-1.68
Delivered	0	1.16	0	0.63	0	0.79	0	0.96	0	0.97	0	0.8
Demand Old	1.53	0	0.93	0	0.5	0	0.2	0	-0.62	0	-0.82	0
Pressure Old	1.52	1.52	0.99	0.99	-0.92	-0.92	-6.49	-6.49	-3.96	-3.96	-4.41	-4.41

Figure 3-7 Old demand separation

3.3.3 Test2 (Better representation of results in EPANET)

- Objective of Test2

The objective of Test-2 is to improve the readability of the EPANET output file for the user. This is achieved by ensuring the separation of the total outflow into two distinct categories: delivered outflows and leakage outflows. This modification allows the user to clearly distinguish between the water reaching the consumer and the water lost through leaks.

- Settings in Test2

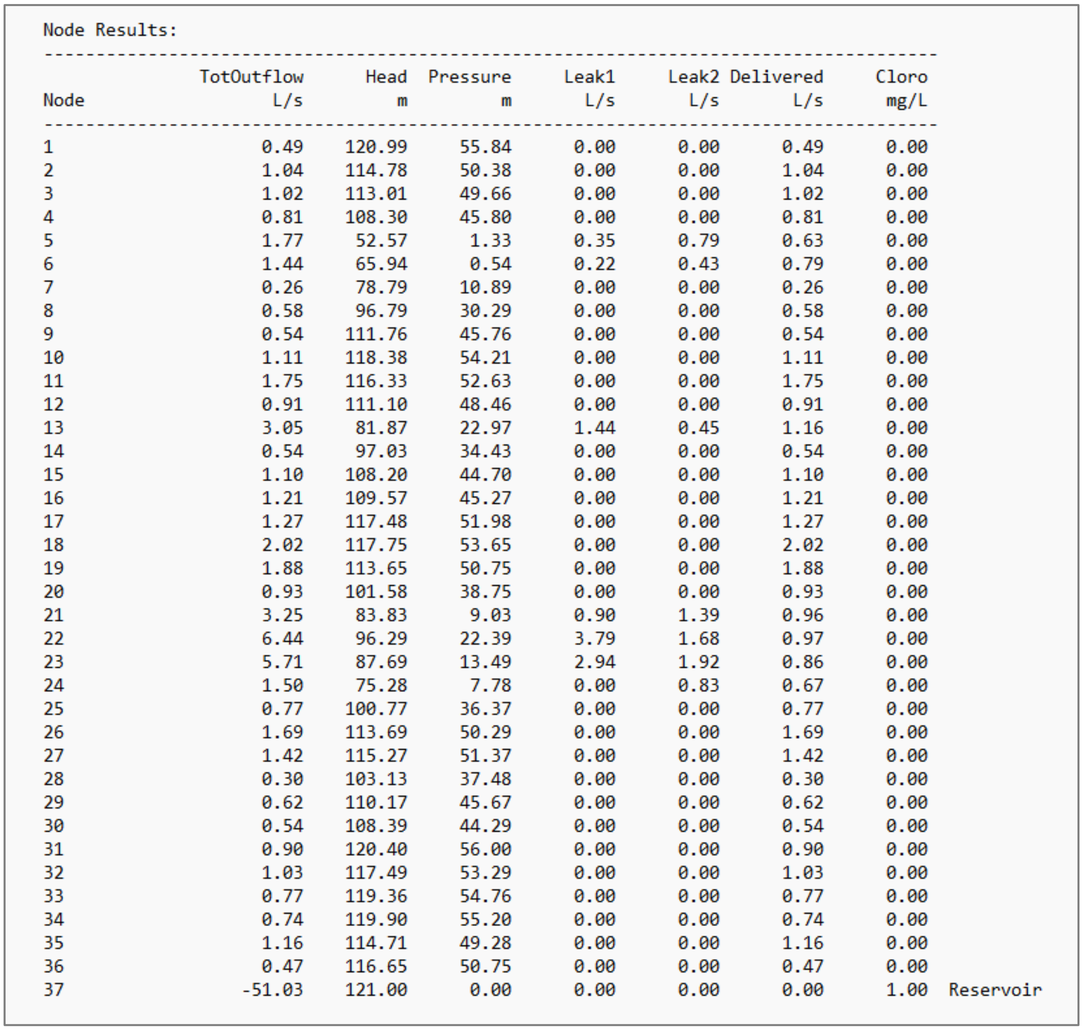
The settings for the Fossolo network are shown in Table 3-6. In this configuration, both Leak-1 and Leak-2 are present in the system. However, the source head remains unchanged because negative pressure is not required for this test. Keeping the pressure positive is necessary because negative pressure would cause the value of Leak-2 to become zero, which would prevent the test from functioning as intended. For evaluating the parameters C1 and C2 a longitudinal crack having a length of 0.6 mm per 1 meter of pipe length and width of 1 mm is considered.

Table 3-6 Setting of the Fossolo network for Test-2

Source Head (m)	121					
Nodes	N13	N5	N6	N21	N22	N23
Base Demand (L/s)	1.16	0.63	0.79	0.96	0.97	0.86
Elevations (m)	58.90	51.24	65.40	74.80	73.90	74.20
Heads (m)	81.87	52.57	65.94	83.83	96.29	87.69
Pressures (m)	22.97	1.33	0.54	9.03	22.39	13.49
Demand (L/s)	3.05	1.77	1.44	3.25	6.44	5.71
Delivered (L/s)	1.16	0.63	0.79	0.96	0.97	0.86
Emitter Coeff	0	0	0	0	0	0
Leak-1 (L/s)	1.44	0.35	0.22	0.90	3.79	2.94
C1 (m)	18.29	18.29	18.29	18.29	18.29	18.29
C2 (-)	1.35	60.25	5.80	1.67	2.64	5.87
Leak-2 (L/s)	0.45	0.79	0.43	1.39	1.68	1.92

- Results of Test2

The primary objective of Test-2 is to demonstrate the successful separation of total outflow into distinct components: delivered demand, Leak-1, and Leak-2. This improvement enhances the readability of the EPANET output, allowing for a clear distinction between water consumed by users and water lost through different types of leakage. As shown in “Node Results "Figure 3-8 the modified software now provides individual columns for Leak-1, Leak-2, and Delivered demand for every node in the Fossolo network.

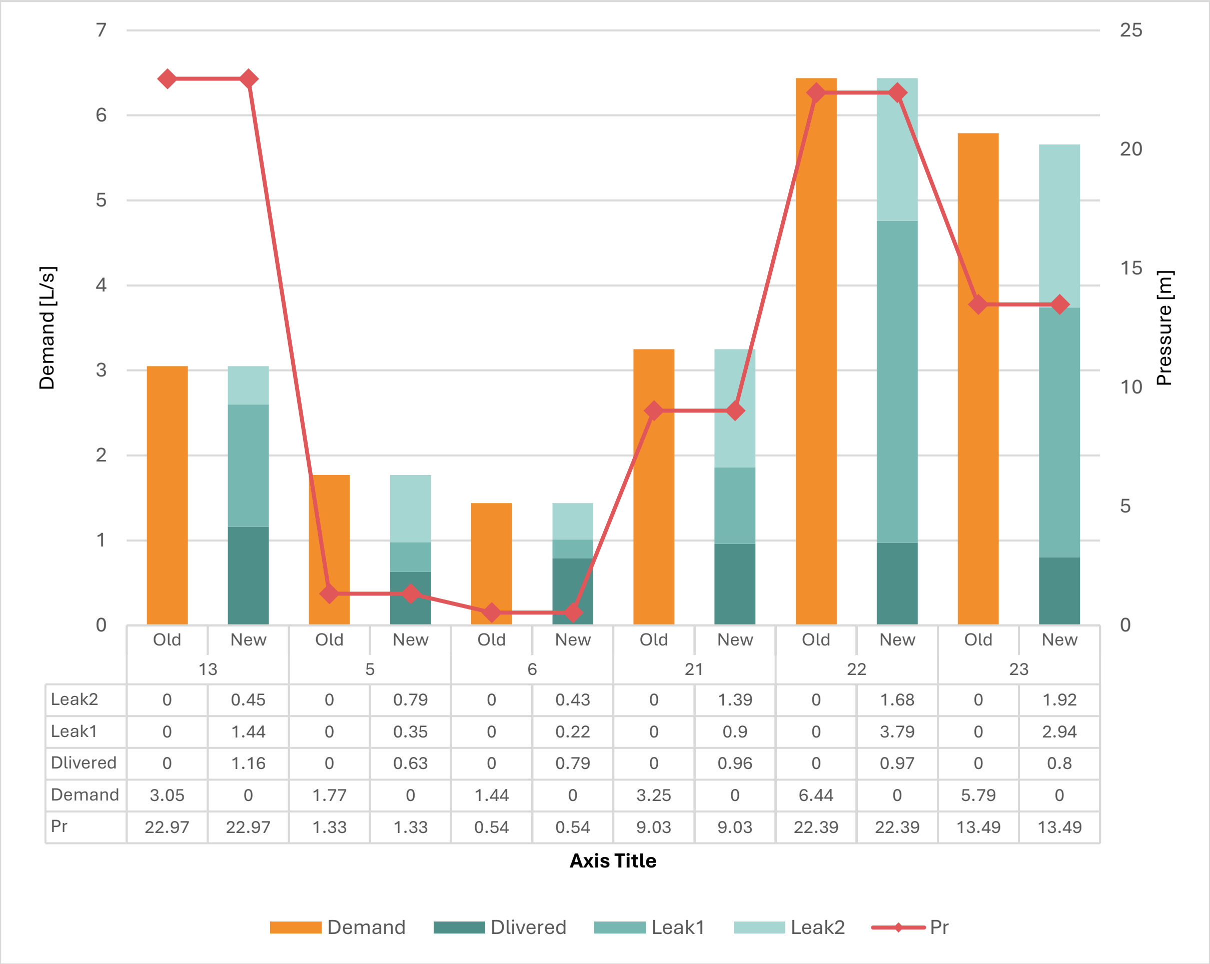


```
Node Results:
-------------------------------------------------------------------------------------
               TotOutflow      Head  Pressure     Leak1     Leak2 Delivered     Cloro
Node                  L/s         m         m       L/s       L/s       L/s      mg/L
-------------------------------------------------------------------------------------
1                    0.49    120.99     55.84      0.00      0.00      0.49      0.00
2                    1.04    114.78     50.38      0.00      0.00      1.04      0.00
3                    1.02    113.01     49.66      0.00      0.00      1.02      0.00
4                    0.81    108.30     45.80      0.00      0.00      0.81      0.00
5                    1.77     52.57      1.33      0.35      0.79      0.63      0.00
6                    1.44     65.94      0.54      0.22      0.43      0.79      0.00
7                    0.26     78.79     10.89      0.00      0.00      0.26      0.00
8                    0.58     96.79     30.29      0.00      0.00      0.58      0.00
9                    0.54    111.76     45.76      0.00      0.00      0.54      0.00
10                   1.11    118.38     54.21      0.00      0.00      1.11      0.00
11                   1.75    116.33     52.63      0.00      0.00      1.75      0.00
12                   0.91    111.10     48.46      0.00      0.00      0.91      0.00
13                   3.05     81.87     22.97      1.44      0.45      1.16      0.00
14                   0.54     97.03     34.43      0.00      0.00      0.54      0.00
15                   1.10    108.20     44.70      0.00      0.00      1.10      0.00
16                   1.21    109.57     45.27      0.00      0.00      1.21      0.00
17                   1.27    117.48     51.98      0.00      0.00      1.27      0.00
18                   2.02    117.75     53.65      0.00      0.00      2.02      0.00
19                   1.88    113.65     50.75      0.00      0.00      1.88      0.00
20                   0.93    101.58     38.75      0.00      0.00      0.93      0.00
21                   3.25     83.83      9.03      0.90      1.39      0.96      0.00
22                   6.44     96.29     22.39      3.79      1.68      0.97      0.00
23                   5.71     87.69     13.49      2.94      1.92      0.86      0.00
24                   1.50     75.28      7.78      0.00      0.83      0.67      0.00
25                   0.77    100.77     36.37      0.00      0.00      0.77      0.00
26                   1.69    113.69     50.29      0.00      0.00      1.69      0.00
27                   1.42    115.27     51.37      0.00      0.00      1.42      0.00
28                   0.30    103.13     37.48      0.00      0.00      0.30      0.00
29                   0.62    110.17     45.67      0.00      0.00      0.62      0.00
30                   0.54    108.39     44.29      0.00      0.00      0.54      0.00
31                   0.90    120.40     56.00      0.00      0.00      0.90      0.00
32                   1.03    117.49     53.29      0.00      0.00      1.03      0.00
33                   0.77    119.36     54.76      0.00      0.00      0.77      0.00
34                   0.74    119.90     55.20      0.00      0.00      0.74      0.00
35                   1.16    114.71     49.28      0.00      0.00      1.16      0.00
36                   0.47    116.65     50.75      0.00      0.00      0.47      0.00
37                 -51.03    121.00      0.00      0.00      0.00      0.00      1.00  Reservoir
```

Figure 3-8 Nodal result of the new version of EPANET

Figure 3-9 illustrates these results for the six selected nodes. In the old version of EPANET, the output only shows a single "Demand" value, which combines all types of outflows into one number. For example, at Node 22, the old version shows a total demand of 6.44 (L/s). In the new version, this total is clearly separated into: Delivered: 0.97 (L/s), Leak-1: 3.79 (L/s), and Leak-2: 1.68 (L/s)

This separation remains accurate even when multiple leak types are active simultaneously. By comparing the "Old" bars to the "New" stack bars in the chart, it is evident that the total outflow remains the same, but the new version provides a detailed breakdown that was previously unavailable. This feature is essential for network managers to identify exactly how much water is being lost to leakage versus how much is being delivered to customers, even when the system pressure is low but positive.



	13		5		6		21		22		23	
	Old	New	Old	New	Old	New	Old	New	Old	New	Old	New
Leak2	0	0.45	0	0.79	0	0.43	0	1.39	0	1.68	0	1.92
Leak1	0	1.44	0	0.35	0	0.22	0	0.9	0	3.79	0	2.94
Dlivered	0	1.16	0	0.63	0	0.79	0	0.96	0	0.97	0	0.8
Demand	3.05	0	1.77	0	1.44	0	3.25	0	6.44	0	5.79	0
Pr	22.97	22.97	1.33	1.33	0.54	0.54	9.03	9.03	22.39	22.39	13.49	13.49

Figure 3-9 Separation of demand for nodes with positive pressure values

3.4 FAVAD in 2.3 vs. Power Law in 2.2

This section compares the traditional Power Law formulation, used in EPANET 2.2 via the emitter function, with the Fixed and Varied Area Discharge (FAVAD) formulation implemented in the updated version of the software. The focus is on evaluating how these different mathematical approaches impact leakage modeling under varying network conditions.

3.4.1 Test3 (Comparing Power Law with FAVAD)

- Objective of Test3

The objective of Test-3 is to compare Power Law and FAVAD formulations by assumption of fixed leakage area to ensure they can produce same results. By setting the specific parameters of the FAVAD equation the model represents a rigid leak. This test validates that the new software version not only can exactly act like traditional emitter results but also provides a more flexible framework for future varied-area modeling.

- Settings in Test3

Table 4 7: Settings with Emitter (Leak-1): This table shows the configuration where leakage is modeled only using the Emitter Coefficient at nodes N13, N5, N6, N21, N22, and N23. The total outflow (demand) includes only the delivered demand and Leak-1, because Leak-2 is set to zero.

Table 4 8: Settings with Leakage (Leak-2): In this configuration, the Emitter Coefficient is set to zero, and leakage is modeled as Leak-2 using the FAVAD parameter C1 (set to 18.288(m)) for all nodes) and C2 (set to 0.00). Setting C2 values to zero ensures the leakage area remains fixed, and it provides a condition for a direct comparison with the Power Law results in Table 4-7.

Table 3-7 Setting of the Fossolo network for Test-2 with Emitter (Leak-1)

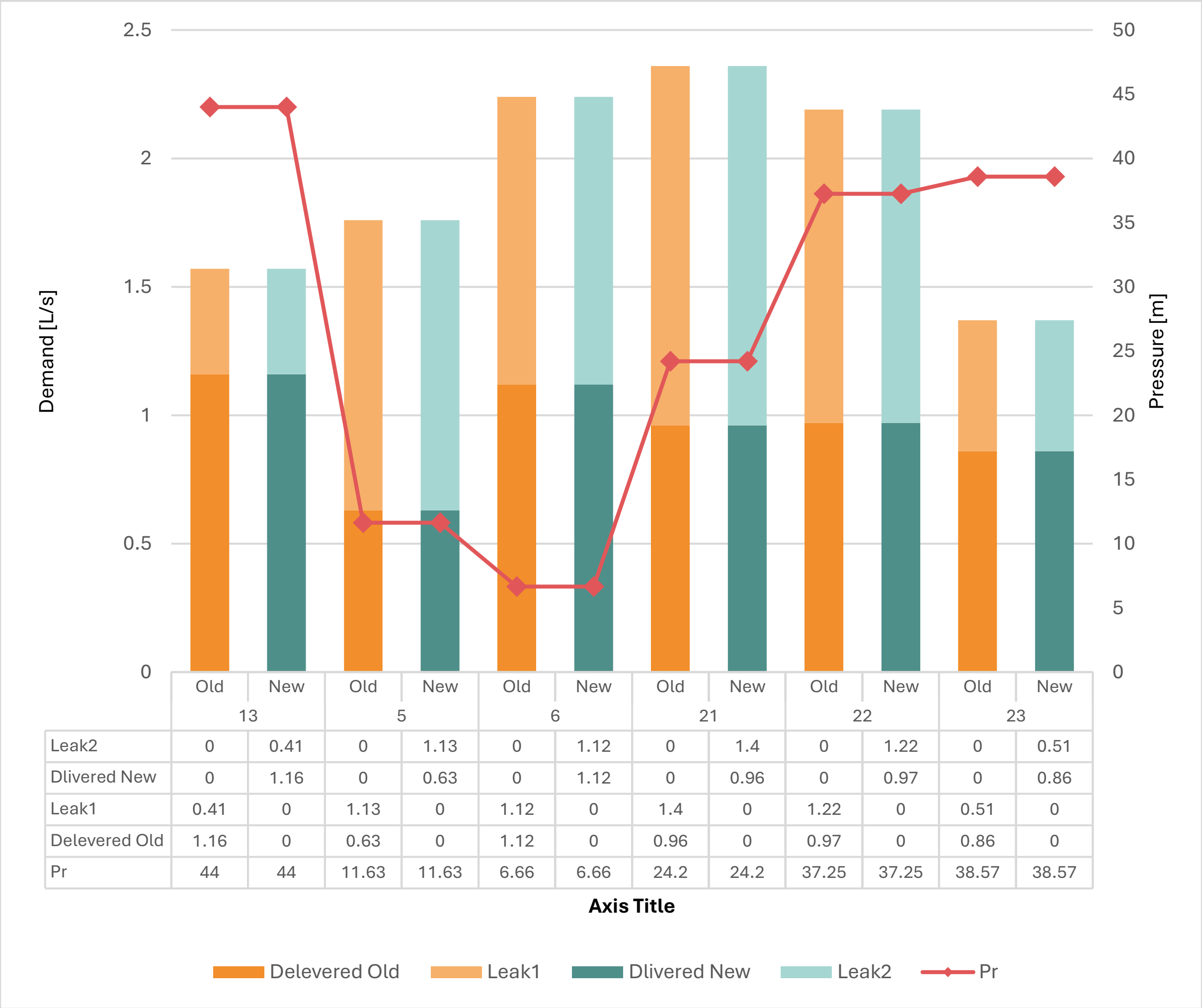
Source Head (m)	121					
Nodes	N13	N5	N6	N21	N22	N23
Base Demand (L/s)	1.16	0.63	0.79	0.96	0.97	0.86
Elevations (m)	58.90	51.24	65.40	74.80	73.90	74.20
Heads (m)	102.90	62.87	72.06	99.00	111.15	112.77
Pressures (m)	44.00	11.63	6.66	24.20	37.25	38.57
Demand (L/s)	1.57	1.76	1.91	2.36	2.19	1.37
Delivered (L/s)	1.16	0.63	0.79	0.96	0.97	0.86
Emitter Coeff	0.0617	0.3299	0.4357	0.2852	0.2004	0.0828
Leak-1 (L/s)	0.41	1.13	1.12	1.40	1.22	0.51
C1 (m)	0.00	0.00	0.00	0.00	0.00	0.00
C2 (-)	0.00	0.00	0.00	0.00	0.00	0.00
Leak-2 (L/s)	0.00	0.00	0.00	0.00	0.00	0.00

Table 3-8 Setting of the Fossolo network for Test-2 with Leakage (Leak-2)

Source Head (m)	121					
Nodes	N13	N5	N6	N21	N22	N23
Base Demand (L/s)	1.16	0.63	0.79	0.96	0.97	0.86
Elevations (m)	58.90	51.24	65.40	74.80	73.90	74.20
Heads (m)	102.90	62.87	72.06	99.00	111.15	112.77
Pressures (m)	44.00	11.63	6.66	24.20	37.25	38.57
Demand (L/s)	1.57	1.76	1.91	2.36	2.19	1.37
Delivered (L/s)	1.16	0.63	0.79	0.96	0.97	0.86
Emitter Coeff	0.00	0.00	0.00	0.00	0.00	0.00
Leak-1 (L/s)	0.00	0.00	0.00	0.00	0.00	0.00
C1 (m)	18.288	18.288	18.288	18.288	18.288	18.288
C2 (-)	0.00	0.00	0.00	0.00	0.00	0.00
Leak-2 (L/s)	0.41	1.13	1.12	1.40	1.22	0.51

- Results of Test3

The results of Test-3, illustrated in Figure 4-11, confirm that when C2=0, the FAVAD formulation produces leakage values (Leak-2) that are identical to the results obtained using the Power Law (Leak-1) via the standard emitter function. This consistency demonstrates that the updated EPANET version correctly implements the FAVAD equation and can serve as a reliable replacement for or addition to the traditional modeling approach.



	Old	New	Old	New	Old	New	Old	New	Old	New	Old	New
	13		5		6		21		22		23	
Leak2	0	0.41	0	1.13	0	1.12	0	1.4	0	1.22	0	0.51
Dlivered New	0	1.16	0	0.63	0	1.12	0	0.96	0	0.97	0	0.86
Leak1	0.41	0	1.13	0	1.12	0	1.4	0	1.22	0	0.51	0
Delevered Old	1.16	0	0.63	0	1.12	0	0.96	0	0.97	0	0.86	0
Pr	44	44	11.63	11.63	6.66	6.66	24.2	24.2	37.25	37.25	38.57	38.57

Figure 3-10 Modeling Leak2 equal to Leak1 (FAVAD = Emitter)

3.4.2 Test-4(Comparing Power Law with FAVAD in whole network)

- Objective of Test4

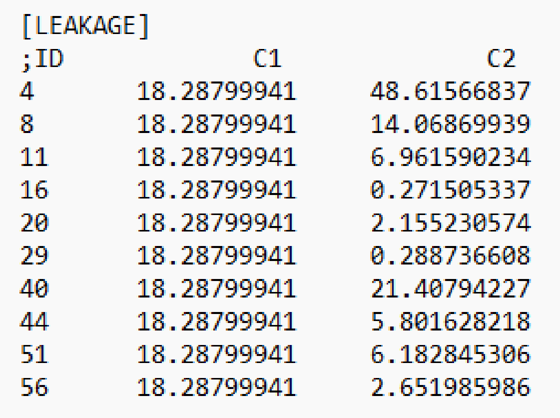
The objective of thest-4 is to show underestimation of total leakage rate when not considering FAVAD in a realistic probable leakage scenario. The network consists of 58 pipes. In this scenario 10 of them are leaking.

- Settings in Test4

In this test, no change is made to the network parameters or settings exactly like test-0. Only changes are adding leakage to 10 pipes in 2 different ways.

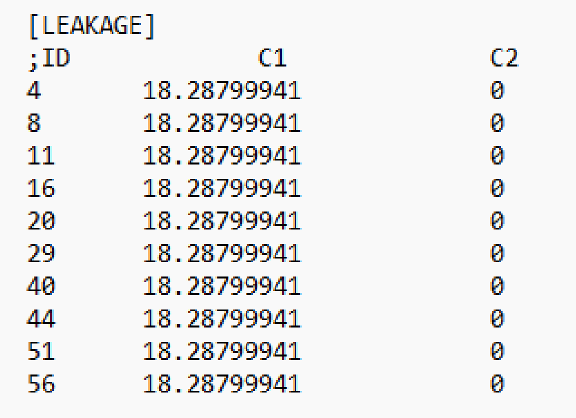
Table 3-9 Leakage modeling details for two scenarios of test-4

Scenario-1 (FAVAD)



```
[LEAKAGE]
;ID             C1               C2
4         18.28799941     48.61566837
8         18.28799941     14.06869939
11        18.28799941     6.961590234
16        18.28799941     0.271505337
20        18.28799941     2.155230574
29        18.28799941     0.288736608
40        18.28799941     21.40794227
44        18.28799941     5.801628218
51        18.28799941     6.182845306
56        18.28799941     2.651985986
```

Scenario-2 (Without FAVAD ≡ emitter function)



```
[LEAKAGE]
;ID             C1               C2
4         18.28799941        0
8         18.28799941        0
11        18.28799941        0
16        18.28799941        0
20        18.28799941        0
29        18.28799941        0
40        18.28799941        0
44        18.28799941        0
51        18.28799941        0
56        18.28799941        0
```

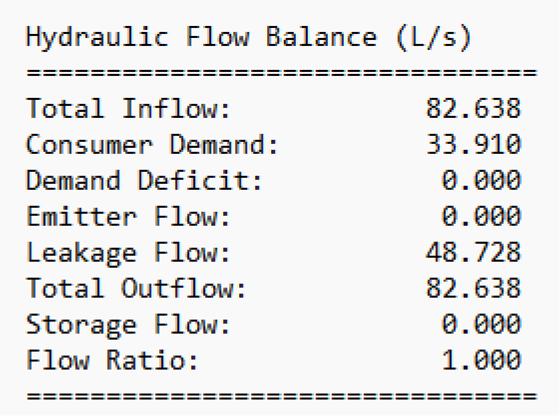
- Results of Test4

Scenario 1 (FAVAD): By applying non-zero coefficients to both **C1** and **C2** parameters across all nodes, the system recorded a significant **Leakage Flow of 48.728 L/s**. This accounts for approximately **59%** of the **Total Outflow (82.638 L/s)**.

Scenario 2 (Without FAVAD): Setting **C2** coefficient values to zero resulted in significant reduction in water loss. Based on the result of this test **Leakage dropped from 48.728 to 18.299 L/s**. Also, it needs to be considered that in these scenarios total inflow is also different, but this difference is exactly the difference between 2 Leakage Flows.

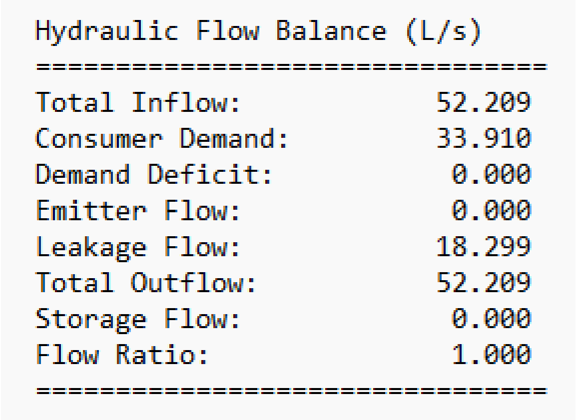
Table 3-10 Leakage modeling Hydraulic result for two scenarios of test-4

Scenario-1 (FAVAD)



```
Hydraulic Flow Balance (L/s)
================================
Total Inflow:            82.638
Consumer Demand:         33.910
Demand Deficit:           0.000
Emitter Flow:             0.000
Leakage Flow:            48.728
Total Outflow:           82.638
Storage Flow:             0.000
Flow Ratio:               1.000
================================
```

Scenario-2 (Without FAVAD)



```
Hydraulic Flow Balance (L/s)
================================
Total Inflow:            52.209
Consumer Demand:         33.910
Demand Deficit:           0.000
Emitter Flow:             0.000
Leakage Flow:            18.299
Total Outflow:           52.209
Storage Flow:             0.000
Flow Ratio:               1.000
================================
```

This example puts in evidence that neglecting the leak area variability is likely to lead to an underestimation of the total leakage rate in a WDN. Thus, considering FAVAD approach would be of great interest mainly when dealing with WDNs formed up of pipelines of higher elasticity.

3.5 DISCUSSION

The series of tests conducted on the Fossolo WDN benchmark provide several key insights into the improved reliability of the modified EPANET software:

- **Baseline Stability:** Test-0 confirmed that the new version maintains the same hydraulic accuracy as the original version in a standard, intact network.

- **Resolution of Backflow Issues:** Test-1 successfully demonstrated that the modified code successfully being able to deal with the "negative leakage" or backflow problem that occurred in EPANET 2.2 when nodal pressures were negative. The new version sets leakage to zero under the condition of negative pressure in nodes.

- **Improved Transparency:** Test-2 showed that the software can now successfully separate total outflow into delivered demand and multiple leakage components

(Leak-1 and Leak-2). This allows for much better readability and detailed analysis of water loss in the output files.

- **Formulation Consistency:** Test-3 validated that the FAVAD implementation is robust and consistent with traditional Power Law models when the varied-area parameter (C2) is not utilized.

Conclusion and Future Work

Summary of Achievements

The result of different designed tests using the Fossolo WDN benchmark successfully showed the reliability and transparency of the new improved EPANET engine based on the objectives of this study. The Fossolo network, a looped WDN with 58 pipes and 37 nodes, provided a complex environment to validate this new version of modified software.

The result of the numerical test confirmed that the new modified version of EPANET is being able to address the modeling issues which were the objectives of this study. Test-1 showed that the software now correctly handles backflow issues in node negative pressure conditions Furthermore, Test-2 showed a significant improvement in the readability of the output of the model by successfully separating demand in old version into its components: delivered, Leak-1 (Power Law), and Leak-2 (FAVAD). Also, Test-3 validated the new FAVAD implementation by fixing the issues in new version can act exactly like Power Low when the area is fixed (C1=0). Finally Test-4 demonstrated that neglecting leak area variability in FAVAD approach for modeling of leakage can lead to a significant underestimation of leakage rates in whole network. Together, this new version of code provides researchers and engineers with a more accurate and user-friendly tool for modeling leakage in water distribution systems.

Future Work

Based on the results of this study, several areas for future research are proposed:

- **Varied-Area Leakage Analysis:** Future studies should utilize the implemented FAVAD formulation to explore cases where the leakage area varies significantly with pressure (where C2 > 0).

- **Real-Time Leakage Detection:** The separated outputs: delivered, leake-1 and leak-2, could be integrated into real-time monitoring systems for leak detection.

- **Large-Scale Validation:** While the Fossolo network provided a robust benchmark, other testing on larger, and more complex networks can confirm the scalability of the new modified code.

- **Optimization of Pipe Design:** Building on the original MINLP studies by Bragalli et al. (2011), the new software features could be used to optimize network designs specifically for leakage reduction.

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