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A Field Experiment Verification of Theoretical Exponent N1 for FAVAD Method in Defining the Relationship of Pressure and Water Losses

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Abstract: The current problem of managing water losses in water supply systems relies on engineering predictions of expected outcomes based on pressure manipulations using hydraulic models or other computational methods. The objective of this experiment was to conduct a field test to validate the theoretical N1 exponent of the fixed and variable area discharges (FAVAD) method. By knowing the pipe material and measuring the pressure and minimum night flow (MNF), the N1 exponent can be defined and compared to recommendations in the literature. Field measurements and experiments were performed in a small settlement in Croatia consisting of 278 house connections and 7.4 km of PVC material pipe network. Pressure manipulation was performed on a pressure-reducing valve (PRV). The resulting value of N1 = 1.76 from the experiment agrees with the literature graphs, which indicate a value of N1 between 1.5 and 2.0. Considering the difference between the studied values and the theoretically calculated MNF of 4%, it can be concluded that the implementation of the presented methodology to determine the N1 exponent can be used in practice. This type of field testing is important because such tests are difficult to perform due to the extensive pressure manipulations during the tests, which can affect the consumers and cause disturbances in the water distribution.

Keywords: FAVAD; N1; water loss; water supply; minimum night flow; hydraulic modeling

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1. Introduction

The best practices suggest that pressure management is one of the most effective ways to reduce the amount of leakage in a water distribution system [1]. Concepts and models for improved interpretation of data and practical management of leakage in distribution systems have evolved from small beginnings in the mid 1990s. The 1994 fixed and variable area discharges concept (FAVAD) was fully applied to predict reductions in zonal leak flow rates from reductions in pressure [1–3]:

$$\frac{L_1}{L_0} = \left(\frac{P_1}{P_0}\right)^{N1} \quad (1)$$

where L_1 is leak value after pressure control (l/s), L_0 leak value before pressure control (l/s), P_1 final pressure (m), P_0 starting pressure value (m), and N1 the leakage exponent (-).

Equation (1) is basis for FAVAD calculation method, which is based on the fact that the change in leakage through a pipe crack depends on the value of the pressure in water distribution systems (WDS) [1,4,5].

N1 value can be determined by field measurements during minimum night flow (MNF) period. A number of field studies have shown that N1 typically varies between 0.5 and 2.79, with a median of 1.15 [6]. This means that leakage in water distribution systems is much more sensitive to pressure than conventionally believed (Figure 1).

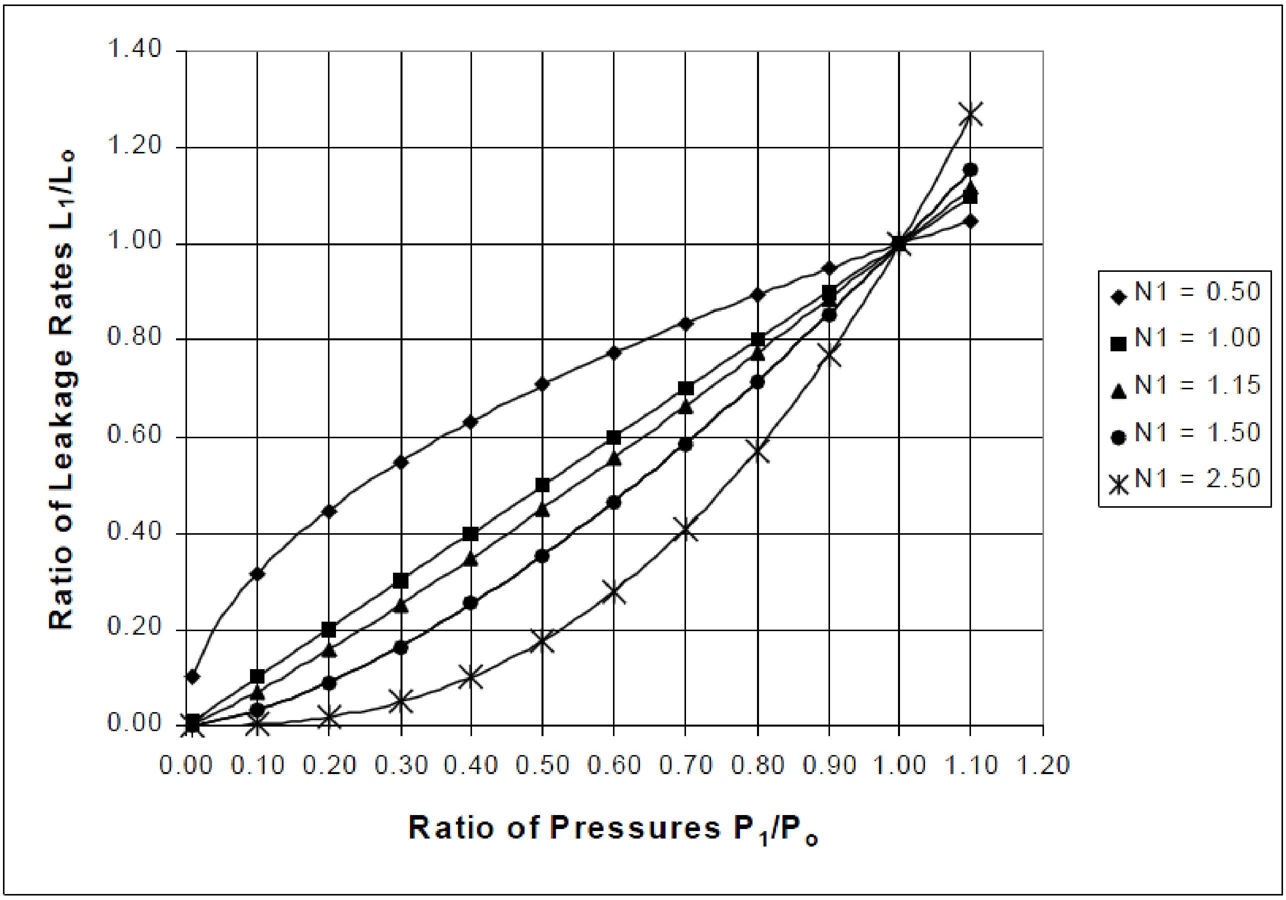

Figure 1. General relationship between pressure and leakage via N1 [7].

Research on the effects of leaks in the systems conducted by Greyvenstain and van Zyl [8] indicate that the leakage exponent depends on the geometry of the crack in the pipe. Table 1 shows that the corroded parts in metal pipes have the highest values of the exponent N1 and that in plastic pipes, N1 generates different values largely depending on the crack geometry [9].

Table 1. Leak exponents obtained by Greyvenstein and van Zyl research [8].

Crack Type	N1 Exponent for Pipe Materials		
	PVC	Asbestos–Cement	Iron
Round hole	0.524	-	0.518
Longitudinal cracks	1.38–1.85	0.79–1.04	-
Circumferential cracks	0.41–0.53	-	-
Corroded hole	-	-	0.67–2.3

Analyzing publications in recent years, it is clear that that there have been significant improvements in understanding how pressure and leakage correlate one to each other [10]. Although much analysis has been conducted on this subject, there are not many on site experiments working with real WDS and real on site pressure management. Some researchers used measured data for computation [11] and application of the scientific hydraulic leakage analysis methods for data interpretation [12–14] or data from water companies such as pump data, pipe burst type, or burst frequency data [8].

Understanding the relationship between pressure and leakage should be based on the results of theoretical, numerical, experimental, and field studies. Prediction of behavior for one real WDS could be modeled and therefore optimized for best-case operation [15–19]. Leakage modeling is one way of predicting pressure/leak dependence and is therefore an approachable way for simulating results for better decision making [20,21].

This paper introduces unique approach in conducting site experiment by real pressure management in WDS. This type of field testing is important, as those tests are hard to conduct due to pressure manipulation during tests, which affects consumers and can lead to disturbance in water distribution. Extensive preparation needs to be undertaken, including hydraulic model simulation of test and checking the condition of the installed equipment, which has been pointed out by other researchers also [22]. The main goal of this paper is to give practical methodology in testing theoretical N1 exponent for specific water pipe material, in this case PVC material. The calculated N1 exponent in this paper, after conducting the field experiment in real WDS, results in N1 = 1.76.

In comparison with other researches on this topic, we can see, for example, results of a pressure–leakage relationship analysis conducted on several pressure management zones in the KwaDabeka Township in KwaZulu-Natal, South Africa, from which is, most significantly for this paper, PMZ DV3197, which calculated N1 was 1.2 with 100% plastic pipes [23]. Plastic pipes seems to be more sensitive in comparison to other viscoelastic materials [24]. Comparing results to values in Table 1, leakage exponents for round holes were close to 0.5, for longitudinal cracks between 0.79 and 1.85, and for circumferential cracks between 0.41 and 0.52 [8]. Other researchers defined the recommended N1 range for PVC pipe material as 0.5 to 1.5 [25].

The innovative approach presented in this article provides a methodology for manipulating the real pressure in the water supply system and determining the real N1 exponent from field measurements compared to theoretical experiments [8,25,26]. Other researchers referenced in this paper who calculated N1 from real measurements [4,23,27] used the MNF difference to calculate N1. The MNF difference depends on field work, including pipeline repair and water loss reduction, which are costly and take time. Some researchers used existing night pressure reduction to calculate N1, which can be considered as more approachable method [28]. In comparison, the field experiment presented in this paper introduces a method to reduce MNF and create a pressure differential by reducing the actual pressure at the pressure reducing valve, which is a less-expensive method to calculate N1 and does not depend on pressure management conducted by water supply company. The calculated N1 value can later be used to make decisions and optimize investments in pipe repairs, water loss programs, etc.

2. Materials and Methods

Flowchart (Figure 2) presents experiment methodology explained in following chapters.

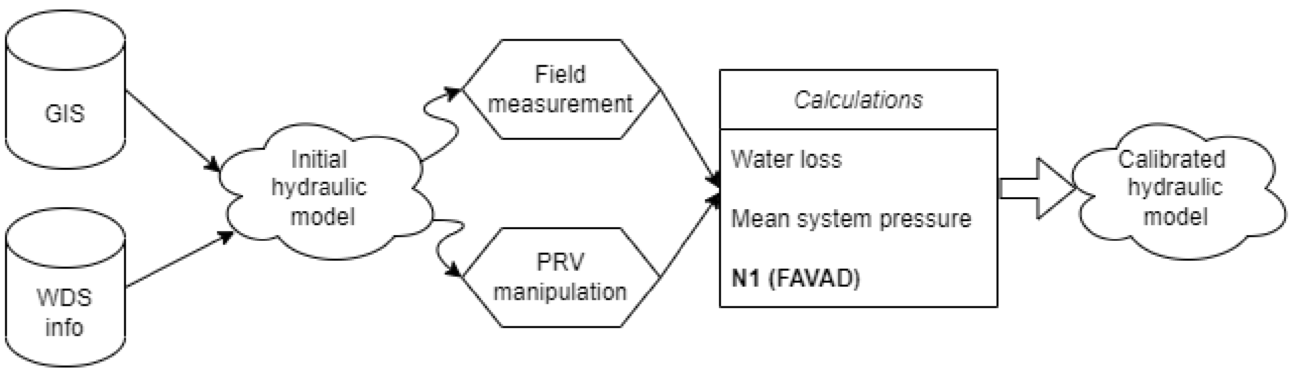

Figure 2. Experiment methodology flowchart.

2.1. Study Area

For this experiment, a step-by-step pressure-reduction methodology on a pressure-reducing valve (PRV) was selected with flow measurement at one location and pressure measurement at two locations.

Field measurements and experiment were conducted in small settlement in Croatia (Figure 3) consisting of 278 service connections and 7.4 km of PVC material pipe network. The water network was built during the years 1980–1985.

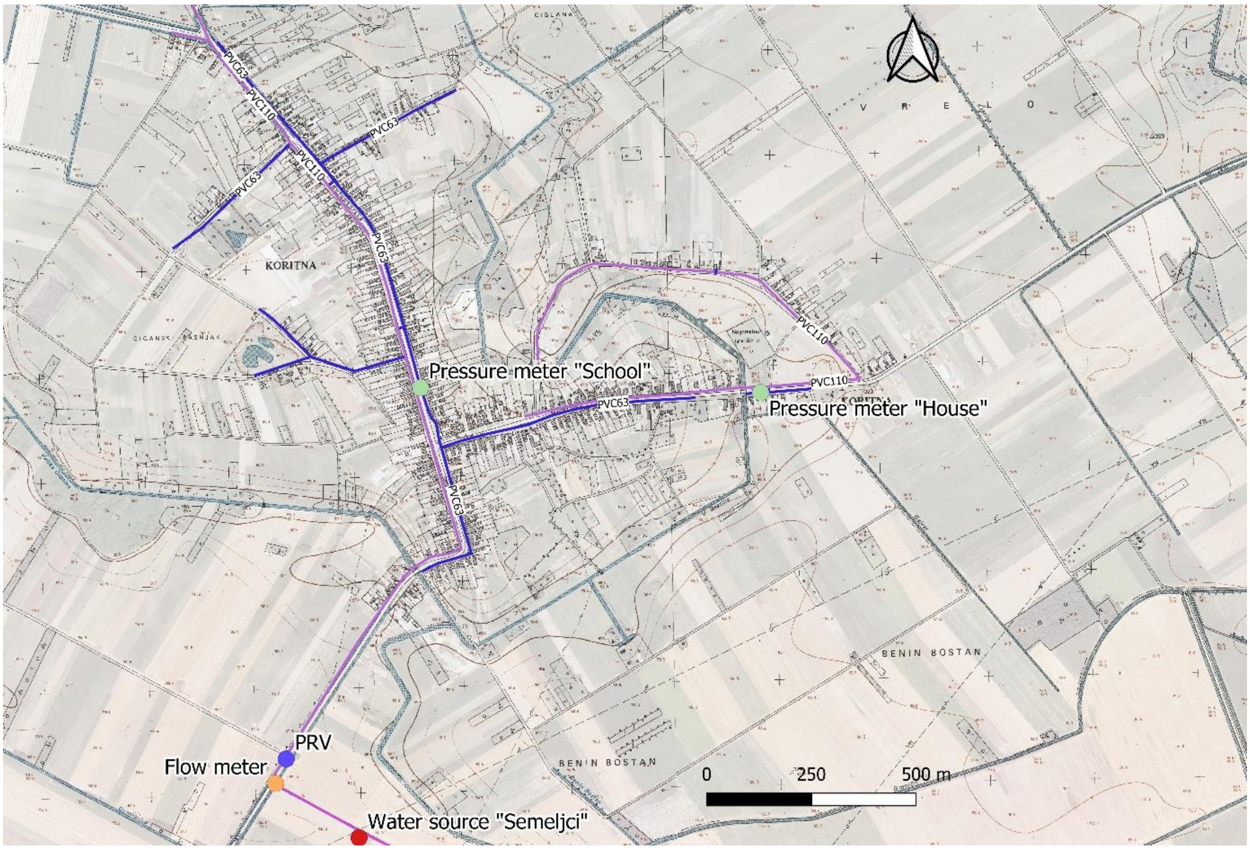

Figure 3. Experiment location.

Flow and pressure measurements were conducted for three consecutive days. Flow measurements were carried out at the location of the outlet pipeline from the water pumping station, while pressure measurements were carried out at the location of the primary school (Pressure 1) and the private residential building (Pressure 2). All flow and pressure measurements were performed at 1 min time intervals. Flow measurement was performed by installing a portable ultrasonic flow meter SebaKMT UDM 200. For the purpose of measuring the pressure, two types of devices were used: Cello and Metrolog. Both devices have a built-in pressure measuring sensor and are connected to the water supply system directly via a flexible pipe.

The purpose of the field measurements was to check the change in MNF based on the pressure change. The pilot-operated-type PRV is located in a concrete shaft downstream of the flow meter.

2.2. Measurements

The initial setting of the PRV is 4.0 bar at the outlet regardless of the inlet pressure. For the purposes of this analysis, the pressure was manually reduced at the outlet according to the schedule in increments of 1.0 bar for two consecutive days (Table 2):

Table 2. Time setting of pressure within the analysis.

Date and Time	Pressure Setting (Bar)
20 December 13:00 h	4.0
21 December 15:00 h	3.0
22 December 15:00 h	2.0

Pressure and flow measurements were used for detailed analysis of minimum night flow (MNF) and pressure relation. Figure 4 shows measured data and MNF trend line with decreasing values, which will be used for real N1 exponent calculation.

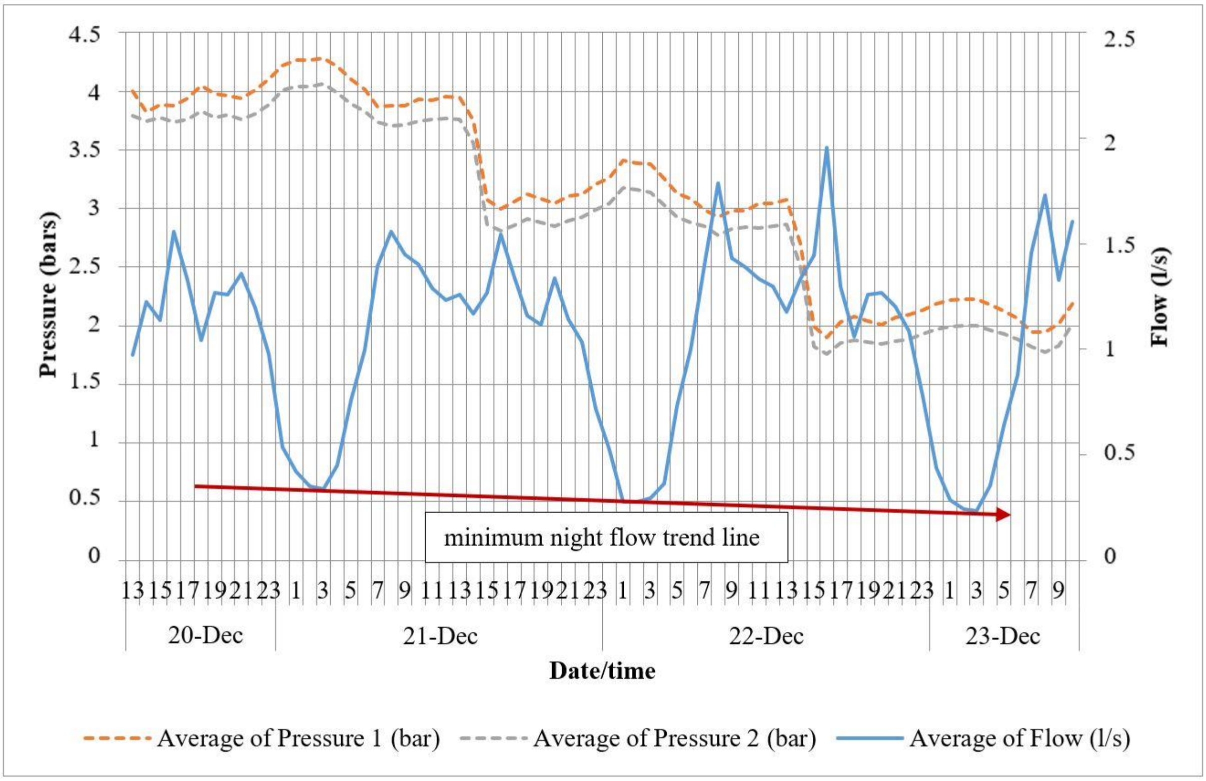

Figure 4. Measured pressure on two locations and measured flow with MNF trend line.

2.3. Formulas and Calculation Methods

2.3.1. Mean Pressure

The mean pressure is calculated according to the principle of the proportion of pressures of each pipeline. In this way, the mean pressure does not depend on the number of points but on the length of the pipeline, with the corresponding inlet and outlet pressure. The calculation is done using the MS Excel program according to the Equation (2):

$$\Delta P_h = \frac{\sum_{n=1}^{i}\left(\frac{P1_n + P2_n}{2}\right)\times L_n}{\sum_{n=1}^{i} L_n} \quad (2)$$

where P_h is hourly average pressure (bar), pipe ordinal number, P1 inlet pressure (bar), P2 outlet pressure (bar), and L pipe length (m).

2.3.2. N1 Exponent

The calculation of the N1 exponent was performed by adaptation of Equation (1):

$$N1 = \log_{\frac{P_1}{P_0}} \frac{L_1}{L_0} \quad (3)$$

The N1 coefficient can also be calculated according to the value of the Infrastructure Leakage Index (ILI). According to [29], ILI is defined as the ratio of the "current annual real losses" (CARL) to the "unavoidable annual real losses" (UARL).

Two Equations (4) and (5) are used for this purpose [30]:

$$\text{Small background leaks} \rightarrow N1 = 1.5 - (1 - 0.65/ILI) \times p/100 \quad (4)$$

$$\text{Large background leaks} \rightarrow N1 = 1.5 - (1 - 0.667 \times ICF/ILI) \times p/100 \quad (5)$$

where p is the proportion of recognizable failures on rigid pipes (%), ICF Infrastructure Condition Factor—ratio of actual background leaks and unavoidable annual real losses (UARL), and ILI Infrastructure Leakage Index.

3. Results and Discussion

3.1. Water Loss Calculation for Measured Dates

Residential night consumption (RNC) was estimated based on number of connection and number of household population [31] (Table 3). Some researches consider different approaches to estimate RNC [32,33].

Table 3. Calculation of water losses for each measured day.

Measurement Day	RNC (A)	Night Flow (B)	Water Loss (C = B − A)
21 December	0.112	0.320	0.209
22 December		0.250	0.139
23 December		0.140	0.029

Note: Flow and water losses units (l/s).

3.2. Calculations of Mean System Pressure

Since the change in the outlet pressure value was performed every day around 15:00, there are no flow and pressure values during one whole day with the same outlet pressure. Therefore, the mean pressures will be calculated according to the actual values for each measured day based on the mean flow over the period of the same outlet pressure.

Implementing Equation (2), the mean pressures for the system were calculated using a reference average daily flow over the period of the same outlet pressure (Table 4):

Table 4. Mean pressure calculation.

PRV Setting Mark	Average Flow (l/s)	Model Time	Mean System Pressure (Bar)	Water Loss (l/s)
PRV1	0.958	7 h	3.9	0.209
PRV2	1.040	23 h	3.1	0.139
PRV3	1.013	43 h	2.0	0.029

Based on the calculated mean pressures and the values of actual losses, the calculation of the N1 exponent of the FAVAD method was performed.

3.3. Calculation of N1 Exponent for FAVAD Method

The task of this research was to experimentally define the N1 exponent on the subject system. Since the pipe material on the subject network is entirely PVC, this paper can also serve as a reference in future analyses of systems with built-in PVC pipes. The calculation of the N1 exponent was performed using Equation (3).

Table 5 below shows the results obtained for the subject system.

Table 5. Calculation of the N1 exponent.

Variable	Value
L1	0.139
L0	0.209
P1	31.5
P0	39.7
N1	**1.76**

According to the instructions in the literature and using Equations (4) and (5), if only PCV pipes are on the system, the factor p = 0%, which in both equations gives the value N1 = 1.5.

Checking the value of the N1 exponent on the graph (Figure 1) shows the value of N1 between 1.5 and 2.0, which corresponds to the value from the experiment.

3.4. Hydraulic Model of Subject WDS

Confirmation of the accuracy of the applied method is visible in the resulting values of MNF calculated in hydraulic model. Daily consumption is not a quality indicator because the value of hourly coefficients from the first measured day were used for all days. Figure 5 shows WDS nodes and pipe structure with inner pipe diameter.

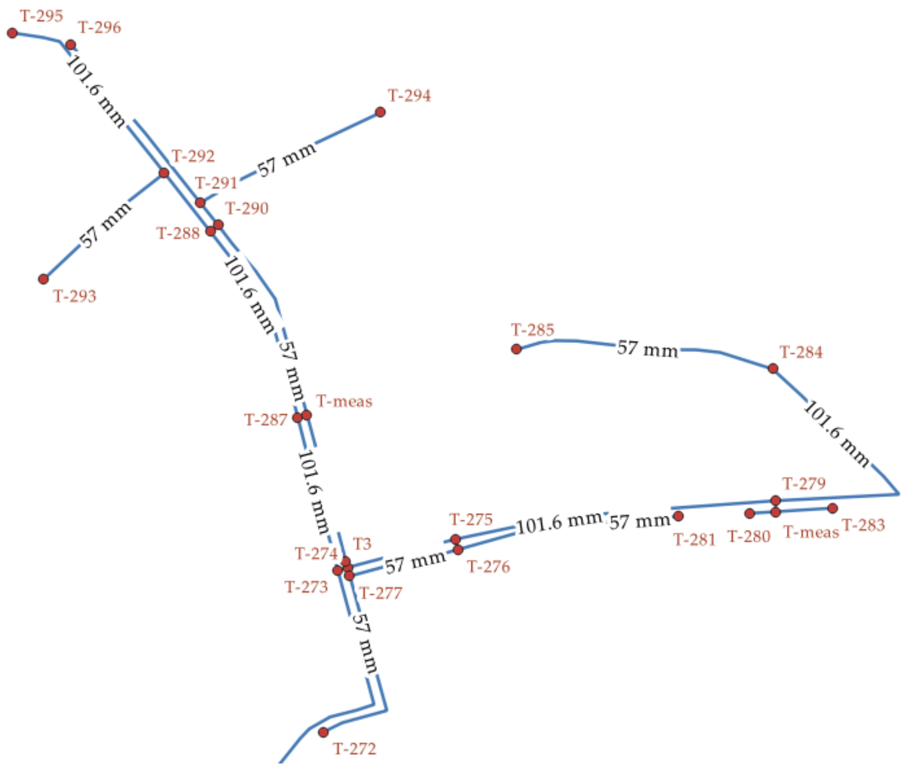

Figure 5. Hydraulic model structure overview with hydraulic pipe diameter.

Hydraulic model analysis was conducted for all PRV output pressure settings (Table 2). Figure 6 shows maximal calculated pressures, while the graph (Figure 7) shows resulting flows with trend line.

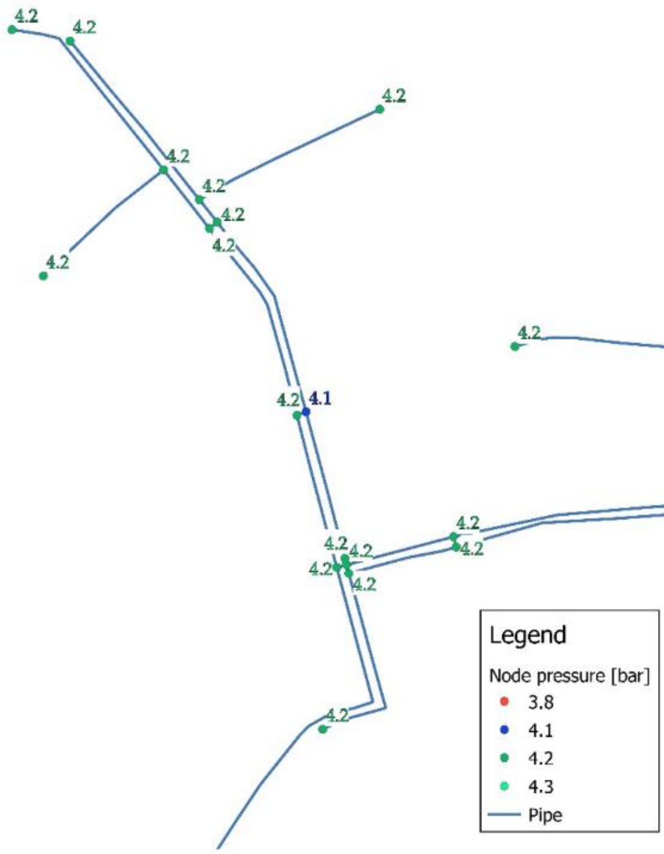

Figure 6. Hydraulic model maximal pressures in every node.

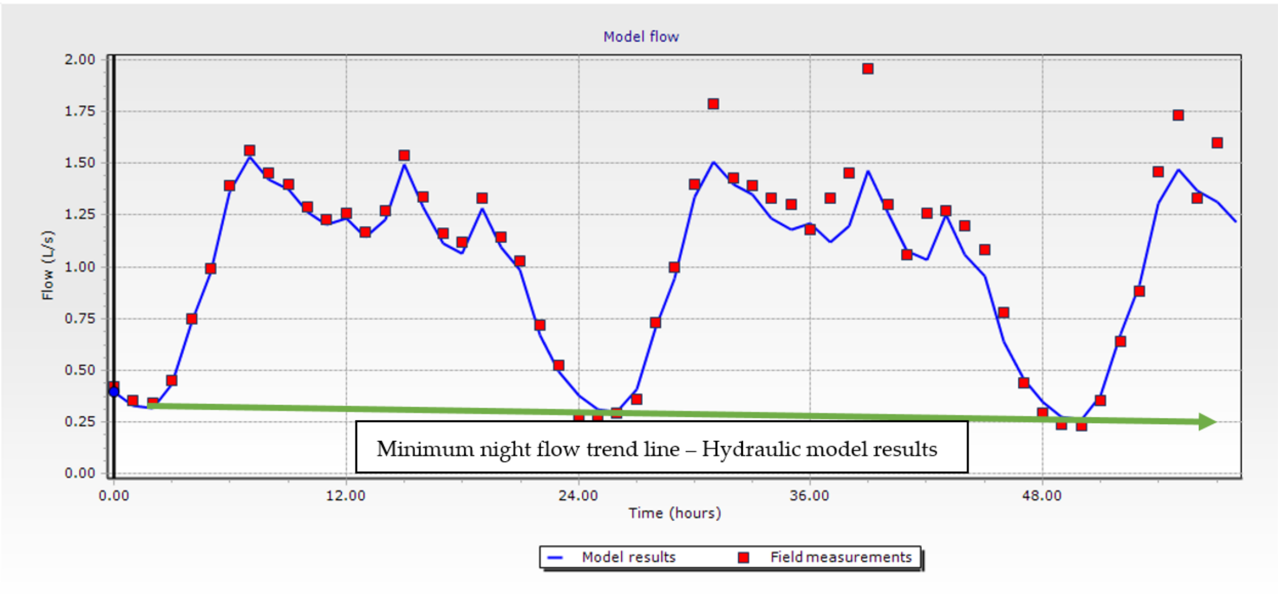

Figure 7. The resulting MNF trend line using hydraulic model calculation (blue line represents theoretical flow derived from hydraulic model, while red points represent measured values).

The calculated MNF using the hydraulic model for subject WDS shows significant matches with average difference in MNF of 0.01 l/s or 4% compared to measured data.

The FAVAD leakage model accounts more accurately for the behavior of leaks in practice [10], and using the hydraulic model tool for MNF identification in WDS proves that the approach is effective in calculating pressure/leakage relationship in real networks, but the results depend on the quality of the observed data, as confirmed in this paper [34], with several practical approaches available besides the one presented in this paper [35].

3.5. Result Comparison

The field experiment was conducted in KwaDabeka township in KwaZulu-Natal, South Africa, from which the most significant location for this paper is PMZ DV3197, where the calculated N1 was 1.2 with 100% plastic pipes [16] compared to N1 = 1.76 in this paper for PVC pipes. Minimum night flow (MNF) for this paper was 0.1–0.3 l/s, while KwaDabeka PMZ DV3197 MNF was 0.4–0.9 l/s. Both results are comparable to theoretical N1 margin, as it depends on type of pipe cracks (Table 1).

Comparing the obtained result of N1 = 1.76 for PVC pipes in the conducted experiment to theoretical ones, there are several different theoretical approaches and results (Table 6):

Table 6. Comparison of obtained N1 exponent by shown experiment to different theoretical values.

Author	Theoretical N1 Value	Experimental N1 Value
Greyvenstein and van Zyl's research [8]	Longitudinal cracks 1.38–1.85	1.76
Lambert, A. [19]	For flexible pipes 1.5	
Van Zyl, J.E [6]	0.5–2.79	

4. Conclusions

The aim of this experiment was to establish a field validation methodology for the theoretical N1 exponent of the FAVAD method. By knowing the pipe material and measuring the minimum night flow (MNF) and the pressure in the system, the N1 exponent can be defined and compared with the literature recommendations given in this paper. Field experiment was conducted in real WDS constructed of PVC water pipes, which enabled precise comparison between measured and theoretical N1 exponent. To be able to conduct this experiment, extensive pressure management was implemented by manipulating real PRV. By changing output pressure values, changes in MNF were expected.

For better understanding of WDS network behavior during pressure management, a detailed and calibrated hydraulic model was designed. Comparing results of MNF after pressure management in the hydraulic model to the ones measured on site, a 4% difference was noticed, which can lead to the conclusion that the N1 exponent validation methodology shown in this paper is valid and can be used for further researches.

In comparison to other authors, the field experiment for determination of N1 in this experiment and also in experiments of other researchers are both comparable to theoretical N1 margin. The obtained result of N1 = 1.76 for PVC pipes in the conducted experiment compared to theoretical ones falls in expected range (Table 6).

Finally, pressure management shows significant results in leakage or real losses reduction, as is confirmed in this research. Implementing pressure management areas (PMA) and pressure management zones (PMZ) with measuring flow and pressure, including real losses calculation for district metering areas (DMA), is confirmed to be an affordable first step in leakage control. The methodology from this paper can be used to predict many consequences regarding real water supply network operation: maintenance operations where the field engineer could use this methodology to provide better understanding of network behavior during branch closures for maintenance works; equipment optimization regarding PRV and pumping stations; and water quality maintenance, for example, pressure drop during pipe flushing. Decision makers could use pressure/water loss correlation principles to determine and optimize investment priorities with quantified values of leak reduction due to pressure manipulation and also prediction of pressure dependent demands during pressure optimization.

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