RELIABILITY ANALYSIS OF BENCHMARK WATER DISTRIBUTION SYSTEM

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Resume

Water is a necessary component of urban structures and a source of life. Nowadays water distribution system's performance might decline for various reasons, resulting in water waste, hence, to maintain a reliable water distribution network, assessing each water distribution study's validity is crucial. Therefore, this research has focused on using durability assessment to evaluate a water supply system. A water distribution network includes an overhead tank and nodes, pipelines, and nodes. The hydraulic properties of every node as well as pipe, including pressure and flow, are calculated utilizing EPANET. This research evaluates the reliability analysis based on the benchmark data's various diameter of pipes, such as 0.6 m, 0.4 m, 0.3 m, 0.2 m, and 0.15 m, usage. Finally, this research analyses the reliability of each set of diameter pipes in the water supply system.

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1 Introduction

Water supply systems move freshwater from centralized rehab centres or groundwater supplies to service connections or consumer taps [1-2]. These devices work to maintain enough pressure in the water supply system, while also maintaining the quality and amount of the water. This network comprises a network of pipes, pumps, valves, reservoirs, storage tanks, and other parts. The supply chain is based on the local topography [3-5]. For distribution, one may use one of the following processes or methods: gravity method, mixed gravity plus pumping system, or pumping system. Water is accessible with appropriate pressure at numerous locations throughout the area due to the gravity system establishing the water supply origin inside the transmission area. The gravity method often requires no pumping [6-9]. The pumping system is the one that is used the most frequently. Water is forced directly into the supply system to generate the necessary force in this manner. Typically, two pumps must be run at different speeds due to the difference in the transmission. The first pump must move fresh water from the reservoir to the treatment facility.

The following described pipelines are primarily used in the water distribution system [10]. Further, Massive pipelines often include steel pipes specially made with space for any required coatings, including cement, mortar, epoxy, etc. Cast iron, ductile iron, PVC, and other pipelines transmit drinking water in minor transportation networks. Freshwater should not be transported through brick and stone ducts to avoid leaks.

Pipe networks, water pumps, storage areas, fire hydrants, house service connections, metres, and other accoutrements are the primary components of the water supply system, as depicted in Figure 1 [11]. The piping systems have nodes and links (pipes). A transmission network's effectiveness is not just determined by the difference between supply and demand [12]. The performance depends on how reliable the system is and satisfies the demand with a minimal loss. Additionally, the network must always be able to meet needs under reasonable pressure. A water supply service's poor performance can be attributed to various factors. The essential causes are pipe failures, low pressure and flow rate in pipes, and shortage of pumping stations, valves, and appurtenances [13].

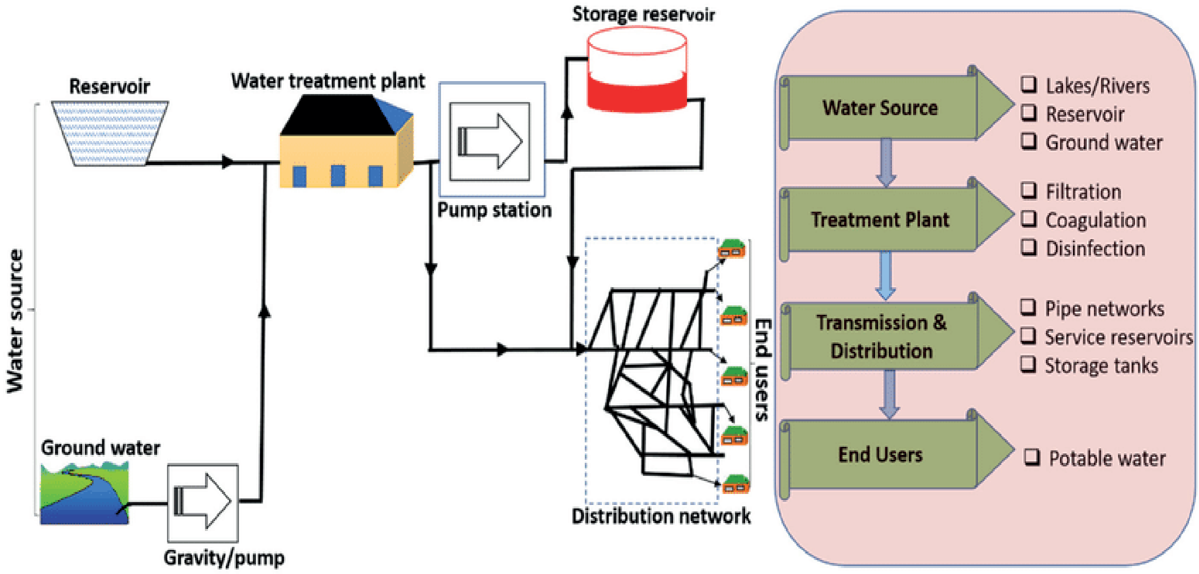


Figure 1 *Architecture of water distribution system [11]*

The distribution of hydraulic characteristics and flow rates in pipes, including pressures (leftover heads) at nodes, are estimated using the simulation software for specific loading and operational circumstances groups. The hydraulic simulation models EPANET help in calculating water distribution piping systems. With the support of hydraulic models, it is difficult to predict the performance of a water supply method. The main contribution of this research paper is as follows: the dependability of water supply is analyzed by the selected benchmark model.

This study paper's format is set up this way: Section 2 examines the current dependability of the water distribution systems. After that, part 3 describes the procedures and materials, and section 4 presents the findings and a commentary. Section 5 brings this paper to a close.

2 Literature survey

The dependability study of current water supply systems is covered in this section. Each Water Distribution System (WDS) element is prone to mechanical malfunction. Still, because of the high level of susceptibility in pipes, the authors Gheisi et al. [14] focused on pipeline breakage (often called mechanical malfunction or pipe failure). The article [14] thoroughly investigates the WDS reliability analysis literature. The research aimed to categorize the appropriate literature and distinguish between various failure kinds and reliability analysis approaches. The three criteria utilized to classify WDS failures were mechanical/physical and hydraulic, as well as the quality of water problems. The main elements affecting the WDS's reliability are the probability of occurrence or failure rates in pipes, pipe disaster groupings, and criteria to quantify consistency. However, this research does not cover the complete network of practical concerns regarding the maintenance of dependability and reliability-based design of WDSs.

Redundancy and surrogate reliability approaches for water distribution systems have been examined by Tanyimboh et al. [15]. Flow entropy, resilience index, network resilience, and excessive power factor were the metrics that were evaluated. The essential objective is to demonstrate that, for water distribution systems, only flow entropy appears to have the attributes of an appropriate indicator of hydraulic dependability and redundancy. One of the main drawbacks is that the flow entropy model it examined was created for a specific operating scenario. Investigating potential expansions to various operational conditions would be desirable.

Additionally, according to Duan et al. [16], the analysis method can be divided into three categories: pipe analysis, node effect analysis, and system stability. The simulation study findings and discussion show that the EPANET is a reliable computation tool for the pipe impact assessment and system reliability tests, including pipe type analysis and pipe network adjustment. The critical pipe sections, most likely to cause widespread cascade breakdown, must be eliminated during the pipe network repair to increase the disaster resilience. The water supply piping system, as well as the breakdown features of the cascade, should also be considered when analyzing the pipe network's dependability.

Jeong et al. [17] examined the relationship between the representative reliability indices with hydraulic processes to provide the maximum suitable reliability index considering the desired organism's effectiveness under numerous circumstances. Six hydraulic measurements, that characterize system performance, were established from redundancy, robustness, and serviceability perspectives. Future research should consider the needs of water managers when creating scenarios that represent actual operational situations and when determining the dependability indices and hydraulic measurements.

Berardi et al. [18] demonstrated a two-level mechanical reliability assessment process appropriate for large authentic Water Distribution Networks (WDNs). The most important scenarios are effectively processed using a path/connectivity-based technique to establish dependability indicators for global-level investigation. The advanced hydraulic model features robust modelling of the water amount in tanks consuming the widespread global gradient approach and automatic topological change detection. An essential test bed for demonstrating the effectiveness of the technique indicated on a practical organization challenge of substantial scale, in addition to the difficulty, was the usage of an actual WDN, with unprecedented difficulty demonstrated.

3 Methodology description

In a water supply system, reliability is "the capacity of a distribution system to meet the demands that are made on it where demands are stated in terms of 1) the flows to be distributed, and 2) the range of pressures at which those flow rates must be provided." This research's primary goal was to determine the effectiveness of a water supply method. The objectives were to (a) analyze the total effectiveness of the water distribution structure using reliability analysis and (b) suggest/recommend needed modifications for the effective operation of the WDS. Following are the steps involved in a water distribution network simulation: (i) distribution system's network representation, (ii) updating object properties in the system, (iii) system operation, (iv) selecting a list of analysis options, (v) executing a hydraulic analysis, and examining the research outcome. Equation (1) is used to determine the reliability analysis.

$$R_i(h) = \left\{ \frac{Q_i}{Q_{i,req}} \right. , \quad (1)$$

where $R_i(h)$ = *Hydraulic reliability at node i*,

$$Q_i = \begin{cases} Q_{req}, & \text{if } H_i \geq H_{i,req} \\ Q_{i,req}\sqrt{\dfrac{H_i - H_{\min}}{H_{i,req} - H_{\min}}}, & H_{\min} < H_i < H_{i,req} \\ 0, & H_i \leq H_{\min} \end{cases} , \quad (2)$$

where H_i = *Evaluated pressure an node i*, Q_{req} = *required outflow an node i*, Q_i = *evaluated outflow at node i*, $H_{i,req}$ = *required pressure at node i*, H_{min} = *Minimum pressure at node at i*.

3.1 Benchmark data

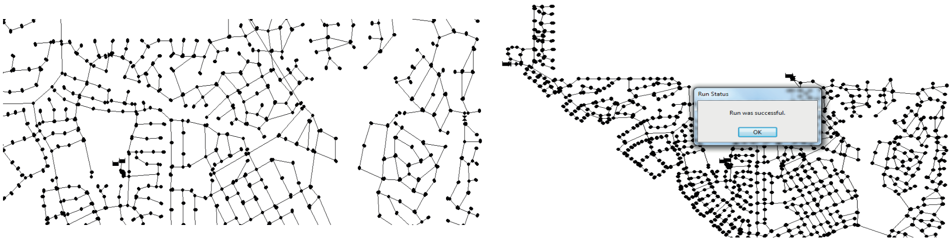
In this research, the Wolf-Cordera Ranch (WCR) Model was taken as the benchmark data shown in Figure 2 [19]. The modest WCR advancement spans 2,400 km^2, but its current mean demand is predicted to be 3.7 million gallons. The WCR design has five pumps and 372 hydrants, with 1981 pipelines. The pipe density per is 0.825 pipes. The majority of pipes in the system have a 0.2032 m diameter. The network must simultaneously open several hydrants to meet significant fire needs of 5250 gpm to 8000 gpm with multiple residential fire demands of 2500 gpm to 2750 gpm. Multi-objective optimization could be applied to satisfy all the physical

Figure 2 *Wolf-Cordera Ranch (WCR) data [19]*

restrictions and achieve overall design goals. Node pressures, fire streams, and overall performance of the model if one of the essential malfunctions are the bare minimum. Pressure at 544 nodes, fire flow at 544 hydrants, concurrently fire flow at 33 business locations and 45 residential sites, pump discharge capacity, and energy life cycle costs for typical day and peak day needs were all assessed for the WCR water system. Removing the hydrants deemed to achieve design specifications with the lowest pipe widths decreased the 625 objective assessments to 40 accurate evaluations.

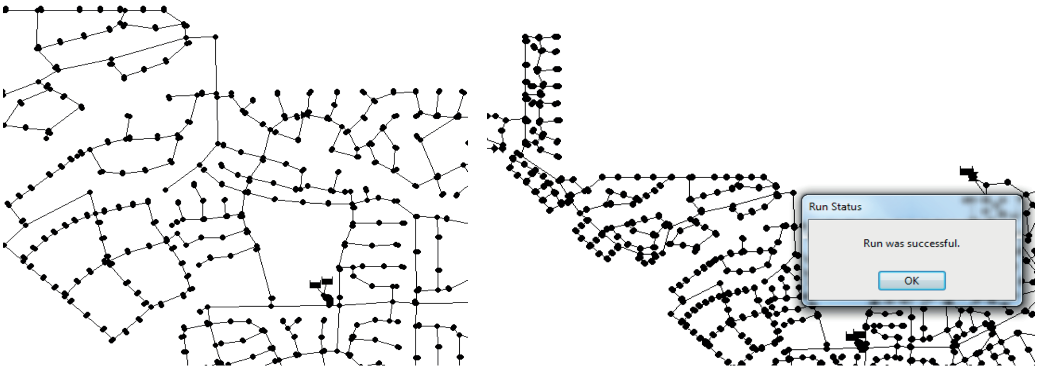
3.2 Water distribution network

The water circulation grid comprises pipes of diameters of 0.15 m, 0.2 m, 0.3 m, 0.4 m, and 0.6 m. The total length of the 0.15 m diameter pipeline is 5491 m, the entire length of the 0.2 m diameter pipeline is 85837 m, the whole length of the 0.3 m diameter pipeline is 18429 m, the total length of the 0.4 m diameter pipeline is 2193 m, and total length of the 0.6 m diameter pipeline is 5056 m. Finally, the cumulative length of the pipeline network is 117 km. Figures 3 - 6 show the layout



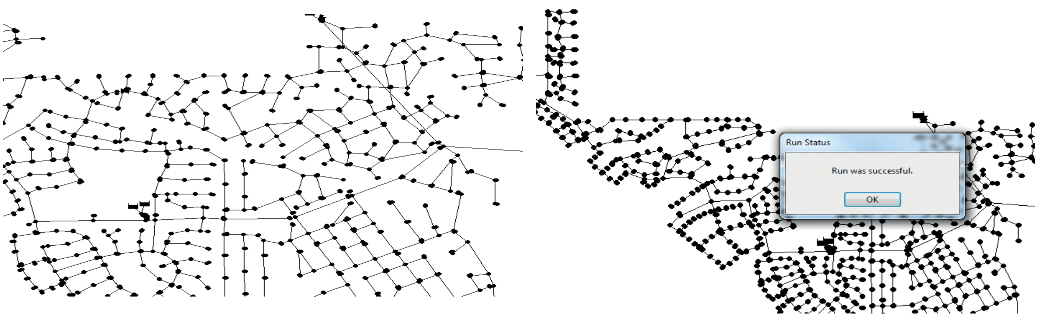
(a) (b)

Figure 3 *Network simulation with 0.6 m diameter (a) Network before simulation, (b) Network with 40 % of pipe damage*



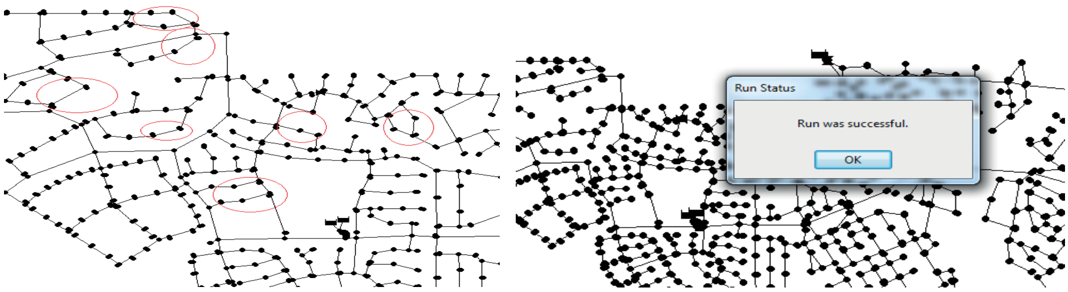
(a) (b)

Figure 4 *Network simulation with 0.4 m diameter (a) Network before simulation, (b) Network with 71 % of pipe damage*



(a) (b)

Figure 5 *Network simulation with 0.3 m diameter (a) Network before simulation, (b) Network with 13 % of pipe damage*



(a) (b)

***Figure 6** Network simulation with 0.2 m diameter (a) Network before simulation, (b) Network with 4% of pipe damage*

***Table 1** The Network statistics*

Parameters	Quantity
Sum of Junctions	1782
Quantity of Reservoirs	4
Amount of Tanks	0
Amount of Pipes	1985
Number of Pumps	6
Number of Valves	4
Flow Units	GPM

***Table 2** Analysis of data*

Sl No	Diameter of pipe (m)	Friction Factor	No. of pipes used	Total length of pipes (m)	Cumulative length
1	0.15	0.005	670	5491 m	117 km
2	0.2	0.036	1033	85837 m	
3	0.3	0.030	235	18429 m	
4	0.4	0.024	14	2193 m	
5	0.6	0.012	33	5056 m	

distribution from the EPANET before and after the simulation for various diameters.

4 Result and discussion

Tool: EPANET
OS: Windows 7 (64 bit)
Processor: Intel Premium
RAM: 8 GB RAM

4.1 Statistics of a network

The parameters employed in this study, including overall junctions, reservoirs, tanks, pipelines, pumps, and valves, are described in this section along with their corresponding quantities, which are explained in Table 1.

4.2 Criteria for the pipe selection

Susceptible to damage: Pipes with the highest flow rate and higher pressures are more prone to damage.

Critical pipes: Pipes connecting the reservoir to the main header and pump discharge lines to the reservoir are essential pipes that must be incorporated into the simulation for the better use.

4.3 Data analysis

From the EPANET analysis, this research provides the % of damage for the various diameters of pipe, such as 0.6 m, 0.4 m, 0.3 m, 0.2 m, and 0.15 m. Moreover, the friction factor, the number of pipes used, and the total length of the pipe for various diameters are described in Table 2.

4.3.1 The failure simulation of a 0.6 m diameter pipe

The EPANET analysis provides a pipe failure simulation of a 0.6 m diameter pipe, results of which are presented in Table 3. The total number of pipes used for 0.6 m pipe is 33. To analyze the system reliability, 5 pipes are initially considered as damaged out of 33 pipes, where the obtained damage is 15 %; thus, the system is reliable. Moreover, the 10 pipes are regarded as damaged out of 33 pipes, where the acquired damage is 30 %; thus, the system is reliable. Then, 13 pipes are considered as damaged out of 33 pipes, where the obtained damage is 40 %; thus, the system is reliable. Finally, the 14 pipes are regarded as damagedout of 33 pipes, where the acquired damage is 42 % and the system has failed. Hence, the system is reliable with a number of 13 damaged pipes.

The diamter of 0.6 m is the largest diameter of pipes used in the entire network. The system is reliable, with 40 % of damaged pipes. The system could deliver water to the entire network with 60 % of pipes of a 0.6 m diameter. The average pressure difference observed was 234 kPa, as shown in Figure 7. System reliability failed above 40 % of damage.

4.3.2 The failure simulation of a 0.4 m diameter pipe

The EPANET analysis provides a pipe failure simulation of a 0.4 m diameter pipe described in Table 4. The total number of pipes of a 0.4 m diameter used is 14. To analyze the system reliability, the 3 pipes are initially considered damaged out of 14 pipes, where the obtained damage is 21 %; thus, the system is reliable. Moreover, the 5 pipes are regarded as damaged out of 14 pipes, where the acquired damage is 36 % thus, the system is reliable. Then, 10 pipes are considered as damaged out of 14 pipes, where the obtained damage is 71 %, thus the system is reliable; Finally, the 11 pipes are considered as damaged out of 14 pipes, where the acquired damage is 78 %, and the system is failed. Hence, the system is reliable with 10 damaged pipes.

The 0.4 m diameter is the second-largest diameter of pipes used in the entire network. Number of pipes used is smaller when compared to the other diameter pipes. The system is reliable, with 71 % of damaged pipes. The system could deliver water to the entire network with 29 % of pipes of 0.4 m diameter. The average pressure difference observed was 20.6 kPa, shown in Figure 8. System reliability failed above 71 % of damage.

Table 3 *The failure simulation of a 0.6 m diameter pipe*

Sl No	Total no. of pipes	No. of pipes damaged	% of damage	Remarks
1.	33	5	15	The system is reliable, with 5 damaged pipes
2.	33	10	30	The system is reliable, with 10 damaged pipes
3.	33	13	40	The system is reliable, with 13 damaged pipes
4.	33	14	42	System failed

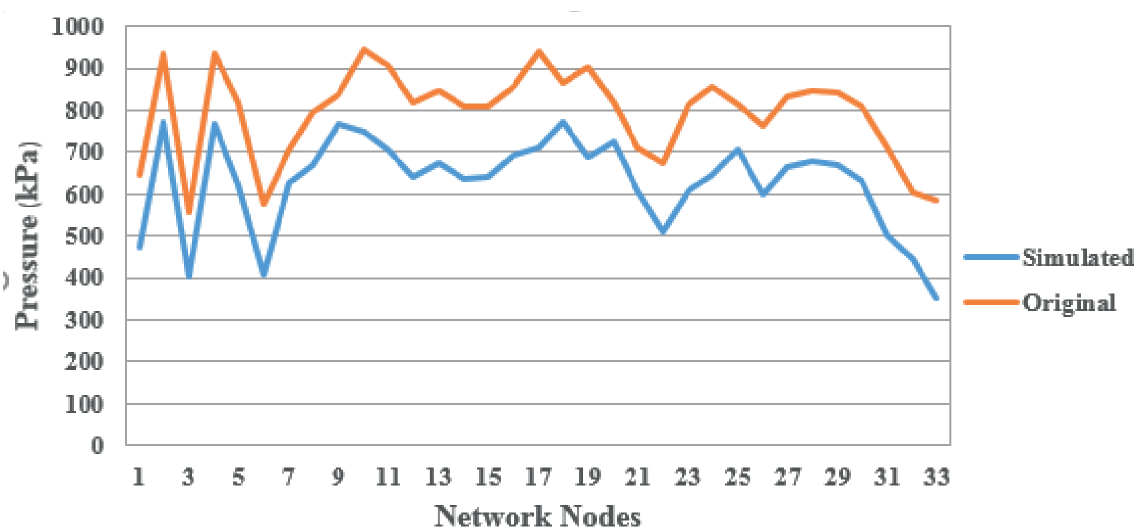


Figure 7 *The pressure difference of a system showing 40 % of damaged pipes (∅ 0.6 m) vs the original network*

***Table 4** The failure simulation of a 0.4 m diameter pipe*

Sl No	Total no. of pipes	No. of pipes damaged	% of damage	Remarks
1.	14	3	21	The system is reliable with 3 damaged pipes
2.	14	5	36	The system is reliable with 5 damaged pipes
3.	14	10	71	The system is reliable with 10 damaged pipes
4.	14	11	78	System failed

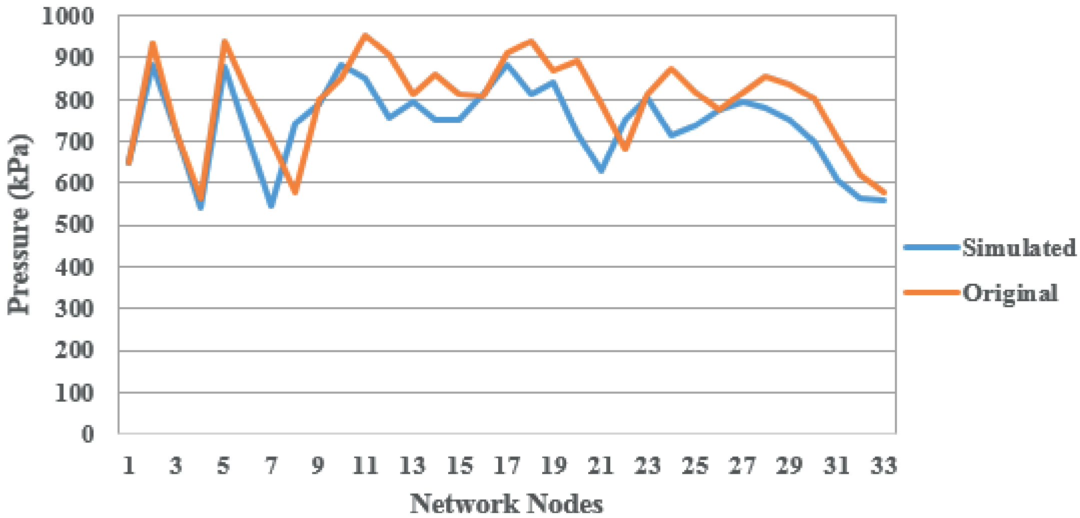


***Figure 8** The pressure difference of a system showing 71% of damaged pipes (∅ 0.4 m) vs the original network*

4.3.3 The failure simulation of a 0.3 m diameter pipe

The EPANET analysis provides a pipe failure simulation of a 0.3 m diameter pipe, illustrated in Table 5. The total number of pipes of a 0.3 m diameter was 235. To analyze the system reliability, initially, the 10 pipes are considered as damaged out of 235 pipes, where the obtained damage is 4%; thus, the system is reliable. Moreover, the 25 pipes are considered as damaged out of 235 pipes, where the acquired damage is 11%; thus, the system is reliable; Then, 31 pipes are considered as damaged out of 235 pipes, where the obtained damage is 13% thus the system is reliable; Finally, the 32 pipes are considered as damaged out of 235 pipes, where the acquired damage is 14%, and the system is failed. Hence, the system is reliable with 31 damaged pipes.

The 0.3 m diamter pipes cover around 18 km of the total network, and 235 pipes are used, as well. The system is reliable, with 13% of damaged pipes. The system could deliver water to the entire network with 87% of pipes of a 0.3 m diameter. The average pressure difference observed was 8.5 kPa, which is shown in Figure 9. System reliability failed above 13% of damage.

4.3.4 The failure simulation of a 0.2 m diameter pipe

The EPANET analysis provides a pipe failure simulation of a 0.2 m diameter pipe as shown in Table 6. The total number of pipes of a 0.2 m diameter is 1033. To analyze the system reliability, the 15 pipes are initially considered damaged out of 1033 pipes, where the obtained damage is 1.4%; thus, the system is reliable. Moreover, the 35 pipes are considered damaged out of 1033 pipes, where the obtained damage is 3.4%; thus, the system is reliable. Then, 42 pipes are considered as damaged out of 1033 pipes, where the acquired damage is 4%; thus, the system is reliable. Finally, 43 pipes are considered damaged out of 1033 pipes, where the obtained damage is 4.1%, and the system fails. Hence, the system is reliable with 42 damaged pipes.

The 0.2 m diameter pipes cover the major area of the network (86 km of the total network and 1033 pipes are used, as well). The system is reliable, with 4% of damaged pipes. The system could deliver water to the entire network with 96% of pipes of a 0.3 m diameter. The average pressure difference observed was 0.95 kPa, as wshiown in Figure 10. System reliability failed above 4% of damage.

Table 5 *The failure simulation of a 0.3 m diameter pipe*

Sl No	Total no. of pipes	No. of pipes damaged	% of damage	Remarks
1.	235	10	4	The system is reliable, with 10 damaged pipes
2.	235	25	11	The system is reliable, with 25 damaged pipes
3.	235	31	13	The system is reliable, with 31 damaged pipes
4.	235	32	14	System failed

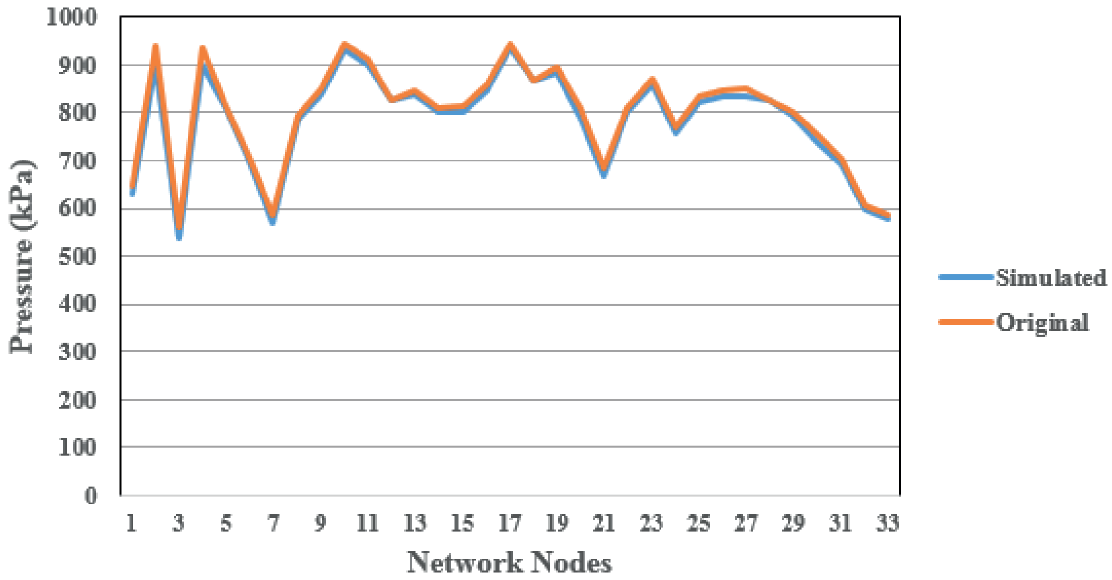


Figure 9 *The pressure difference of a system showing 13% of damaged pipes (∅ 0.3 m) vs the original network*

Table 6 *The failure simulation of a 0.2 m diameter pipe*

Sl No	Total no. of pipes	No. of pipes damaged	% of damage	Remarks
1.	1033	15	1.4	The system is reliable with 15 damaged pipes
2.	1033	35	3.4	The system is reliable with 35 damaged pipes
3.	1033	42	4	The system is reliable with 42 damaged pipes
4.	1033	43	4.1	System failed

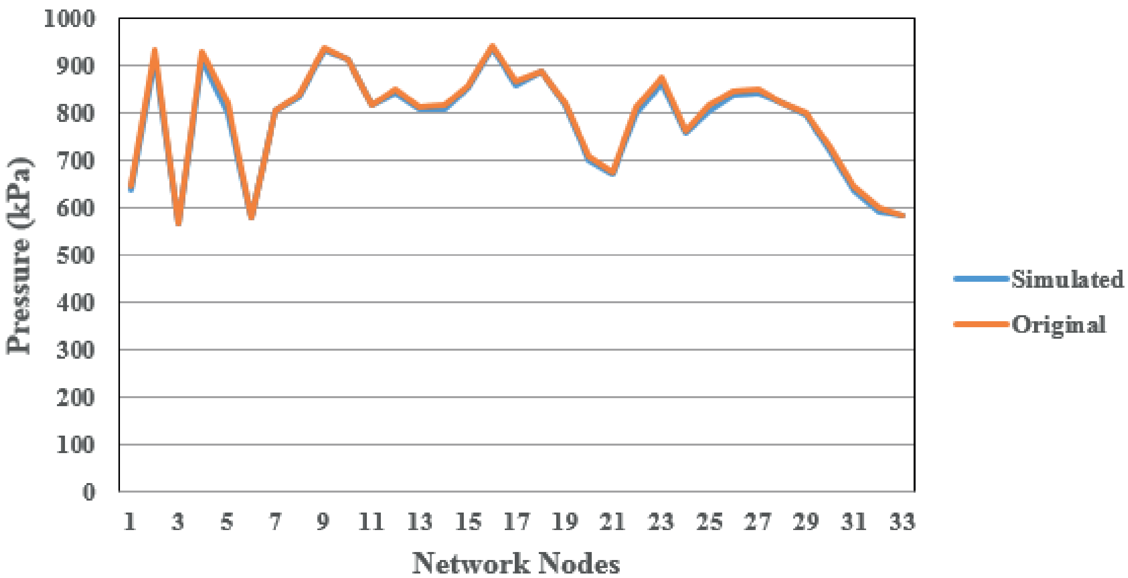


Figure 10 *The pressure difference of a system showing 4% of damaged pipes (∅ 0.2 m) vs the original network*

Table 7 *Final analysis of data*

Sl No	Diameter of pipe (m)	No. of pipes used	Minimum no. of pipes to be healthy	Allowed % of the damage	Pressure difference (kPa)	Network status
1	0.15	670	670	0	0	Reliable
2	0.2	1033	991	4	0.95	
3	0.3	235	204	13	8.5	
4	0.4	14	4	71	20.6	
5	0.6	33	19	40	234	

4.3.5 The failure simulation of a 0.15 m diameter pipe

The 0.15 m diameter is the smallest diameter of all the pipes in the network. It is the end connection pipe to the consumers, and if one pipe fails, supply to that consumer/s will be stopped, and system reliability will fail. Howevere, that will not affect the other consumers or the total network. For the above four failure cases (0.6 m, 0.4 m, 0.3 m, and 0.2 m), a single consumer was not affected by a supply failure, and system reliability was intact during a limited % of failure.

4.4 Final data analysis

The allowed % of damage and their pressure difference for various pipe diameters are presented in Table 7. From the EPANET analysis, this research provides reliability for the various pipe diameters such as 0.6 m, 0.4 m, 0.3 m, 0.2 m, and 0.15 m.

5 Conclusions

This study provides a systematic approach for evaluating the WDS's reliability using the EPANET because the WDS's functionality is crucial for a consistent water supply. Moreover, the benchmark data such as WCR are used as inputs, and its findings can be used to measure any network's dependability after testing and validation. This research evaluates the % of acceptable damage for various pipe diameters such as 0.15 m, 0.2 m, 0.3 m, 0.4 m, and 0.6 m from the EPANET simulation. The system reliability failed above 40 % for 0.6 m, 71 % for 0.4 m, 13 % for 0.3 m, and 4 % for 0.2 m. As a result, this study indicates that reliability testing can be done using this data on every network since it depends on the diameter, length, and number of pipes used in a network and since almost every water distribution network has a consistent ratio of pipes. The benchmarking ratio acquired by comparing various types of networks will be tested and validated in the future. In addition, we may establish a hypothesis with benchmarking ratios/safe damage limit for any water distribution network.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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