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Distribution system water loss in a selected urban part of Bangladesh: Numerical modeling

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Abstract

Based on an intensive field investigation on the Khulshi area in Chittagong city, in this study US Environmental Protection Agency (US EPA)'s EPANET was used to model pipe leakage. A detailed simulation was carried out to feature the demand and pressure in the EPANET network consisting of 19 nodes with 23 connecting pipes using spatial data and base demand. The simulation duration was 24 hours, following the time pattern, and reported that the pressure increases with the decrease of water demand. Considering the simulated water demand and pressure model could suggest water loss, which may affect the leakage, the model could offer the potential leakage area. The model showed reasonable responses against field observation also. In the maintenance and operation of a WDS, this is expected that the model could provide valuable guidance about leakage location to the decision support system, which is time and cost-effective.

Keywords: Non-revenue water (NRWs), water distribution systems (WDS), EPANET, leakage.

1. Introduction

Compared to the continuous online operation and monitoring service in developed cities, the developing cities lack information on previously performed operation and maintenance activities. Developed countries already adopted water audits to determine the efficiency of a Water Distribution System (WDS) and identify the location and magnitude of water losses. Developing cities need input database or GIS-based information systems to enable flow analysis in the Water Distribution Networks (WDNs) and provide early warnings on leakage. Some cities from developing countries already introduced a GIS-based information system, while others are still working with the conventional methods for collecting, storing, processing, and retrieving information systems. Not only cost-effective, but also GIS can work with old data as well as stored digital data. Modeling of urban networks and intermittent water supply systems is often challenging due to (i) WDSs are not fully pressurized pipeline networks, and external pressures persist within the WDNs, (ii) limited water supply hours per day, and (iii) with numbers of overhead tank connections. Along with these, the alternate emptying and refilling of water pipelines pose difficulty while applying standard EPANET based hydraulic models. Since 1936, the Hydraulic analysis of flows and pressures in a WDS has been a standard form of engineering analysis by Hardy Cross. Since the mid-1960s, WDS computer models have been practicing and capable of simulating large distribution systems (Walski et al. 2001). The ability to model water utility and water age has also been incorporated with the hydraulic models (Clark and Grayman, 1998). EPANET, developed by USEPA, is an open-structured, public domain hydraulic and water quality model (Rossman, 2000). This is expected GIS extracted information, and EPANET model setup could provide an initial idea on the pressure distribution network and provide detail on leakage in a WDS.

Modeling WDN is the prime concern to evaluate the current hydraulic and water quality condition of a WDS towards analyzing future scenarios for planning and design. Generally, numerical models predict water pressure, flow, and water quality parameters within a WDS to evaluate structure and performance. Usually, these models are based on a set of energy, continuity, transport, or optimization equations engaged in estimating pressure, flow, and water quality parameters (AWWA, 1987). Apart from the user-designed computer programs, viz., Artificial Neural Networks (ANNs), Open Database Connectivity (ODC), GIS, there are also commercially available models exist namely AQUIS, Stoner SynerGEE, WaterCAD, H2ONET, KYPIPE, Customer Information System (CIS) and so. Advancement in the commercially available software with advanced graphical interfaces and GIS tools contributed to an advanced database management system (Islam and Babel, 2013; Makaya and Hensel, 2015). Different researchers have described techniques for pressure reduction as a conditional parameter to identify leakage in a WDS in the last two decades (Jowitt and Xu 1990; Alonso et al., 2000; Vitkovsky et al., 2000). Few models were developed to locate valves in WDS (Reis et al. 1997), and some deal with valve operation incomplete open or closed positions. The TOOLKIT developed by Rossman (2000) for the EPANET calculations is usually made automatically; this TOOLKIT allows the creation of external programs to manage the process of measures. Therefore, it is beneficial for calibration.

Araujo et al. (2006) worked with two operational models i.e., EPANET and Genetic Algorithm technique. Leaks were modeled in EPANET as an orifice by pressure-dependent function for effective optimization of leakage levels through allowing optimized number and location of control valves, along with their opening adjustments (Table 2.2; Greyvenstein and Zyl 2005; Araujo et al., 2006). Thus, leakage also studied considering as orifice.

EPANET engaged in tracking the water flow in each pipe, the pressure at each node, the water height in each tank, and the chemical species concentration throughout the WDN during a simulation period. According to Koppel and Vassiljev (2009), all models of WDS need calibration with pipe roughness, pipe diameter, and demand. Roughness also varies for comparatively pipe age, pipe material, water quality in WDS, and associated factors (Koppel and Vassiljev 2009). WDS model calibration relies upon field measurements, for instance, junction pressures, pipe flows, etc. (Koppel and Vassiljev 2009). Lijuan et al. (2012) detected leakage using EPANET and genetic algorithm optimization by correlating changes in flow characteristics within a hydraulic model for the studied network. For leak detection through pressure control, parameters of a different type, number, and location of valves were used by Araujo et al. (2006). Thus, the roughness, number, and location of valves, the coefficient of head loss for economic and technically viable, were considered during optimization model studies (Araujo et al., 2006). Mashford et al. (2009) modeled leakage using EPANET following the Torricelli equation, and the generated data were engaged to form a training set of Support Vector Machine (SVM). Node pressure, flow rate, temperature were considered for leakage detection (Mashford et al., 2009) (Table 1).

Table 1
Leakage detection in literature

Author	Leakage Study	Method	Outcome	Limitation
Araujo et al. (2006)	pressure control	experiment with valve genetic algorithm and EPANET	pressure control through valves and leakage reduction by genetic algorithm optimization method. EPANET is used as a hydraulic solver to define the location and optimum numbers of valves to simulate the network.	Simulation of the network made 24-hour period with 1-hour interval. A more significant number of valves produce the best solution.
Arsene et al. (2012)	simulation of leakage based on the loop corrective flows equation	numerical Model, GFMMNN (General Fuzzy Min-Max Neural Network) graph-theory	the simulator algorithm was based on the loop corrective flow algorithm defined for a WDS within nodes, loops, and pipes.	24-hour operational period. The additional demand was not modeled as a pressure-dependent variable and thus can be set to any desired value.
Bremond et al. (2009)	pressure-dependent leakage	Navier- Stokes equation PDE numerical model	leakage could vary the flow rate nonlinearly with the pressure. more prominent leakage exponents increase the flow rate while a larger volume of water demand persists higher leakage levels correspond to the smaller heads within the pipes.	In numerical calculation, all physical time and space phenomena should take into account. The timestep needs to be lower than 1000.
Goulet et al. (2013)	physical properties of leaks	sensor placement, leak scenario or model falsification	detectability was expected for leaks of 50 liters/min or more. Additional pipes are needed to detect more negligible leak levels. to identify leaks, the flow was monitored during low water consumption.	the methodology was tested on single location leaks uncertainties expected from consumption and model simplifications
Mashford et al. (2009)	leak detection by pressure monitoring	SVM EPANET ANN	EPANET is used to generate data required to form a training set of SVM. SVM can be used for regression or classification.	EPANET sensitivity failed to register the slight difference in pressure.
Koppel and Vassiljev (2009)	calibration of the model on different aged pipe	EPANET LMA (Levenberg-Marquardt Algorithm) PDE	to overcome the difficulties in the calibration of pipe roughness of the WDS of additional aging pipe, EPANET was used for calibrating Darcy Weisbach and Hazen Williams formula. The approximation of the dependence of pipe roughness on age found easier for the fewer parameters than the group pipes	to calibrate a large number of pipes, there were only a few measurements available. LMA had failed because of the oscillation of (Objective Function).
Lijuan et al. (2012)	pressure, model-based test work	EPANET genetic algorithm	leakage could be detected by correlating changes in flow characteristics in a hydraulic model for the WDN. A model-based leak detection method was performed using EPANET and optimized by the genetic algorithm.	If the leakage amounts increased considerably, then leakage may not be detected and estimated.
Poulakis et al. (2003)	leakage flow	mathematical hydraulic models	leakage locating and computing its severity for single and multiple leakages	the model might not identify the damage if any model error and noises persist
Silva et al. (2011)	pressure, hydraulic characteristic	SVM EPANET transient flow through orifice plates	EPANET used to simulate data and SVM analyzing in detecting leaks to 90 liters/hr to find out leaks provide a novel technique on leak locations finder. Identifying the effectiveness of SVM methods using flow rates and depends upon the accuracy of EPANET simulation.	SVM leak detection technique is unlikely in a successful application. Background effects should be minimized, which cannot be guaranteed to eliminate during measurement.

WDS safe water supply is the most priority, and thus the pipe leakage is attracting issue for water industries, governments, and research institutes. Numerical model analysis, detection, modeling of pipe leakage for a WDS system are essential issues considering the drinking risk, waste of quality water, risk of contamination, etc. Institutional attention to pipe leakage is also increasing. Thus:

- the model used to perform WDN simulation while designing and planning, and therefore can improve hydraulic system performances;
- to simplify the process of building WDN models, a visual network editor can be provided and to edit their properties, i.e., pipe, pump, and valve placement and sizing, flow analysis, operator training, etc.; and
- model is suitable for small pipe leakage considering flow and pressure generated by leakage.

Loss of water due to leakage was reported globally as 30 to 40% for the drinking water supply systems (Lambert, 2002; Araujo et al., 2006). Leak detection depends on performances ranging from simple visual observation to more sophisticated instruments, equipment, and methodologies. Sophisticated devices include acoustic, sensor tube, tracer compound techniques. Transient flow simulations with real-time at pipe inlet and outlet were developed for a single pipeline by (Liggett and Chen, 1994) (1994) and later on practiced for leak detection (Silva et al., 1996). To analyze hydraulic transients caused by leaks, Silva et al.(1996) engaged an online computer-based program for transducer data reading and displaying transient plots for location identification. For leakage identification in a water pipe network, a Bayesian system was introduced by Poulakis et al. (2003); based on flow data, this system is supposed to estimate the most probable leakage events (magnitude and location of leakage) as well as the inherent uncertainties during the estimate. Although Partial Differential Equations (PDE) are rarely used to model leakage, Bremond et al. (2009) studied pressure-dependent leakage along with Navier–Stokes equation in a water distribution system. Using a Frequency Response Diagram (FRD) based numerical study, multiple leak locations were detected by Lee et al. (2005). Based on the loop corrective flows equation leakage, Arsene et al. (2012) modeled it as an additional demand in-between the two end nodes of a pipe using a numerical model.
The NRW measures losses over a period as the difference between the amount of water put into a system and the metered or estimated quantity of water taken by consumers, while Minimum Night Flow (MNF) is an indicator of the probable rate of losses for a given time. To identify the existence of unreported leaks and bursts, MNF measured in moderately sized sectors (up to around 3000 service connections) is very useful. However, continuous night flows can also engage for annual average actual losses assessment (Farley and Trow, 2003). However, in dense urban areas with more blocks of flats and large storages, those might fill in at night. Nevertheless, the MNF is a direct indicator of parts of a system (Twort et al., 1994). On the other hand, fully metered situations consider that the annual water balance can only be taken as a guide as the calculations are susceptible to errors; analyses show this uncertainty in the calculated annual losses to be even +/- 46% (Lambert and Wallace, 1993).

The total water demands often exceed available production capacity due to the studied distribution network’s water losses and associated factors. Pressure regulations are constantly introduced to minimize losses and provide an equitable distribution of public water supplies. In this context, a numerical details understanding is urgent, and specifically, a numerical model can provide relevant information. The objective of this modeling was to develop a simplified model, and node demand is dependent on the pressure at the junction nodes to reduce the water loss and maximize the flow rate at the users’ end.

2. EPANET

The USEPA developed software, standalone program EPANET (Rossman 2000), has been widely used by the modelers for its available source code. EPANET performs an extended period simulation of hydraulic and water quality features within a pressurized pipe network consisting of pipes, nodes or junctions, pumps, valves, and storage tanks or reservoirs. The model computes junction heads and link flows for a fixed set of reservoir levels, tank levels, and water demands over a succession of points in time (Rossman, 2000). Figure 1 illustrates a node-link representation of a simple water distribution network.

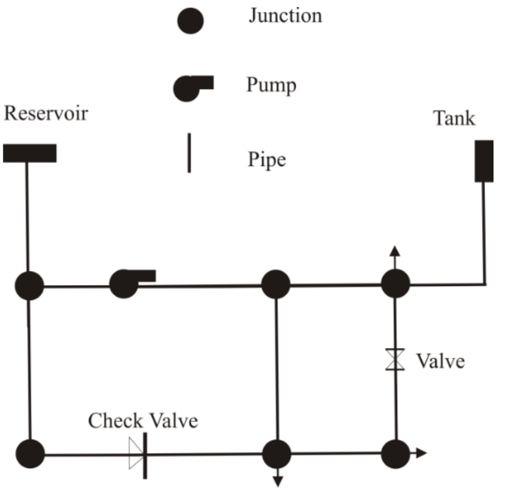

Fig. 1. Node-link representation of a water distribution network.

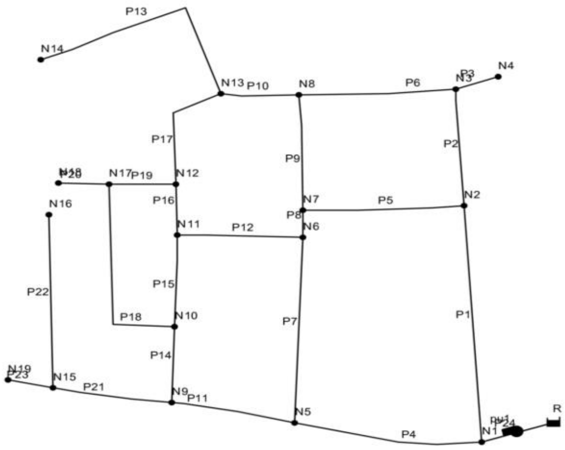

Fig. 2. Model setup for the sub-system.

EPANET can model pipe networks, nodes, reservoirs, and tracks of water flow in each pipe and the pressure at each node simulation (Rossman, 2000). Intermittent flow is the most critical condition to deal. EPANET assumes a constant pressurized system, with instantaneously full pipes at the start of distribution. Thus, relatively significant discrepancies might arise between the model and the actual dynamics of the system. Some of the vital hydraulic capabilities of EPANET while working with a wide range of WDN includes sizes time-varying demand or controls (e.g., opening and closing valves), simulating a pressure-driven node using the concept of emitter coefficient, handling multiple head-loss equations, and pump operation control (e.g., based on tank water levels) (Rossman, 2000). The program warns while changes in the system persist, such as negative pressure occurrences in the system. In this study, the water demand was not influenced by diurnal variations of order but by the maximum water collected during supply hours. This was dependent only on the available pressure heads in the network. Thus, water passing within a loop can be accounted for and used to solve flow-related issues for a model.

The two fundamental concepts of distribution network hydraulics are conservation of mass and energy. In a loop, mass continuity equation:

$$\Sigma Q_{in} - \Sigma Q_{out} = Q_e \tag{1}$$

Where,
$Q_{in}$is the inflow, Q_{out} is the outflow, and Q_e is the external flow into or out of the system at each node. Energy conservation is written as:

$$\Delta E = \Sigma h_L - \Sigma E_p \tag{2}$$

Here,
ΔE is the difference in energy grade, and h_L is losses considering pipe length, diameter, roughness, minor losses, and the pump head. Node equations expand the mass continuity equations to express discharge in terms of the head difference between nodes a and b (H_a-H_b) and resistance of the pipeline (K_{ab}):

$$Q_{ab} = \left[\frac{H_a - H_b}{K_{ab}}\right]^{1/n} \quad (3)$$

Here, n was selected based on the head loss equation (Viessman and Hammer, 1998).

The single path adjustment method by Hardy-Cross is best known for solving loop equations. A grade was assumed for each junction node, followed by computation of a grade adjustment factor to satisfy continuity. In a distribution system, leakage is relatively insensitive to pressure, and considering as orifice, the equation is:

$$q = \mathrm{C}d\ A\sqrt{2gH} \quad (3)$$

Where q is the leakage flow rate, C_d the discharge coefficient, A the orifice area, g acceleration due to gravity, and H the pressure head. The general form of this equation is:

$$q = CH^{\alpha} \quad (4)$$

Where C is the leakage coefficient, and α is the leakage exponent. α varies between 0.5 and 2.79 (Greyvenstein and Zyl, 2006). The leakage exponent also expresses the pipe material and the crack criteria. They consider the pipe network and materials of the study area the leakage exponent as 0.52 and within 0.78-1.04 respectively for PVC and AC. Leakage behavior is identified in specific ways considering the pipe materials. Pipe made with lower strength material may cause leakage while taking water pressure stressing in the pipe wall, linked with the internal pressure of the pipeline.

3. Model setup

Throughout the process in EPANET, surveyed pipe lengths were verified against computed distances to make sure the field lengths were correctly recorded from the spatial data of the Khulshi road network. Besides, direct measurements for slope were taken into account, whereas the length feature only provides the planar distance between two points. A roughness of 150 was selected for the PVC pipes. The pipes were reasonably new, but considering the stagnation periods due to the system’s intermittent nature, build-up would rise roughness. Minor losses are included within lines, not at the tee or elbow junctions. There were 19 nodes marked on the pipe network based on their pipe direction observed during the field survey (Table 2, Figure 2). The base demand was calculated based on the average demand record during the field survey (Table 3).

Table 2
Data collection details

Parameters	Unit	Details	Data source
Road	feet	Spatial data	CDA, 2006
Roughness co-efficient		Value for Hazen-Williams equation (Table 2.3)	Rossman, 2000
Pipe network	feet	Spatial data	PANI, 2011
Base demand	gpm	Table 4.2 Multiplier	Field Survey (Chapter 3)

Table 3
Base demand details

Node ID.	Connecting pipes ID.	Base demand	
		gpm	m^3/s
N1	P1, P4, P24	16.35	0.00103
N2	P1, P5, P2	3.18	0.00020
N3	P2, P3, P6	4.74	0.00030
N4	P3	7.89	0.00050
N5	P4, P7, P11	5.46	0.00034
N6	P7, P8, P12	2.44	0.00015
N7	P5, P8, P9	3.28	0.00021
N8	P6, P9, P10	4.14	0.00026
N9	P11, P14, P21	1.93	0.00012
N10	P14, P15, P18	3.35	0.00021
N11	P12, P15, P16	2.78	0.00018
N12	P16, P17, P19	3.04	0.00019
N13	P10, P13, P17	5.93	0.00037
N14	P13	3.10	0.00020
N15	P21, P22, P23	2.27	0.00014
N16	P22	3.34	0.00021
N17	P20, P21, P22	3.43	0.00022
N18	P20	3.88	0.00024
N19	P23	0	0.00000

Note: 1 m^3/s = 15850.37 US gpm

Table 4
Details on simulated flow and velocity of water in the pipe

Node ID.	Off-Peak Hour		Peak Hour	
	Flow (gpm)	Velocity (fps)	Flow (gpm)	Velocity (fps)
P1	2.80	0.07	20.98	0.55
P2	1.91	0.05	14.32	0.38
P3	1.58	0.04	11.84	0.31
P4	10.04	0.01	75.29	0.06
P5	0.25	0.01	1.90	0.05
P6	-0.62	0.02	-4.63	0.12
P7	3.07	0.08	23.04	0.61
P8	2.14	0.06	16.06	0.42
P9	1.74	0.05	13.04	0.34
P10	0.29	0.01	2.20	0.06
P11	5.87	0.02	44.06	0.13
P12	0.44	0.01	3.32	0.09
P13	0.62	0.02	4.65	0.12
P14	4.37	0.12	32.75	0.86
P15	2.00	0.05	15.03	0.40
P16	1.89	0.05	14.17	0.37
P17	1.51	0.04	11.35	0.30
P18	1.69	0.04	12.70	0.33
P19	-0.23	0.01	-1.73	0.05
P20	0.78	0.02	5.82	0.15
P21	1.12	0.00	8.42	0.02
P22	0.67	0.02	5.01	0.13
P23	0.00	0.00	0.00	0.00

Note: 1 m^3/day = 0.18 US gpm, 1 fps = 0.3048 m/s.

The properties and hydraulics set up on the model were assigned the status of the control valve, guiding water flow only in the direction of their first to their second node. This setting could avoid backward flow from the reservoirs comprised of inlets discharge above surface water or emitter taps which could become sources in the absence of flow.

3.1 Input parameters

Under hydraulic options, the Hazen-Williams equation was used to find head loss. For laboratory temperature 25°C, the specific gravity of water was set to 1 and a relative viscosity of 1. The emitter coefficient is 0.52, and the bulk reaction coefficient is 0 (Rossman, 2000). The hydraulic accuracy represents the threshold ratio of the variation in total flow from one loop to the next. If this ratio is under the specified accuracy, iterations in the model are terminated. For this study, the maximum iteration value was 40. A lower value for this accuracy would give more accurate results. For simulation purposes, 0.001 accuracy value is suggested by Rossman (2000). A lower accuracy would also increase the model solution time and slow down the model from converging on a solution.

This represents a reasonable accuracy while the magnitude of error is considered in the surveyed elevations. Quality tolerance is another critical parameter.

Table 5
Details on simulated pressure and demand at node

Node ID.	Off Peak Hour		Peak Hour	
	Demand (gpm)	Pressure (psi)	Demand (gpm)	Pressure (psi)
N1	3.27	5.56	24.52	5.56
N2	0.64	7.72	4.77	7.50
N3	0.95	9.41	7.11	9.14
N4	1.58	9.15	11.84	8.87
N5	1.09	7.37	8.19	7.36
N6	0.49	9.63	3.66	9.42
N7	0.66	9.45	4.92	9.24
N8	0.83	9.28	6.21	9.02
N9	0.39	8.51	2.89	8.50
N10	0.67	9.33	5.03	9.16
N11	0.56	10.37	4.17	10.16
N12	0.61	9.63	4.56	9.40
N13	1.19	8.89	8.89	8.63
N14	0.62	16.47	4.65	16.2
N15	0.69	9.28	5.14	9.05
N16	0.78	8.89	5.82	8.66
N17	0.45	10.02	3.4	10.02
N18	0.67	9.07	5.01	9.05
N19	0.00	9.89	0.00	9.89

Note: 1 m^3/day = 0.18 US gpm, 1 bar = 14.5 psi, 1 psi = 6894.757Pa (N/m^2)

Besides hydraulic setup, time characteristics needed to be set up to use EPANET properly. Other parameters include the hydraulic time steps as well as time pattern and reporting time steps.

The duration of these time increments is engaged to determine the time resolution for analysis, control setting, and reporting. This time pattern makes the network simulation more realistic by analyzing water flow, pressure, demand, etc., at different periods in a day (Rossman, 2000). In this time pattern, a scenario is generated by multiplying a factor with minimal demand of respective hours in a day. Based on these, the water loss analysis was carried out considering the leakage and pressure relationship. In this model, most of the nodes are containing less pressure than the previous.

3.2 Model simulation

The model simulation was done 24 hours by providing fixed base demand (as described in section 3.1). Data generated from the simulation in EPANET for pipe flow and velocity of water (Table 4, Figure 3) and corresponding pressures in nodes are presented (Table 5 and Figure 3).

The negative value means the opposite direction of the assumed flow direction, shown for P6 and P19. The maximum flow was observed for pipe P4 due to more diameters and the nearest pipe from the start point and P11. Based on the consumer demands in the Khulshi area and the general demand patterns, the acquired flow and pressures are presented in peak hours (7-9 am, 12 am-1 pm, and 8-10 pm), and the rest are considered as off-peak hours.

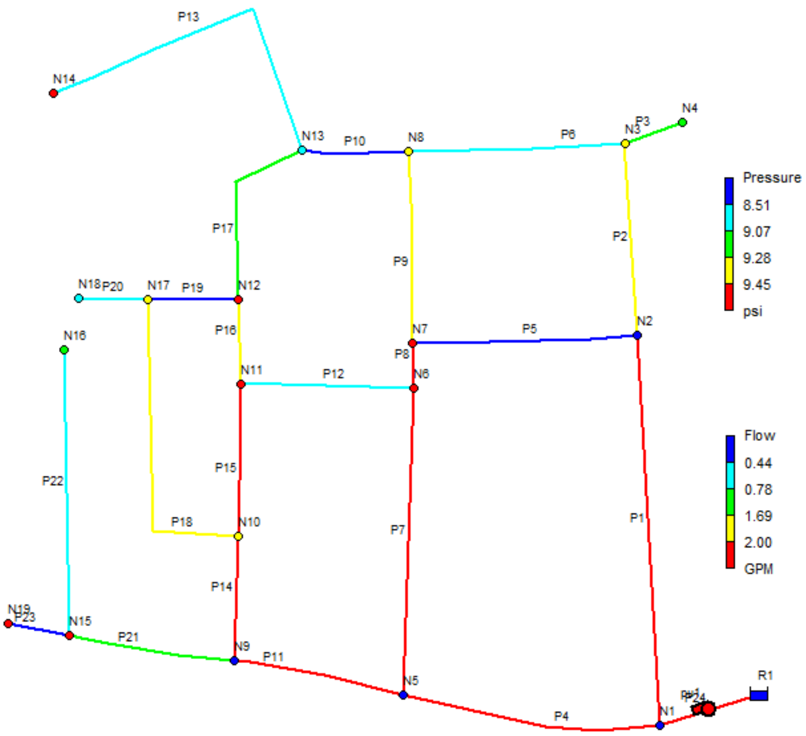

Fig. 3. Illustration of predicted pressure and flows using the EPANET graphical interface.

EPANET could reasonably present pressures, demand at different nodes, flows, velocities, and head loss in pipes throughout the distribution period. Results are then exported to tables and graphics or visualized on the graphical interface, as illustrated in Figure 3. A node N14 showed comparatively more pressure due to its existence in a low-lying area and contained fewer consumers. For demand at N1 at peak hours, it showed higher quantity because of having relatively more consumers.

4. Model outcome

4.1 Pressure

EPANET extrapolates the pressure distribution to areas without pipes ID. It should be noted that the pressure distribution is not the only illustration of pressures at end users' taps but also the pressure at all different nodes in the WDS. Extremes, low and high pressures exist throughout the system mainly due to the topography and the elevation of the WDS. The pressure is only necessary as it ensures the flow to provide water to the sub-system consumers.

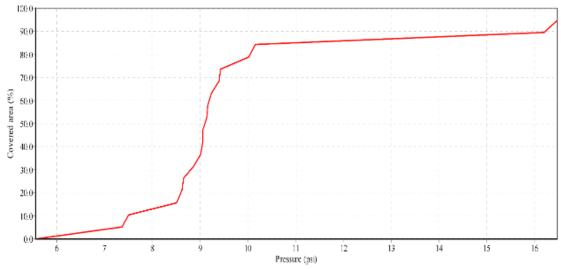

Fig. 4. Numerical distribution of pressure in sub-system (peak hours).

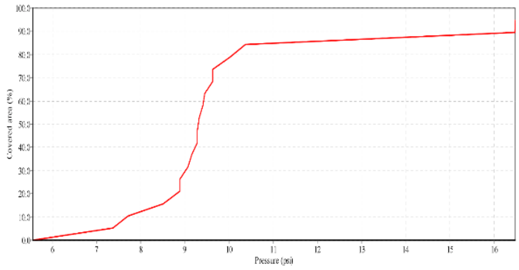

Fig. 5. Numerical distribution of pressure in sub-system (off-peak hours).

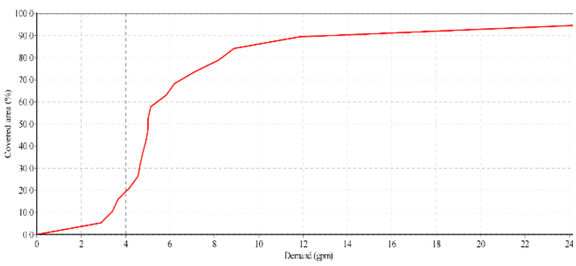

Fig. 6. Numerical distribution of demand in sub-system (peak hours).

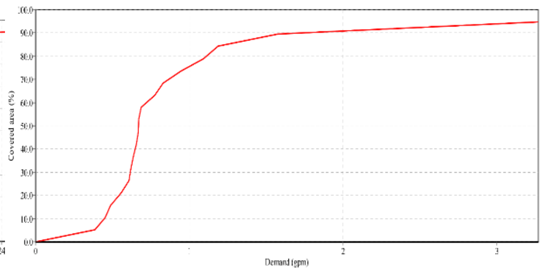

Fig. 7. Numerical distribution of demand in sub-system (off-peak hours).

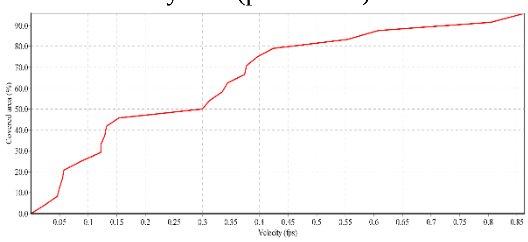

Fig. 8. Numerical distribution of velocity at peak hours in sub-system.

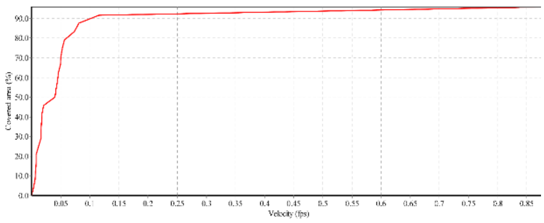

Fig. 9. Numerical distribution of velocity at off-peak hours in sub-system.

The simulated model showed for peak hours that about 12% area of the distribution network covered below 8 psi, likely 28% is between 8-9 psi, more than 40 % area covered between 9-10 psi and rest area covered different value up to about 16.5 psi (Figure 4). On the other hand, for off-peak hour pressure distribution for the study network likely the same but here 10% less area covered by 8-9 psi and about 10% more area covered by 9-10 psi than the peak hours (Figure 5). Unfortunately, there are no pressure records for this system with the service provider. The average pressure for this area is supposed to be 5 - 8 psi through communication with PANI project personnel. Thus, this simulation showed a reasonable response against field values.

4.2 Demand

Numerical distribution of demand throughout the Khulshi sub-system area showed that water demand at peak hour more than 80% area of the distribution network covered by 4gpm and more up to about 24 gpm and about 70% area covered 4-12 gpm (Figure 6). On the other hand, the distribution of demand for the study network in the off-peak hour was not more than 4 gpm, and about 75% covered below 1 gpm (Figure 7).

4.3 Velocity distribution

Velocity at peak hours showed about 30% distribution network is covered by the velocity below 0.1 fps, about 30% area covered within 0.1 to 0.3 fps. The remaining 50% of the network covers acceleration within 0.3 to .85fps (Figure 9). On the other hand, the velocity at off-peak hours indicated that 90% of the distribution network contains a velocity slower than 0.1 fps. The remaining portion of the network has a velocity between 0.1 to 1 fps (Figure 8). So, the majority of the pipes have low velocity.

The purpose of this distribution system modeling would represent the WDS for the Khulshi sub-system. It would serve as an analysis tool to increase understanding of the system's complexities and plan improvements. A numerical model could provide relevant information. For this research, EPANET was used to develop a simplified model; node demand depends on the pressure at the junction nodes to reduce the water loss and maximize the flow rate for the distribution system. Findings from the numerical model can be summarized as:

- About 70% of areas in the study sub-system occupy pressure 8-10 psi. In peak hours, about 40 % area covered the pressure range 9-10 psi, whereas, in off-peak hours, this simulated pressure covered 50 % of the distribution network (Figure 4 and 5).
- In the peak hour, the demand calculated up to about 24 gpm, and about 80 % area covered demand more than 4gpm but in off-peak hour demand range below 4gpm (Figure 6 & 7).
- The distribution network shows the velocity range 0 to 0.1 fps covered only about 20% area during peak hours, whereas for off-peak hours, this range for 90 % area (Figure 8 and 9).

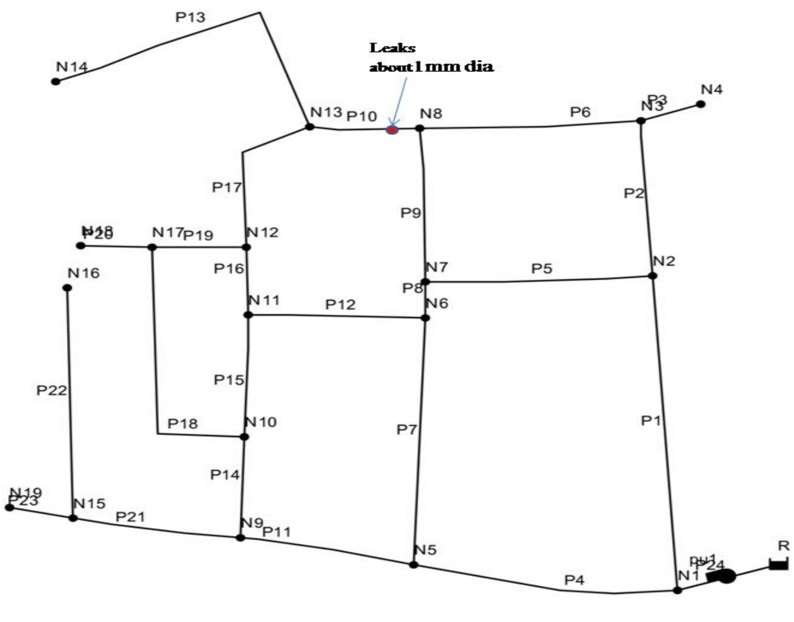

Fig. 10. EPANET network showing two leaks location in service line.

5. Leakage prediction

Water loss in a distribution system through leaks plays a crucial role in sustainable water supply management. Losses of water are influenced by various factors, as described in the introduction section. Four factors were identified and analyzed, which may be considered responsible for higher leakage, and those are leak hydraulics, pipe material behavior, soil hydraulics, and water demand. By controlling pressure, both leakage from the network and the occurring new failure rate can be reduced significantly. However, the effects of pressure on pipe leakage rate remain unexplored and might vary with the range of leakage exponents. Reducing water losses through pressure control is the most cost-effective measure. The model was used to simulate existing conditions and a scenario of pipe leakage in terms of consumer water demand and pressure. There were two leaks about 1 mm diameter found in the study area, and the detailed observation was described in Part I of this paper. A distribution network was developed, showing the details of leaks and their approximate location (Figure 10). The figure shows the leaks in pipe P10 contain two nodes: N8 and N13. Though the leaks were found in the service connection line, it was supposed to influence distribution networks' flow.

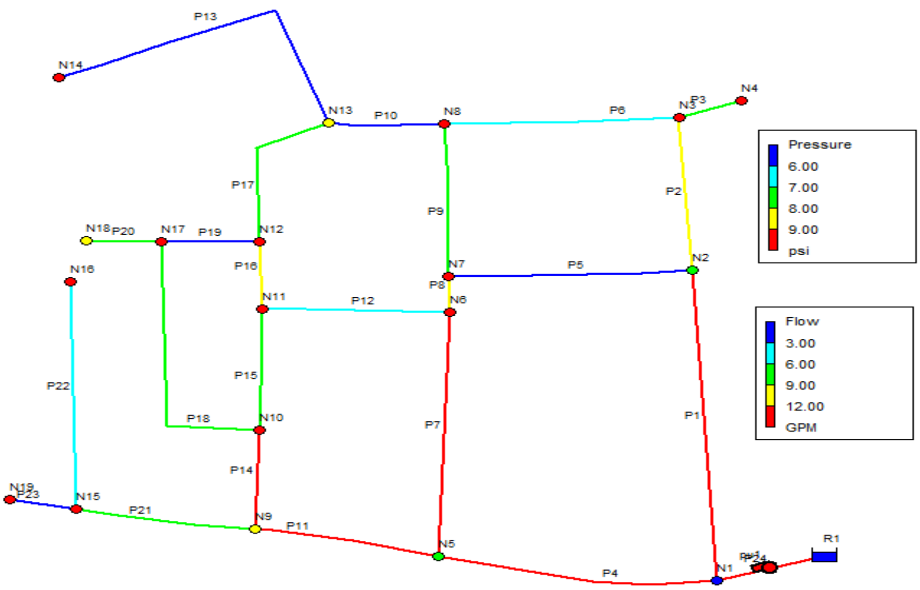

Fig. 11(a). Simulated pressure and flow for the study area during leaks at 8am.

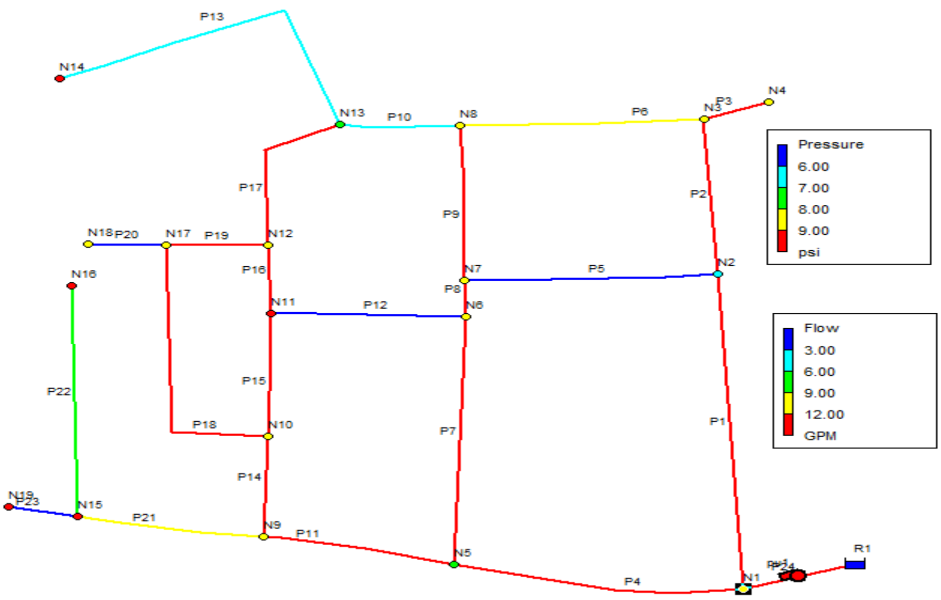

Fig. 11(b). Simulated pressure and flow for the study area after repairing at 8 am.

5.1 *Analysis using EPANET*

Detailed analysis on leakage prediction in the distribution system carried out through modeling and the simulated pressure; demand for the respective nodes and flow and velocity for the individual pipes have been described in this section. Analysis was carried out for two phases, i.e., during the leaks observation period and after repairing the leaks.

5.1.1 Network analysis

Details simulation for the distribution network has shown and focused on N8 and N13 for explaining the effects and type of leakage (Figure 11, 12 (a) and (b)). The graphical distribution also presented for understanding and locating the area. (Figure 13 (a) and (b))

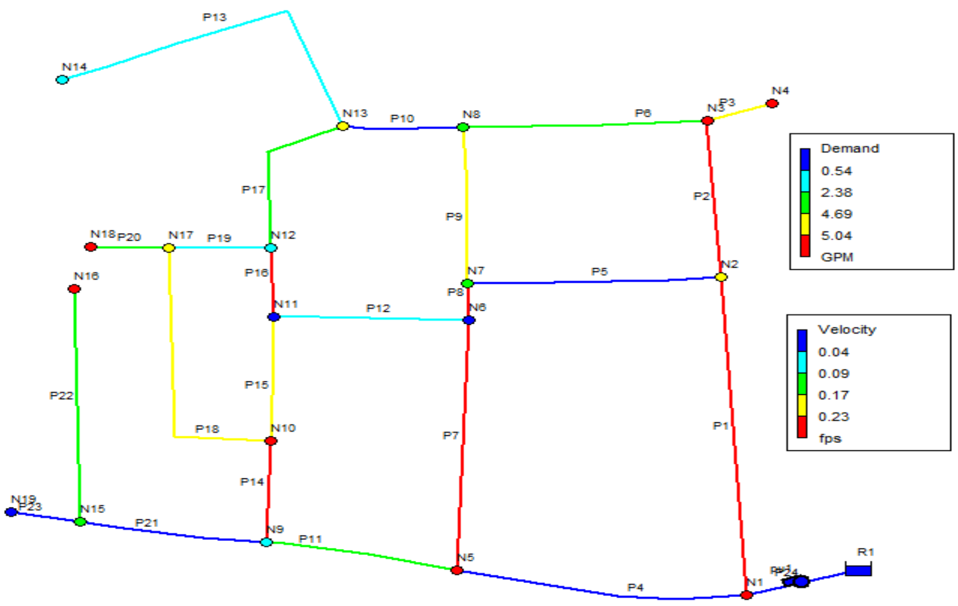

Fig. 12(a). Simulated demand and velocity for the study area during leaks at 8 am.

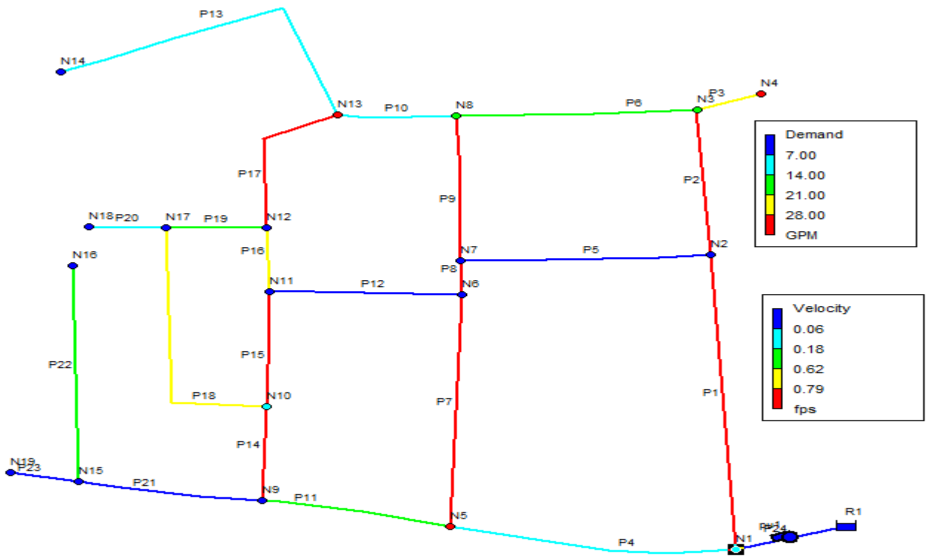

Fig. 12(b). Simulated demand and velocity for the study area during leaks at 8am.

5.1.2 Simulated data analysis

A dataset can be obtained for demand and pressure at the node and then flow for the pipe using EPANET. Demand and pressure for a specific time were observed and noted during leaks and after repairing conditions and flow and velocity in the pipeline (Table 6). Here, node N8 and an N13 and the connecting pipe P10 were focused. Simulated data showed N8 carried out more pressure than N13, whereas the demand value for N13 is more than N8 in both peaks and off-peak conditions. The flow is relatively less than the surroundings for pipes, i.e., P13, P9, P6, and P17.

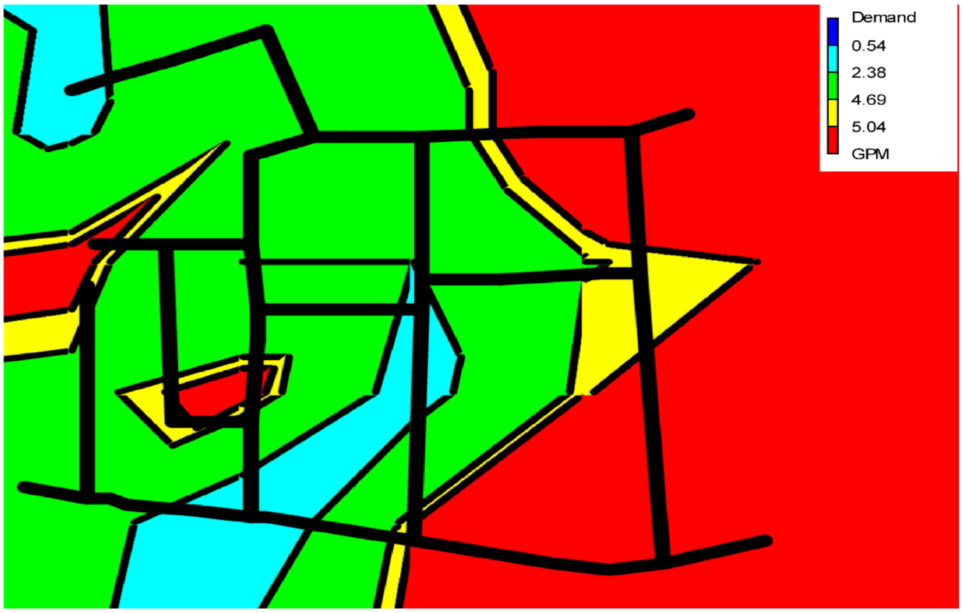

Fig. 13(a). Geographical distribution of demand for the study area during leaks

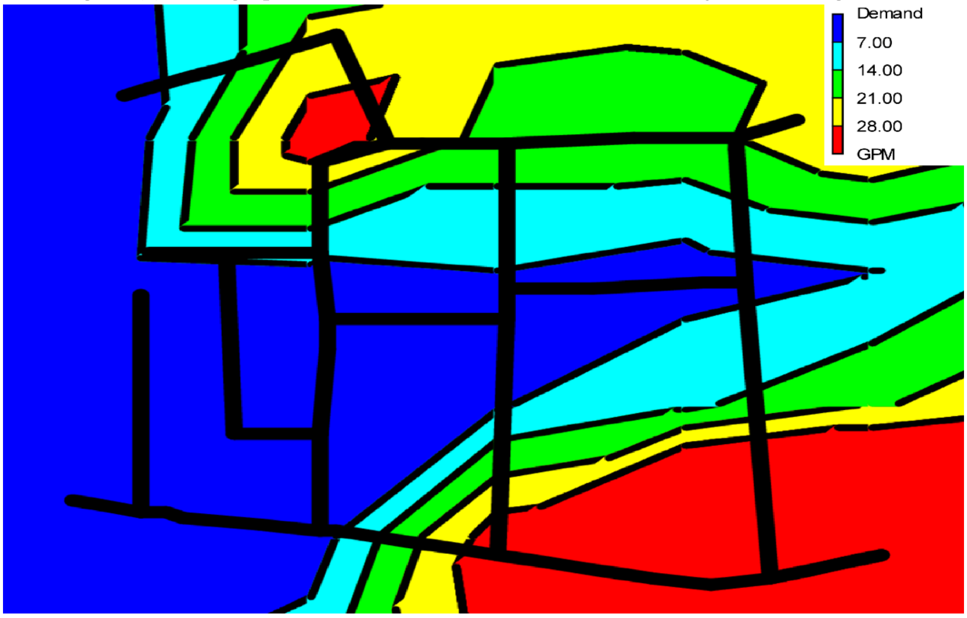

Fig. 13(b). Geographical distribution of demand for the study area after repairing leaks at 8 am

5.2 Effect of leakage in study area

Generally, the different values in two other times are relatively the same worldwide, but N8 and N13 responded to distinguished fluctuations. Demand increased inversely proportional to the pressure, and N8 occupied more pressure than the N13 in both conditions. After repairing, N13 consumed relatively more demand water than the N8; the pressure was less. On the other hand, during leaks, although the demand for water consumed through N13 is less and the pressure was expected to be more, the recorded pressure remains less. The average node pressure for these two nodes about 9 psi, and the head was relatively 6.327 m. Thus, following the Greyvenstein and Zyl (2006), leakage rate was considered about 15 liters/hour. As a result, the water was supposed to be consumed or lost, which affected the expected pressure value and demand.

Table 6
Simulated flow and velocity for the study area at the same time

	During leaks		After repairing	
Node ID.	Flow (gpm)	Velocity (fps)	Flow (gpm)	Velocity (fps)
P1	1.88	0.05	5.46	0.14
P2	1.35	0.04	4.82	0.13
P3	1.10	0.03	3.83	0.1
P4	6.96	0.01	20.25	0.01
P5	-0.09	0.00	0.17	0
P6	-0.61	0.02	-1.42	0.04
P7	2.04	0.05	5.84	0.15
P8	1.57	0.04	5.26	0.14
P9	1.16	0.03	4.52	0.12
P10	0.04	0.00	0.66	0.02
P11	4.24	0.01	10.05	0.03
P12	0.41	0.01	0.05	0
P13	0.25	0.01	0.48	0.01
P14	3.03	0.08	8.1	0.21
P15	1.14	0.03	4.01	0.11
P16	1.50	0.04	3.53	0.09
P17	0.85	0.02	4.62	0.12
P18	1.12	0.03	3.14	0.08
P19	0.33	0.01	-1.9	0.05
P20	0.80	0.02	0.32	0.01
P21	1.14	0.00	1.53	0
P22	0.68	0.02	0.92	0.02
P23	0.00	0.00	0	0

Flow depends on the elevation, pump pressure, pipe diameter, leakage, etc. Due to the topographical variation of the study area, flow values also fluctuated. The pipe P10 flow value was relatively more minor than others, and then after repairing the leakage, the value shows more. For the study area from pipe P10, the simulated water was lost by leakage of about 30 liters/hours and about 0.13 gpm. This leakage quantity combined affects the pressure and demand at N8 and N13 and in connecting pipes. Leaks may affect the flow rate for the respective line. So, it is concluded that the potential leakage area could be suggested by considering demand and pressure. Leakage prediction using EPANET numerical model could be summarized as:

– In analysis, EPANET was used to simulate the relevant data such as demand, pressure, flow, and velocity for both conditions to understanding the leakage effect in the distribution network.
– More input pressure causes more loss and leakage for a leaked network, dependent on pipe properties, hydraulic properties, soil behavior, demand, etc.
– Simulated demand, pressure, flow, and velocity vary with time depending on elevation, base demand, time pattern, pipe properties, etc., and EPANET network could indicate the value range for a prospective node and pipe as well as graphical overview (Figure 10 and 11).
– During the leak, demand and pressure as 0.5gpm and 9.28 psi at node N8, respectively. On the other hand, it found 2.74 gpm demand and 9.26 psi pressure at N8 after repairing the leaks (Table 5)

- N13 simulated demand and pressure during leaks were 0.64gpm and 8.89 psi, but it found 4.79 gpm demand and 8.87 psi pressure after repairing the leaks (Table 6).
- Demand and pressure pose an inversely proportional relationship.
- During leaks for node N13, demand decreased more value, but the pressure did not increase for leaks and water loss, affecting the normal pressure.
- Considering the existing leakage model showed an effect on the pressure and demand, and thus if a detail field records for pressure distribution among pipe network is available, this model could predict the presence of leakage in the network.

6. Conclusions

This research project was carried out in two phases, i.e., field investigation and numerical modeling. The specific objective of this study is to model pipe leakage, and the available technical supports featuring the existing scenario were carried out. The conclusions can be drawn for the n*umerical modeling* phase as:

- US EPANET could simulate hydraulic phenomena within the pressurized pipe networks.;
- the whole pipe network of Khulshi sub-system presented using spatial data of 19 nodes for 23 connecting pipes, and Hazen-Williams equation was engaged for head loss calculation;
- Based on the field investigation, the consumer demands in the Khulshi area and also following the general demand patterns, the model analyzed water flow, velocity, direction, and pressure distribution among the pipe network;
- The increase in demand causes lower pressure. So, it could be suggested about water losses if the proportion of simulated demand and pressure is not shown respectively and that significantly affected by leakage;
- This model showed the pressure range of 5 psi to 16 psi based on the peak and off-peak hours and the maximum area covered as 8 to 10 psi and pipe location. It could mimic the real pressure value once the field records are available; and
- Although the model could not predict the exact leakage, it suggests the potential leakage area considering pressure and demand, which may greatly support a WDS maintenance and operation.

The targeted pipe leakage prediction could represent very close to the field observation using a numerical model during this research project. However, this fully developed model lacks proper validation as the field measurements on pressure distribution and leak identification information are absent. Thus, to improve the prediction, improvements on field data surveys are recommended for further study.

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