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Middle Eastern Smart Water Technologies for Distribution Networks

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Middle Eastern Smart Water Technologies for Distribution Networks

by

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MIDDLE EASTERN SMART WATER TECHNOLOGIES FOR DISTRIBUTION NETWORKS

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DECLARATION OF ORIGINALITY

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ABSTRACT

The hydraulic analysis of water distribution systems (WDS) can be analyzed by two main approaches: demand-driven analysis (DDA) and pressure-driven analysis (PDA). The DDA works well under normal operating conditions, while the PDA produces reliable results under partially failed conditions of a network. Comparisons are carried out by semi-pressure driven analysis (SPDA), Emitter normal pressure driven analysis (ENPDA), Emitter UNESCO pressure driven analysis (EUPDA) and the DDA. The verification is carried out by one of the most commonly used hydraulic modelling software developed by the United States Environmental Protection Agency, EPANET. Applying EPANET demonstrates that unrealistic results from an initial DDA, in the form of pressure deficiencies, could be transformed into the partial fulfillment of nodal demands without losing computational efficiency by PDA methods. The fixed demands of the hydraulic engine in EPANET software is not suitable for analysis of WDS with low pressure. ENPDA is one of the PDA approaches and depends on an emmiter equation which is built-in EPANET software. Another approach of PDA is carried out by the modifications of EPANET (EUPDA) for pressure impact in DDA employing emitter modelling of demands. The EUPDA proposed version can work in a fully transparent way with standard EPANET network files. The verification was carried out to select the most convenient approach for the reliability analysis. The results of the selected PDA modelling approach will be utilized to apply a Middle Eastern solution by adding the elevated tank. Smart enhancement solutions can eliminate the impacts of burst pipelines and/or the effects of firefighting.

DEDICATION

This work is dedicated to my parents Alaa and Amal, who have shown love, caring, support to my brother all of our lives and me. They are my support in this life, and their dedication, as well as their sacrifices, made my academic achievements possible. I would also like to add my special thanks to my brother, Amr, who has always supported me. I am always deeply appreciative of his support.

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CHAPTER I

INTRODUCTION

Water distribution systems (WDS) represent the backbone of potable water supply that must be reliably delivered to customers at acceptable levels of quality and quantity [1]. It includes all potential operating conditions, such as extreme emergency scenarios like burst pipes or failed pumping stations [2]–[4]. The hydraulics of WDS can be analyzed through two approaches: demand-driven analysis (DDA) and pressure-driven analysis (PDA). DDA works well under normal operating conditions while the PDA produces realistic results under the partially failed conditions of a network [5], [6]. This study found that a smart solution to ensure water distribution system reliability requires both the required pressure enhancements as well as necessary reinforcements of the source of supply to the WDS.

1.0 Water Distribution Systems (WDS)

Hydraulic models that simulate the behaviour of WDS have become standard engineering tools of water utilities for applications such as design, calibration, rehabilitation and operation [7]. DDA is the conventional approach used as it assumes that demands are known functions at a certain time and independent of the pressure in a WDS [8]. The objective of a hydraulic model is to create nodal pressures, and pipe link flows that fulfill fixed demand values at system nodes [9]. Many hydraulic models based on DDA have provided practical solutions under normal conditions [7], [10]. A weakness in many hydraulic models is that they are not able to show how they will perform during emergency conditions due to the negative pressure that can occur at nodes as the result of a lack of pressure [11].

1.1 Demand-driven analysis (DDA)

DDA hydraulic simulators, such as EPANET, which are used in optimization processes, are configured to simulate water delivery even when there is insufficient pressure to do so [11–13]. In the analysis of physically poor pressure of WDS, recent studies have emphasized the limitations of demand-driven models [14].

The supplied flow at a demand node is dependent on the pressure at that node of the WDS; when the network is deficient in pressure, consumers' demand for water cannot be fully supplied [15]–[17]. The objective is to deliver the domestic water supply efficiently including the fire flow at desirable pressures in large pipes [18]. Weak pressure sections are unavoidable in a WDS and can occur as a normal part of operational problems, such as pump failure, pipe bursts, the closing of main pipes, and extreme firefighting demands [19]. This approach is termed as DDA and is used by nearly all the traditional network hydraulic modellers, such as EPANET [20]. Statistical analysis surveys globally show that 56% of utilities had no need for the maximum pressure distributed to consumers, and 67% did not manage the ultimate pressures in their systems [21].

The main disadvantage of the DDA is its inability to evaluate a less than operational network performance, which may produce deviations in the components of water distribution systems [1]. An accurate evaluation of a fully functioning water network can be accomplished by assessing demand through a pressure dependent analysis (PDA) [22]. This analysis approach presents a modified application of DDA based on the hydraulic simulator EPANET 2.0 to integrate PDA [23].

1.2 Pressure dependent analysis (PDA)

WDS modelling practice still relies mostly on DDA calculations of steady and uniform flows in pressurized networks. For scenarios in which regular conditions with sufficient pressure are present DDA is accurate while providing a rapid and strong algorithm. DDA is used by almost all of the traditional network hydraulic solutions, such as EPANET and KYPIPE [24], [25]. The PDA models have become essential tools for hydraulic analysis of WDS under stress conditions and are also applied for the modelling of leakages. In a simplified approach, PDA models can be based on the principle of the emitter coefficient available in EPANET software [20]. Common approaches assume the definition of pressure threshold as an indicator of a sufficient service level, which is then used to switch between the DDA and PDA modes. A semi-pressure driven analysis (SPDA) can be used to develop an algorithm for network analysis; it can avoid the problem of false negative pressures due to forced demand conditions in the hydraulic analysis [26]. The technique called the demand-driven analysis available-method (DDA-AM) can be used for a more realistic reliability assessment of WDS compared to pure DDA. The pressure sensitive-demand implemented version of EPANET uses the object-oriented modification of EPANET known as OOTEN and utilizes the emitter functionality of traditional EPANET [26]. Furthermore, there are new numerical algorithms that have produced results to handle PDA in networks [27]. EPANET 2.0 software was modified by reforming the computational engines and adding the emitter equation for the entire node of WDS to implement pressure sensitive demand in network calculations which is one of PDA methods [26], [28].

1.3 The study’s main objectives and assumptions

The first objective of this study is to predict the impacts on the performance of the WDS during normal and emergency conditions when the main pipes of the WDS burst. The second objective is to evaluate and verify the result of applying SPDA as one of the common reliability analysis methods and efficiency tests in comparison to DDA during an emergency or in a contingency plan for the water distribution network [29]. The third objective seeks to evaluate, verify and compare the result of applying PDA methods that are SPDA, EPANET's normal emitter method (ENPDA), and EPANET's UNESCO Emitter method (EUPDA). Each is a common reliability analysis method that is modified to be more efficient in an emergency or during contingency scenarios of a WDS [30]. The results of the approaches will be compared with each other and to the conventional DDA to determine which method is more reliable, sensitive and time effective. The fourth objective is to determine the smart Middle Eastern solution to enhance and reinforce the reliable water supply in line with the selected PDA method. The smart Middle Eastern solution is to allocate and design proper methods to eliminate the effects of emergency situations on WDS; in this study elevated tanks are used.

1.4 The applied theory of reliability

The mandatory part of the network reliability model is the phase during which a network's deficiencies are predicted under partially failed conditions. DDA usually assumes that a nodal demand is always satisfied regardless of the validity of the calculated pressure values at these nodes [30], [31]. Consequently, once the pressure drops below the proposed threshold value, a shortfall begins in the volume of water flow that is delivered to consumers. The threshold pressure value for a junction depends on the type of service connection, and the amount of demand value in the area served by this junction. In general, nodal heads of 14 m to 25 m can guarantee satisfactory service at all related stop taps in a WDS [32]. An emitter is modelled as a setup of a dummy pipe connecting the actual node with a dummy reservoir whose initial head equals the nodal elevation. The standard DDA explains the factors that first place demands on the network and then calculate the pressures in the system [33]. When there is enough pressure in the WDS, the customers decide the demand. Thus, in this circumstance, the DDA is valid.

1.5 The emitter approaches

Full featured and accurate hydraulic modelling is a prerequisite to creating effective water quality modelling. EPANET contains a hydraulic analysis engine that can model the pressure dependent analysis and the flow issuing from an emitter (sprinkler) with an EPANET normal emitter pressure driven analysis including the demand time pattern that can be applied [34]. The emitter exponent power going to that pressure is raised when computing the flow through an emitter device that models the flow through a nozzle or orifice which discharges into the atmosphere [35]. EPANET operates emitters as a property of a node and not as an independent WDS element to compute the actual demand in a PDA [35], [36]. Emitter coefficients were first introduced in EPANET to simulate the operation of fire hydrants and irrigation sprinkler systems. By specifying the emitter's coefficient, the demand node would turn into an emitter node.

1.6 The smart Middle Eastern solution

The smart Middle Eastern solution can be defined as the best practice for hydraulic analysis applications to achieve the reliable water supply for WDS. The reliability assessment can lead to applying either one or all of the smart solutions. The main objective is to supply a suitable quantity of water with an acceptable level of pressure at all nodes under all modes of supply, such as peak hourly demand or fire flow without further negative impact to WDS [37], [38]. Many suitable smart solutions can, for example, increase the diameter size, provide an additional water source, construct an additional pump station, build automated control systems, or provide an elevated balanced tank. Many criteria can be considered; however, the three most important are the following: criterion one is the topology characteristic of the ground level's profile or the distance from the community. The second criterion is the network's features such as the pipe diameter, type of the pipe materials, the age of the pipe, and the availability of the pumps, etc. The third criterion involves environmental factors such as the placement of the districts within the main cities, where industrial areas are focussed, and the different temperatures between the winter and the summer seasons.

1.7 Case studies

Two different WDS were used in this study to apply different approaches to resolving the emergency cases. The first case study had a main, single source tank and a system using a three pumping stations system. The second case study operated by gravity as the main single source tank to analyze how the four different model approaches operated under emergency conditions. The proposed, reliability model approaches include semi-pressure driven analysis (SPDA), and EPANET normal emitter pressure driven analysis (ENPDA). Another important reliable approach is EPANET-UNESCO emitter UNESCO pressure driven analysis (EUPDA). As well, the conventional DDA model approach is demonstrated through WDS [39]. The smart Middle Eastern solution depends on adding WDS's components such as the elevated tank, pipeline, pumping station, or automated water system, ensuring the reliable water supply. The smart solution has been applied, and the proper size of the elevated balanced tank, location and the height have been selected with a 110% extreme ultimate demand pattern. Extreme ultimate demand pattern is the maximum design demand for the entire lifecycle of the certain WDS. The Middle Eastern smart solutions provide strong enhancement and reinforcement to the WDS.

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CHAPTER II

Water Distribution Networks Performance under Emergency Conditions

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NOMENCLATURE

DDA	Demand Driven Analysis	OOTEN	Object Oriented Modification
D-W	Darcy Welsbach	PDA	Pressure Driven Analysis
EPS	Extended Period Simulation	WDS	Water Distribution Systems
H-W	Hazen-William	W-C	White Colebrook
M	Meter	LPS	Liter Per Second

Keywords: Demand-Driven Analysis; Efficiency; EPANET; Hydraulic; Pressure Driven Analysis; Water Distribution System

1.0 Introduction

Water distribution systems (WDS) represent the backbone of potable water supply. A key factor in potable water supplies is that water must be reliably delivered to customers at acceptable levels of quality and quantity [1]. This includes all potential operating conditions, such as extreme emergency scenarios like burst pipes or failed pumping stations [2]-[4]. The fixed-demand hydraulics engine EPANET software, in its original form, is not suitable for the analysis of water distribution networks with low operating pressures [5]-[8]. Hydraulic models that simulate the behaviour of WDS have become standard engineering tools of water utilities for applications such as design, calibration, rehabilitation and operation [9]-[10]. DDA is the conventional approach,

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which assumes that demands are known functions at a certain time independent of the pressure in the system [15]. The objective of a hydraulic model is to create nodal pressures, and pipe link flows that fulfill fixed demand values at system nodes [16]. Water utilities have, in the Middle East, applied guidelines or have collected field data to evaluate and verify system demands to be used as input within these simulation models [9], [17]. Many hydraulic models based on DDA have provided practical solutions under normal conditions. The models are not able to show real-life behaviour during emergency conditions because of the negative pressure that can be reached [18]. Demand-driven hydraulic simulators, such as EPANET, which are used in optimization processes, are configured to simulate water delivery even when there is insufficient pressure to do so [18]–[20]. In the analysis of physically poor pressure of WDS, recent studies have emphasized that the restriction, the availability of minimum threshold pressure, to use the demand driven models [21]. The current research explores the reason and the need for this restriction. To overcome the mentioned restrictions, reliable hydraulic performance can be achieved by utilizing another hydraulic approach like Pressure Driven Analysis, PDA [11]-[14]. The second approach is to apply surrogate reliability process to simplify the calculation analysis with a high degree of accuracy for pressure deficient water distribution systems [22].

1.1 The current applied method

The traditional hydraulic analysis, EPANET, is the hydraulic model in which a nodal demand is supplied without consideration of the availability of the pressure. In this type of model, even when the pressure is negative, the nodal demand is still supplied, which is not realistic. This type of analysis approach is called demand-driven analysis or DDA [23], [24]. DDA is the first step in all reliability or calibrated analysis methods. To achieve the required demand at a certain node, the pressure at the node must be greater or equal to the lowest required residual pressure [25], [26].

The DDA approach has limitations in its ability to analyze water distribution systems (WDS) when the pressure is low during emergencies, when a pipe has burst, when there is a pumping failure or when firefighting is in progress [27], [28].

1.2 The main objectives and assumptions

The first objective of this paper is to predict the impacts on the performance of a water distribution system during both normal and emergency conditions. The first case study will examine the WDS performance when there are burst pipes in pipes 2, 4 and 6. The second case study will examine WDS performance when there are burst pipes in the main pipes 2, 3 and 8. The second objective is to illustrate the demand-driven analysis characteristics and its standard performance in handling these emergency scenarios. Certain limitations, as well as the assumption that the flow is one-dimensional, are required to achieve these two objectives. The steady state flow with a minimum pressure range is set from 1.4 bar to 2.5 bar, or 14.0 m to 25.0 m head. In this study, the applied frictions factor equations are: Hazen-William (H-W); Darcy Welsbach (D-W); and White Colebrook (W-C) equations. As well, the velocity will be limited in the range of 0.3 m/sec and 3.0 m/sec. All minor losses are not applicable to valves or pipes because they are very small. The pipe diameter range used in the study ranges from 0.1 m to 2.0 m. The main assumption of the study is that only one pipeline will burst in each scenario of the emergency hydraulic model.

1.3 The applied criteria and algorithm

The applied criteria per the flow chart (see Fig. II-1) are listed below:

1. Build and run water distribution network model as usual for normal status.
2. Extract the consumption and pressure for each junction.
3. Create spreadsheet table that includes the extracted consumption and pressure.
4. Apply simulation for the emergency scenario of a burst pipe by removing one pipe.

5. Extract the pressure and consumption to a spreadsheet table.
6. Calculate the efficiency of the available pressure at each junction in the following manner:
    a. Junction Efficiency = the current junction pressure for the model scenario with specific burst pipe / the pressure for the same junction of the original model scenario……..…(2.1)
    b. Average Efficiency = the summation of the efficiency for each junction within model scenario/number of the junction within the same model scenario……………………(2.2)

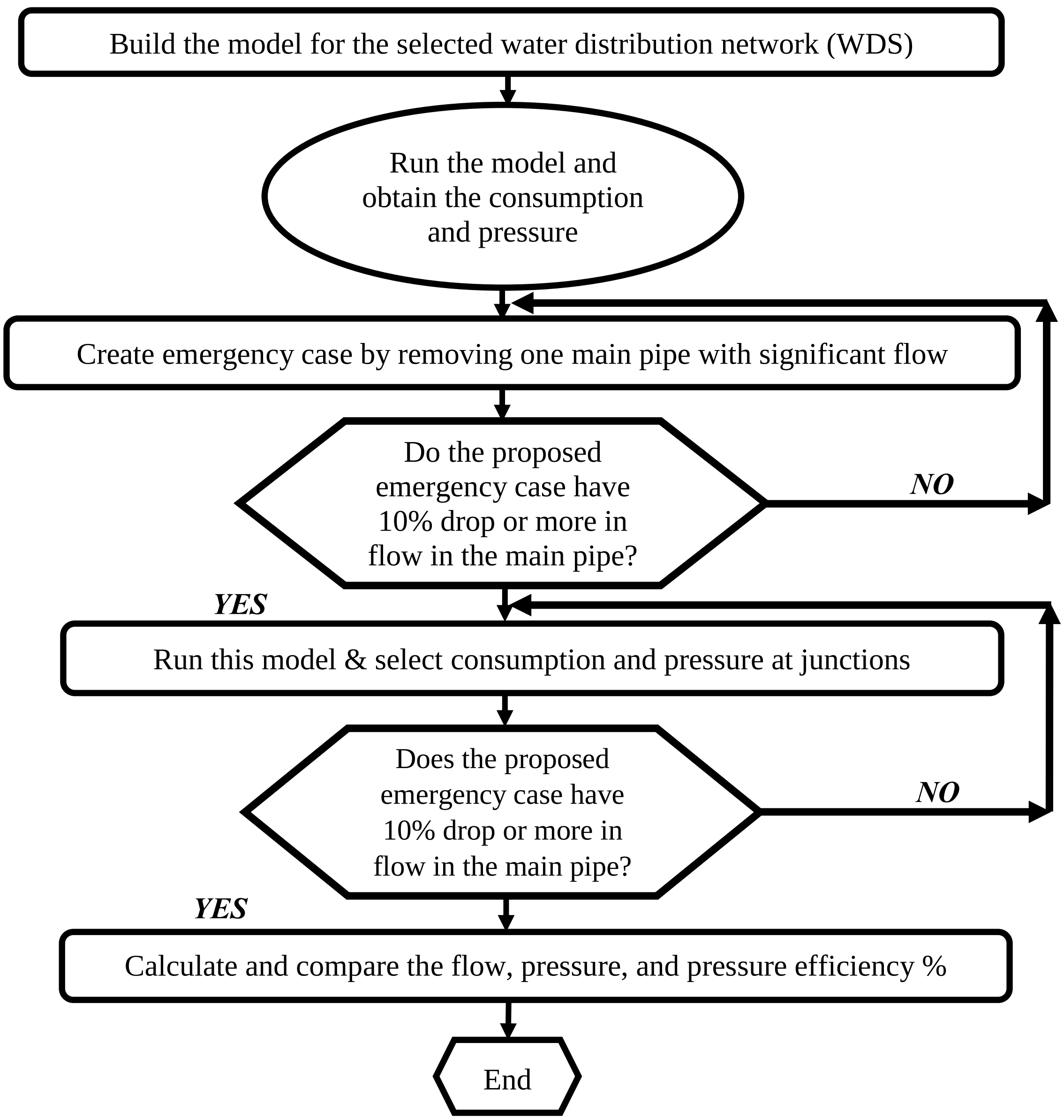

Figure II-1: The flow chart of the pipes networks analysis by demand driven analysis (DDA)

2.0 Case Studies

In the current study, there are two case studies which have been applied as follows:

2.1 The first case study

The proposed reliability evaluation and optimization methods are demonstrated within a hypothetical example of a water distribution system. The system has a single source node; one pumping station has three pumps, 16 demand nodes and 33 links as shown in Fig. II-2. This network is a theoretical network and utilized in by many researchers for example reference [26]. This WDS was selected because it contains many of the fundamental elements of a water distribution system [26]. The hydraulic analysis is applied to normal water demand scenarios and three emergency scenarios for burst pipes 2, 4 and 6, respectively, as follows:

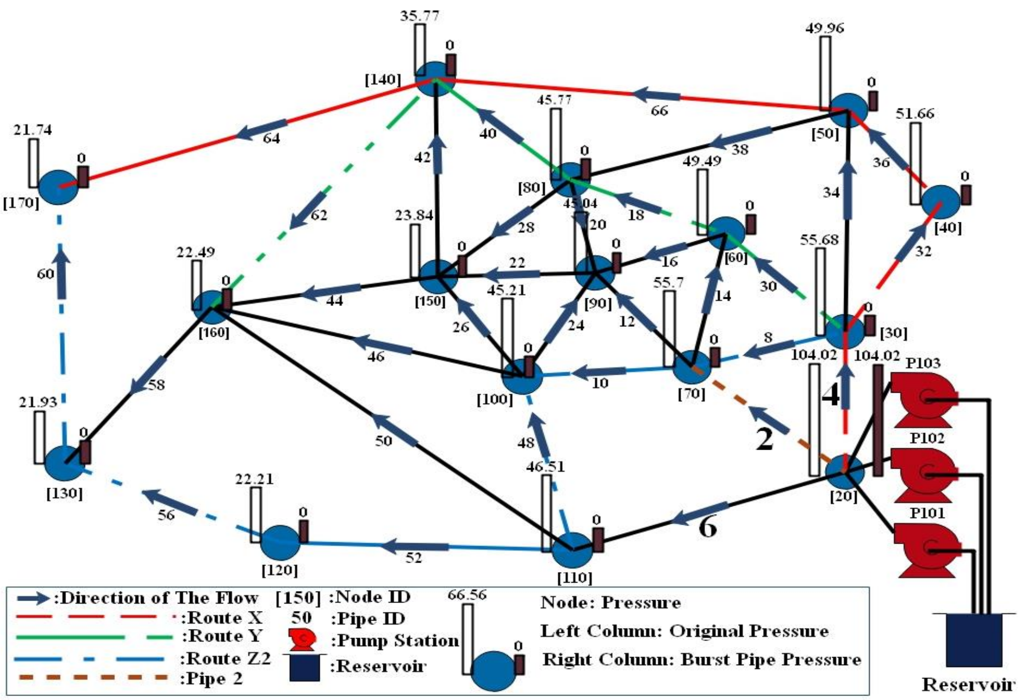

Figure II-2: The first case study viewing pressure at the original and burst pipe 2.

2.1.1 The analysis of the first case study results

First of all, it should be noted that the obtained pressure and consumption for each node have been tabulated in Table B-1 (in Appendix B). Pipes 2, 4 and 6 had a flow rate equal to 159.75, 128.53

and 83.95 lps accordingly. Pipes 2, 4 and 6 are selected for the analysis of reliability since they are the main pipeline with a huge flow rate that is equal to 10% or more than the flow in WDS. Secondly, it should be noted that the full analysis, as shown in Table B-2 (in Appendix B), demonstrates that the WDS's pressure efficiency for burst pipes 2, 4 and 6 are 6.25 %, 6.8 % and 27.64 %, respectively, compared to the original pressure.

Additionally, Fig. II-2 represents the WDS with the original pressure column, which is high enough to supply the network with pressure above the minimum threshold within a range of 34.47 m to 68.94 m. It also shows that the pressure column of burst pipe 2 is low and this is in a range between 17.23 m to 34.47 m, which was reduced dramatically compared with the pressure at the same nodes of the original WDS. The scenarios with burst pipes 4 and 6 indicate a large reduction in pressure range as shown in Table B-2 (Appendix B).

Also of relevance is the demand for both scenarios. That is the original WDS analysis and the one with burst pipe 2 have the same value, while the pressure was reduced sharply without any effect on the demand or the flow rate. The results suggest that the DDA model analysis provides suitable pressure efficiency when the pressure is above or within the minimum requirement of 14–25 m, while in an emergency it does not have reliability when the pressure is less than 14 m.

2.1.2 The first case study result verification

To verify the analysis of the original hydraulic scenario and the three scenarios (burst pipes 2, 4 and 6), the pressure profile should be traced through three different routes within the WDS, which are X, Y and Z2. The route means the flow track is in a certain direction within WDS. The three traced routes (X, Y and Z2) started from the node near the source of the supply (node 20), and are directed to the far nodes of the WDS based on the flow directions. The three routes should provide an analysis of the behaviour of the hydraulic grade line and, consequently, the pressure for different nodes in the WDS [18]. Fig. II-3 as well as Fig. A-6 and Fig. A-7 (in Appendix A) illustrate the profile pressure in both original WDS scenarios and the WDS scenario for the burst pipes 2, 4 and 6.

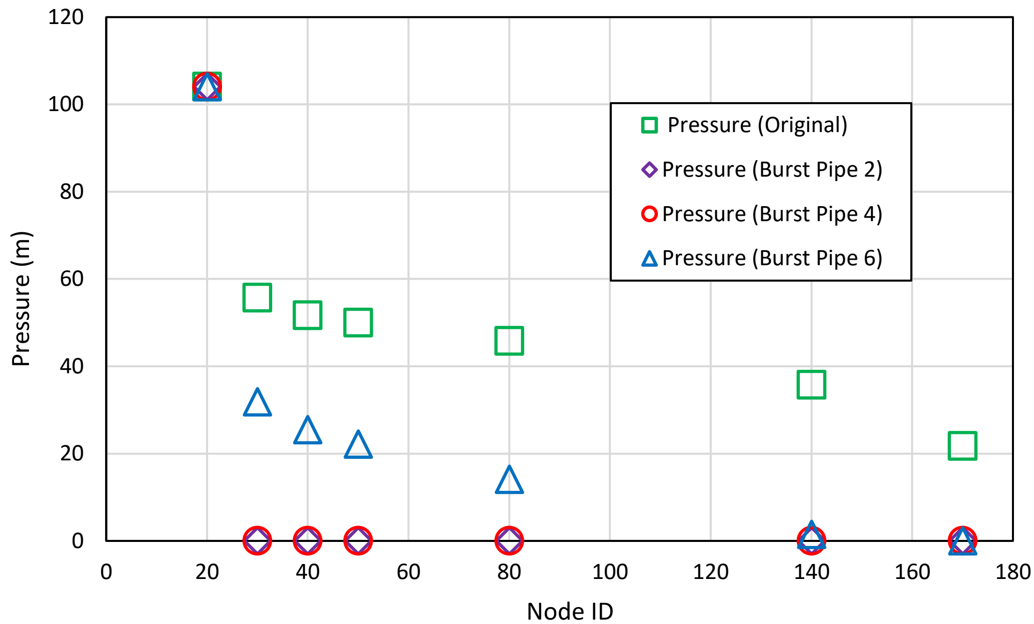

Figure II-3: The first case study: The pressure route X for original and burst pipe 2, 4 and 6.

2.1.2.1 Route X

Shown in Fig. II-3 are the scenario results for burst pipes 2, 4 and 6. The results demonstrate the pressure profile for the original WDS scenario from 20–105 m where the demand can be achieved. The figure illustrates the pressure profile of WDS for burst pipe 2 scenario; it is in the range of 0–105 m and the most of nodes have a pressure equal to zero. This is in line with a pressure efficiency of 6.25% as seen in Table B.2 (Appendix B). The WDS for the scenario of burst pipe 4 has a pressure profile to be in the range of 0–105 m and most of the nodes have a pressure equal to 0. Route X has a robust agreement with pressure efficiency of 6.8% as seen in Table B-2 (Appendix B). The table also illustrates the pressure profile for burst pipe 6 to be in the range of 0–105 m with pressure in the range from 30–12 m for many of the nodes that are in line with a scenario pressure efficiency of 27.4%.

2.1.2.2 Route Y

Fig. A-6 (in Appendix A), regarding burst pipes 2, 4 and 6, represents the pressure profile for the original WDS scenario that is in the range of 20–105 m where the demand can be accommodated. The figure also illustrates similar pressure profiles for burst pipes 2, 4 and 6, which are the same as the pressure efficiency of route X.

2.1.2.3 Route Z2

Fig. A-7 (in Appendix A), for burst pipes 2, 4 and 6, represents the pressure profile for the original WDS scenario from 20 to 105 mm where the demand can be accommodated. The figure illustrates similar pressure profiles for burst pipes 2, 4 and 6 that are the same as the pressure efficiency of routes X and Y. These pipes represent a highly significant flow rate above 10% of the flow in WDS.

2.2 The second case study

The proposed reliability evaluation and verification methods are demonstrated using a theoretical example of a water distribution system (WDS). It is a system with a single source node, 32 nodes and 44 links shown in Fig. II-4. This WDS is based on research on the planned future city of El-Mustaqbal, in Egypt, because it contains all the significant elements as pipelines, nodes, and reservoir of a water distribution system (WDS) [29]. There are 32 junctions and one reservoir. However, there are no tanks, no pumps and no valves. Finally, the flow rate entering the WDS is 352.49 lps, the pipes' diameter is between 150 mm–600 mm. The model has been applied using DDA under normal conditions as well as three emergency scenarios with burst pipes 2, 3 and 8 as discussed in the following sections.

2.2.1 The analysis of the second case study's results

In Table B-3 (in Appendix B), the analysis shows that pipe 2 (300 mm in diameter) originally supplied 100.82 lps; pipe 3 (300 mm in diameter) supplied 100.82 lps, and pipe 8 (150 mm in diameter) supplied 9.17 lps. Pipe 8 is selected to evaluate the pressure efficiency where the flow is lower than 10% of the WDS' total inflow. In Table B-4 (in Appendix B), the WDS pressure efficiency for the scenario of burst pipes 2, 3 and 8 is shown to equal 60.96%, 62.66% and 99.36%, respectively, compared to the original pressure.

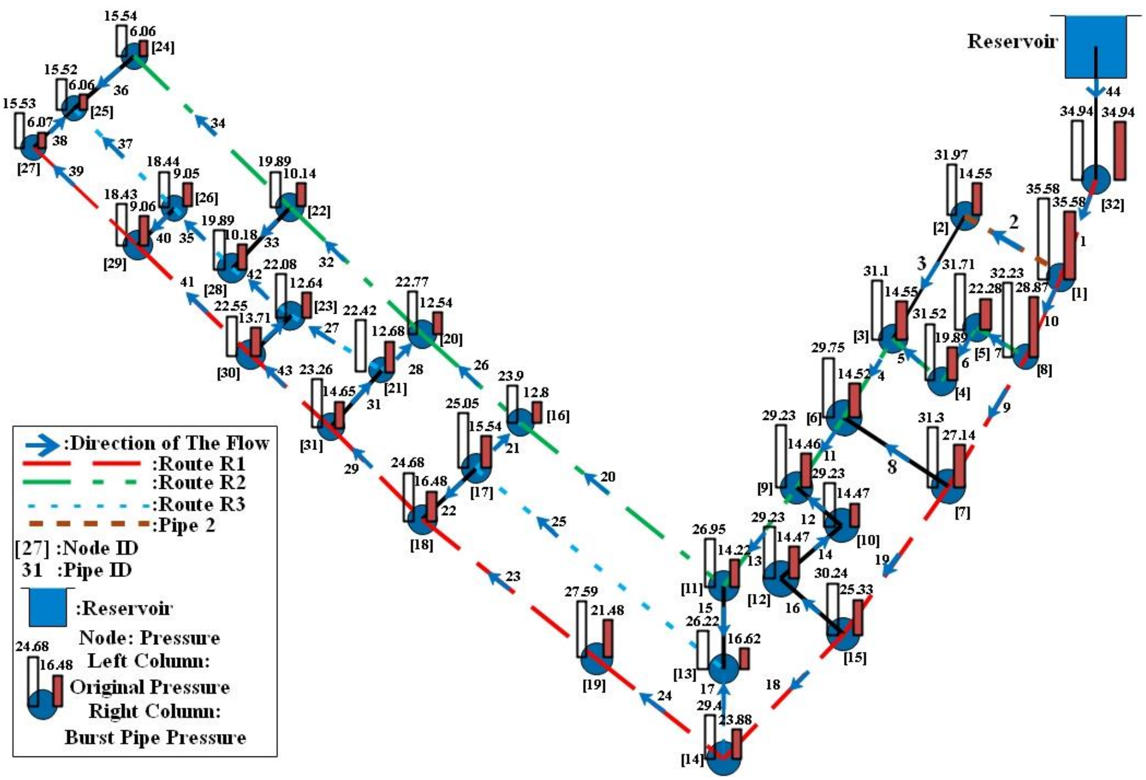

Figure II-4: The second case study viewing pressure at the original and burst pipe 2.

Fig. II-4 represents the pressure column of the original scenario of WDS and the pressure column for the original WDS analysis, which are high enough to supply the network with pressure above the minimum threshold with a range between 15–45 m. The case of burst pipe 2 has pressure in the range between 5–30 m with pressure (head) is less than 14 m at many nodes. The same analysis can be applied to burst pipe 3. However, the analysis is not applicable to burst pipe 8 since it has a low flow rate that is less than 10% of WDS' total inflow in with no impact on the efficiency.

Fig. II-5 shows the demand in both original scenario and the burst pipe 2 scenario as shown in Table B-4 (in Appendix B). While the pressure is reduced sharply without affecting flow rate and consumption. The DDA provides good efficiency when the pressure is above the minimum requirement. However, in an emergency scenario, it would not be reliable.

The demand for both scenarios as found in the original, as is shown in Fig. II-5, and for the scenarios of burst pipes 2, 3 and 8 are the same, as is shown in Table B-4 (in Appendix B), while the pressure reduced sharply without any effect on the flow rate or the consumption. The DDA provides good efficiency when the pressure is above the minimum threshold pressure. However, in an emergency scenario where there is low pressure and the DDA efficiency is low the DDA does not provide reliable results.

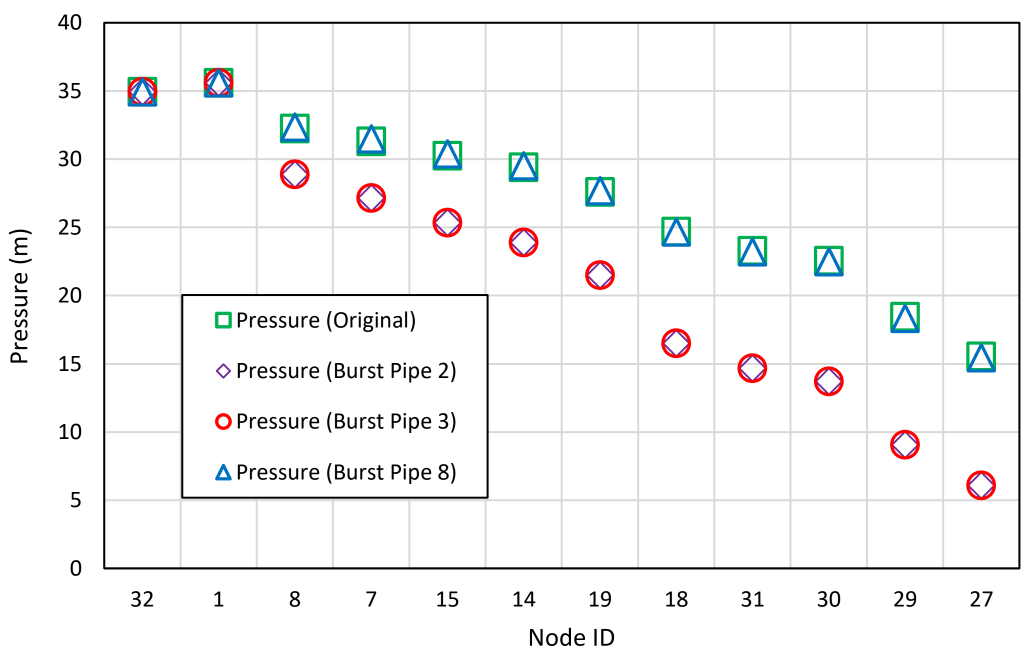

Figure II-5: The second case study: The pressure for route R1: burst pipes 2, 3 and 8.

2.2.2 The second case study's results—Verification

To verify the analysis of the original hydraulic scenario and the scenarios of the three burst pipes 2, 3 and 8, three different routes within the WDS were selected: R1, R2 and R3. These routes start from node 32, near the source of the supply, and are directed to the far nodes of the WDS. The flow routes are traced to examine the impact of the emergency on the pressure for different nodes in the WDS. The figures illustrate the profile pressure in both the original WDS scenario and in the WDS scenario for the burst specified pipe such as burst pipes 2, 3 and 8. The figures are verified and validated by the obtained results as are discussed in the following sections.

2.2.2.1 Route R1

Fig. II-5 focusses on burst pipes 2, 3 and 8; it demonstrates the pressure profile for the original WDS scenario from 15–40 m where demand can be accommodated. The figure shows that the pressure profile for the WDS scenarios of burst pipes 2 and 3 is in the range of 5–35 m with low pressure at many nodes that have low-pressure efficiency.

Fig. II-5 illustrates the pressure profile in the WDS scenario for burst pipe 8, which is in the range of 20–35 m where the pressure is above the minimum threshold pressure (14 m) for all the nodes. Both the pressure profiles of the original WDS and the WDS for the burst pipe 8 have similar trends and approximately the same efficiency values equal to 99.36%, which is very high, as the flow through pipe 8 is very small at 9.17 lps and that is less than 10% for the overall total flow.

2.2.2.2 Route R2

Fig. A-8 (in Appendix A) shows similar results as those found in routes R1 and R2 for the burst pipes 2, 3 and 8, respectively. The verification proves that the results have a high level of agreement in accuracy with the analysis of the different routes.

2.2.2.3 Route R3

Fig. A-9 (in Appendix A) show similar results like the previous analysis in routes R1 and R2 for burst pipes 2, 3 and 8, respectively. This verification proves that the results have a high level of agreement regarding the accuracy of the analysis of the different routes.

3.0 Conclusion

The purpose of this study is to clarify the limitations of the traditional hydraulic model (demand-driven analysis) DDA for scenarios where demands may reach emergency levels. The EPANET hydraulic simulation model presented both normal and emergency water distribution scenarios for two different case studies. The two WDSs case studies illustrate both the DDA characteristics as well as its standard performance in handling these emergency scenarios. There is a variation in the performance of the two WDS during the original and emergency conditions when the DDA method was applied to the systems. The results of the two WDS show that the pressure profile and pressure efficiency for the burst pipe scenarios are lower than the original pressure profile, with no change in node demand. In conclusion, the traditional hydraulic analysis is built on the concept of DDA where the nodal demands have to reach the consumer without consideration of the available pressure heads. As a result, the network may experience low or negative pressure, which is less than the threshold pressure of the WDS. The results of the analysis indicate that the pressure driven analysis (PDA) modelling should be applied to two different networks under burst pipe conditions to measure the ability of PDA modelling to perform under conditions when there is an insufficient amount of nodal pressure.

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CHAPTER III

Water Distribution Network Performance by using Semi Pressure Driven Analysis Approach during Emergency Conditions

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NOMENCLATURE

DDA	Demand Driven Analysis	OOTEN	Object Oriented Modification
DDP	Demand Dependent Pressure	PDA	Pressure Driven Analysis
EPS	Extended Period Simulation	SPDA	Semi Pressure Driven Analysis
H-W	Hazen-William	WDS	Water Distribution Systems
M	Meter	LPS	Liter Per Second

Keywords: Demand-Driven Analysis; Efficiency; EPANET; Hydraulic; Pressure Driven Analysis; Water Distribution System

1.0 Introduction

The supplied flow at a demand node is dependent on the pressure at that node of the WDS when the network is deficient in pressure, and the consequence of that deficient pressure is that consumer demand will not be fully supplied [1]–[4]. Weak pressure sections are unavoidable in WDS and can happen as a normal part of operational problems, such as pump failure, pipe bursts, the closing of main pipes, or extreme firefighting demands [5], [6]. This approach is termed as DDA and is used by nearly all the traditional network hydraulic modelling software, such as EPANET [7], [8]. The main disadvantage of DDA is its inability to evaluate the pressure and flow performance in WDS, which may affect the analysis and the proper design of the components of water distribution systems [9].

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A true illustration of a water network's functioning can be accomplished by linking demands to the PDA [10]. This approach presents a modified application of the well-known DDA that is based on the hydraulic model EPANET 2.0 to integrate pressure dependent demand (PDD) [11]. The reliability is based on the hypothesis of connectivity and assumes a WDS is continuously connected to the topological elevation of the system. This study considered the hydraulic approach as it is fully hydraulic calculation with actual collected data [11], [12]. The PDA method is a realistic approach to the hydraulic analysis of water distribution systems with a priority placed on the pressure within the network [13]. Each node can reach the completion demand only if a minimum required pressure is satisfied at that node. If the minimum pressure required cannot be met, then only a partial demand can be satisfied in these nodes. Moreover, the hydraulics of a water distribution system can be approached from several different perspectives. The difference between the approaches comes from the level of primacy given to nodal demands versus nodal pressures [1]. The different flow head relationships provide a detailed comparison of proposed hydraulic analysis approaches by researchers [4], [16]. This is demonstrated by the following equation:

$$H_j = H_j^{min} + K_j Q_j^{n_j} \quad (1)$$

Where: H_j is the head at node j, Q_j is the demand at that node, K_j is the flow resistance coefficient, n_j is an exponent, and H_j^{min} is the threshold pressure below which the outflow at the node is inadequate or 0. A reliable hydraulic performance can also be achieved by utilizing a surrogate reliability process to simplify the calculation analysis with high accuracy [17]. A reliability analysis established through a combination of the extended period simulation (EPS) of WDS and the pressure driven approach (PDA) is more accurate than the traditional DDA [18], [19].

1.1 The applied solution method

The semi-pressure driven analysis (SPDA) method is applied to adjust nodal water demands to fulfill the minimum pressure required, and it can be applied to any network where the pressure is less than the minimum threshold pressure [4]. The enhanced water supply demand calculated by the SPDA method might be less than the supplied water demand calculated by the conventional demand node method [20], [21]. Both methods will be compared, evaluated and verified with an original scenario for each network.

1.2 The main objective and assumption

The current study seeks to evaluate and validate the result of applying the semi-pressure method as one of the common reliability analysis methods and to establish the most efficient method of water supply for a water distribution network during the emergency or contingency [22]. Both DDA and SPDA illustrate and evaluate the network's performance during normal and emergency conditions when main pipe bursts or is removed [23]. The present study is operating under that assumption that the flow is a one-dimension flow, with a minimum threshold pressure that equals 14 m. The number of iterations is 8 with a tolerance that will not exceed 0.5%. Any negative pressure will be considered to be 0. The study's operating assumptions also include that: the velocity is in the range between 0.3 m/sec and 3 m/sec: no minor losses are applicable; the pipe diameter is in the range from 0.1 m to 2.0 m; and that only one pipe segment will be considered burst/closed in each scenario. The efficiency equations for the study are as follows:

a. Junction Efficiency = the current junction pressure for the model scenario with a certain burst pipe / the pressure for the same junction of the original model scenario……….....(3.1)
b. Average Efficiency = the summation of the efficiency for each junction within the model's scenario/number of the junction within the same model scenario………………..……..(3.2)

1.3 The applied criteria and algorithm

In SPDA, once junctions that are lacking pressure are identified from an initial DDA, the first problem that needs to be resolved is to determine the realistic demands at the nodes, possibly knowing that the remaining nodes are fully supplied with pressure and are affected by full demand. For this purpose, the following adjustments are made at each pressure lacking node [9]:

1. Ensure the new node elevation = original node elevation + threshold pressure head.
2. Set demand to 0, initially.
3. Connect an imaginary elevated tank to the node by a short control valve (CV) pipe that only allows flow from the node to the reservoir.
4. Install an imaginary tank elevation equal to the new node elevation.

In SPDA, the demand, at each pressure deficient junction in the algorithm is treated as an unknown while a pressure threshold is fixed [24].

Fig. III-1 shows a flowchart of the semi-pressure algorithm. The algorithm proceeds in an iterative approach [25]. This means that if one or more imaginary tanks receive more water than their original nodes demand, these imaginary tanks will be removed from the network. Then the original elevations and the original demands will be returned to the corresponding nodes. [26].

2.0 Case Studies

Two different case studies have been analyzed using the reliable hydraulic analysis approach SPDA during emergency conditions [27]. Both WDS were selected from published papers to validate the obtained results of this study avoiding the long process and possible difficulties to get information regarding the water distribution system from the municipalities or water authorities due to the confidentiality and security.

2.1 The first case study

Fig. III-2 and Fig. III-3 depict a system with one source node, one pumping station contains 3 main pumps, 16 demand nodes (K-nodes) and 35 links. This network is taken from a previous academic journal paper and is often used for hydraulic and reliability calculations as it contains all the significant elements of a water distribution system [17]. The number of junctions, reservoirs, pipes, pumps and valves are 16, 1, 34, 3 and 0, respectively. The flow is 403.77 lps. The model has been applied in DDA and SPDA for normal cases and emergency conditions by removing pipes numbers 2, 4 and 6, respectively, in different scenarios. The results for DDA and SPDA approaches include nodes with pressure deficiency as explained per in Tables B-1, B-2 and B-5 to B-7 (in Appendix B).

2.1.1 The analysis of the first case study results

The obtained pressure and consumption from running EPANET have been tabulated. This is demonstrated in Table B-1 (in Appendix B). The complete analysis is in Tables B-2 and B-5 to B-7 (in Appendix B) for DDA and SPDA approaches utilized during different scenarios of burst pipes 2, 4 and 6. Examples for evaluation and verification are described in the following sections.

2.1.2 The results analysis of demand-driven analysis (DDA)

In Table B-1 (in Appendix B) the evaluation of the burst pipe 2 scenario the passing flow rate through pipe 2 (400 mm diameter) is 159.75 lps. In pipes 4 and 6 (with a 300 mm diameter) have flow rates passing through them that are equal to 128.53 lps and 83.95 lps, respectively. The total supplied flow was equal to 403.77 lps for the entire WDS. In Table B-2 (in Appendix B), burst pipe 2, pipe 4 and pipe 6 scenarios have an average pressure efficiency of 6.25 %, 6.8% and 27.64%, respectively. In Fig. III-2, the original pressure in the WDS was high enough to supply the network with pressure above the minimum threshold within 34.45 m to 68.94 m. Fig. III-2 also shows that the pressure in the case of burst pipe 2 has a low pressure range between 17.25 m to 34.45 m. It should be noted that burst pipes 4 and 6 have comparable results.

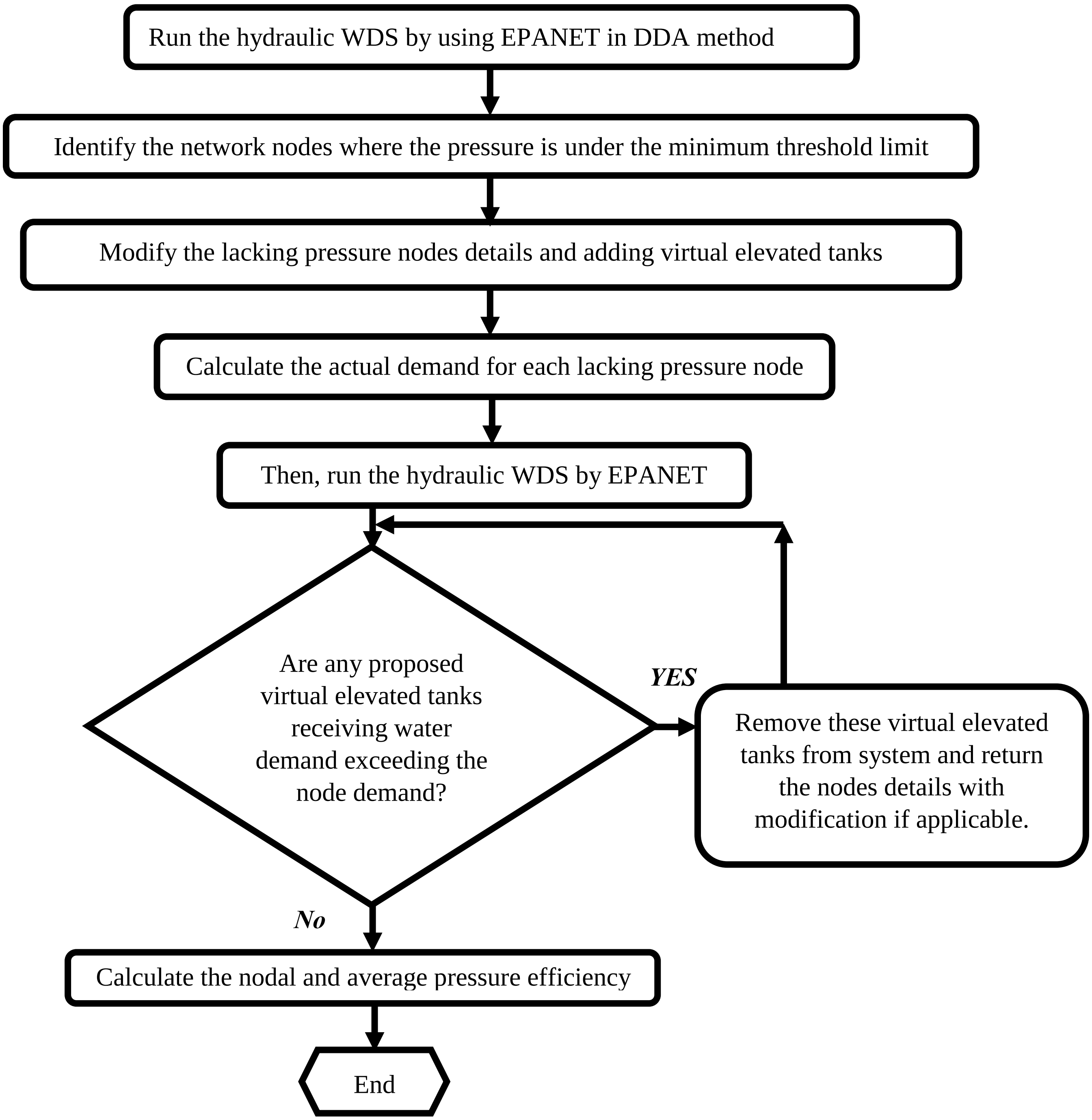

Figure III-1: The flowchart of semi-pressure driven analysis (SPDA) algorithm

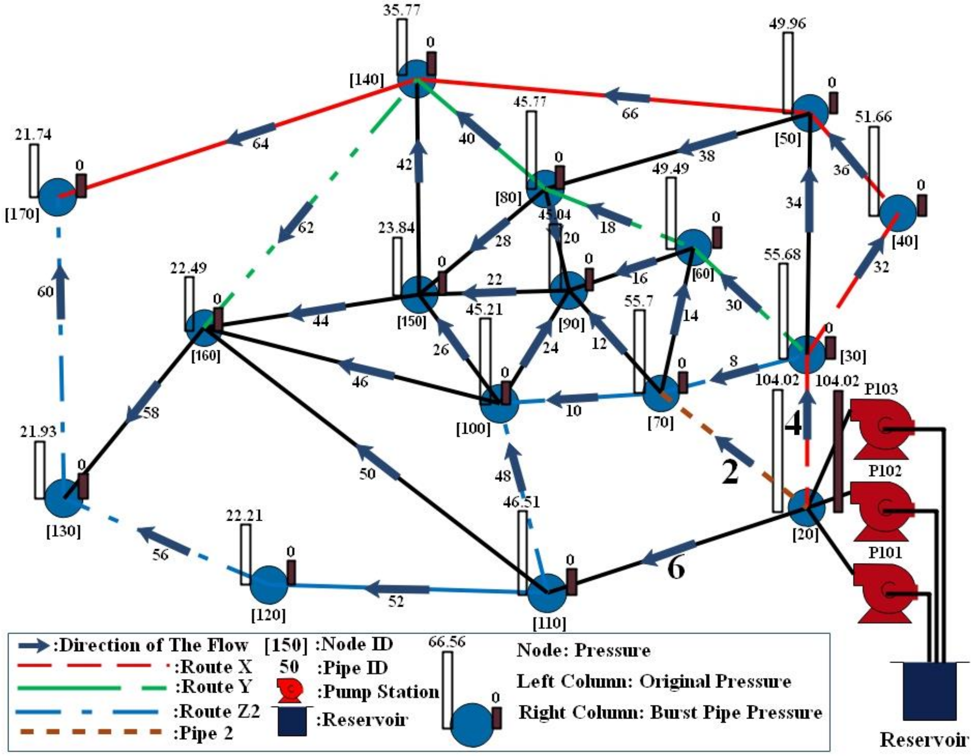

Figure III-2: The first case study with viewing pressure at the original condition and after applying the demand driven analysis (DDA) in burst pipe 2.

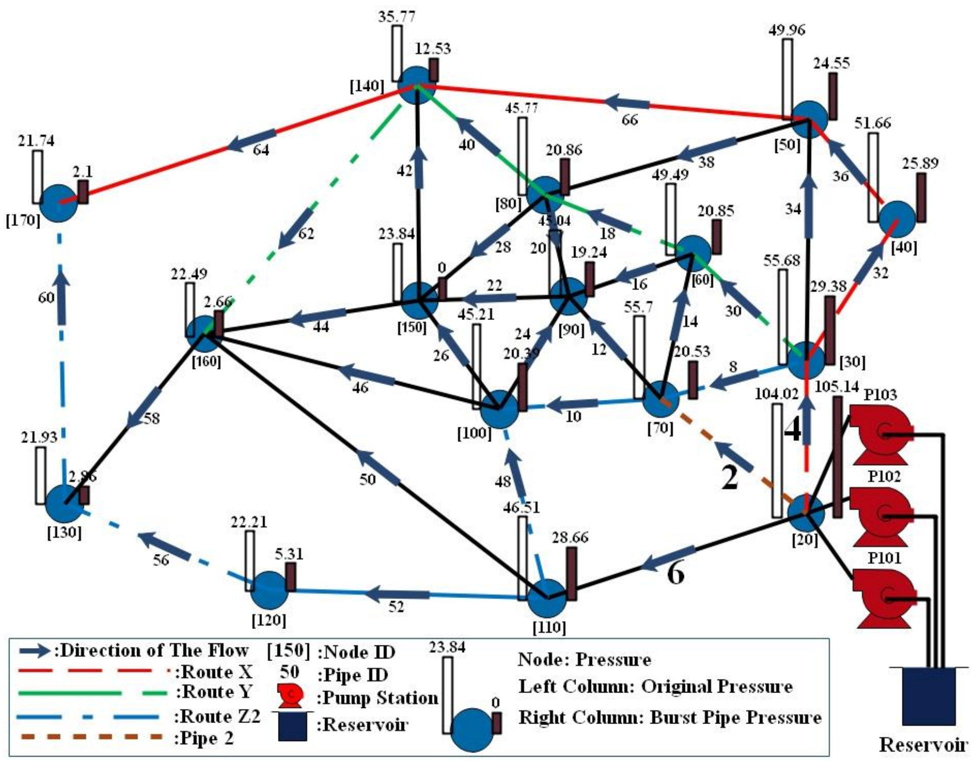

Figure III-3: The first case study with viewing pressure at the original condition and after applying the semi pressure driven analysis (SPDA) in burst pipe 2.

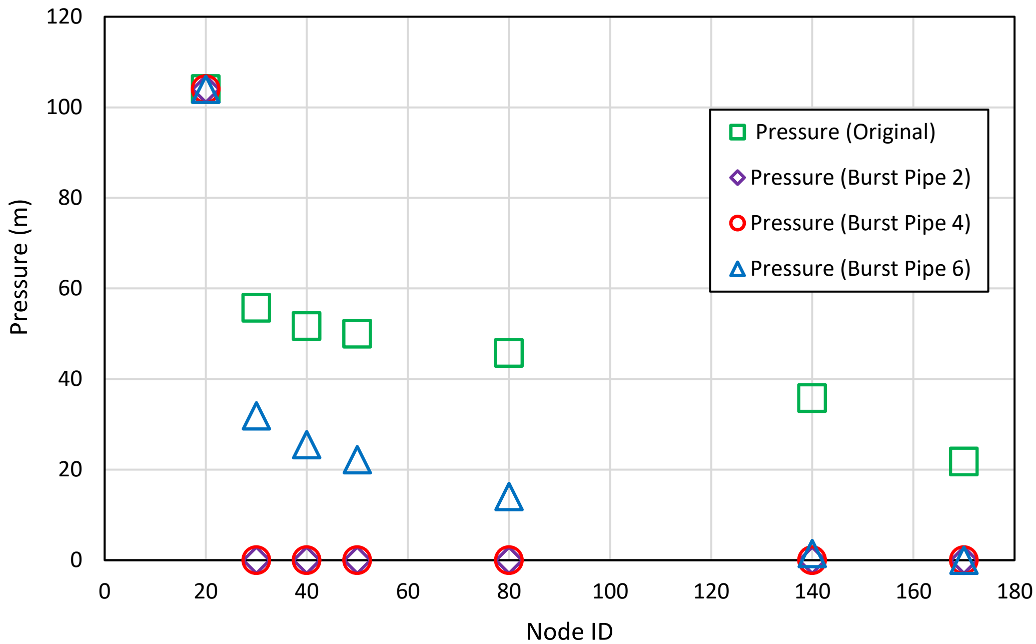

Figure III-4: The case study I: The pressure profile for route X by demand driven analysis (DDA) for the original condition and burst pipes 2, 4 and 6.

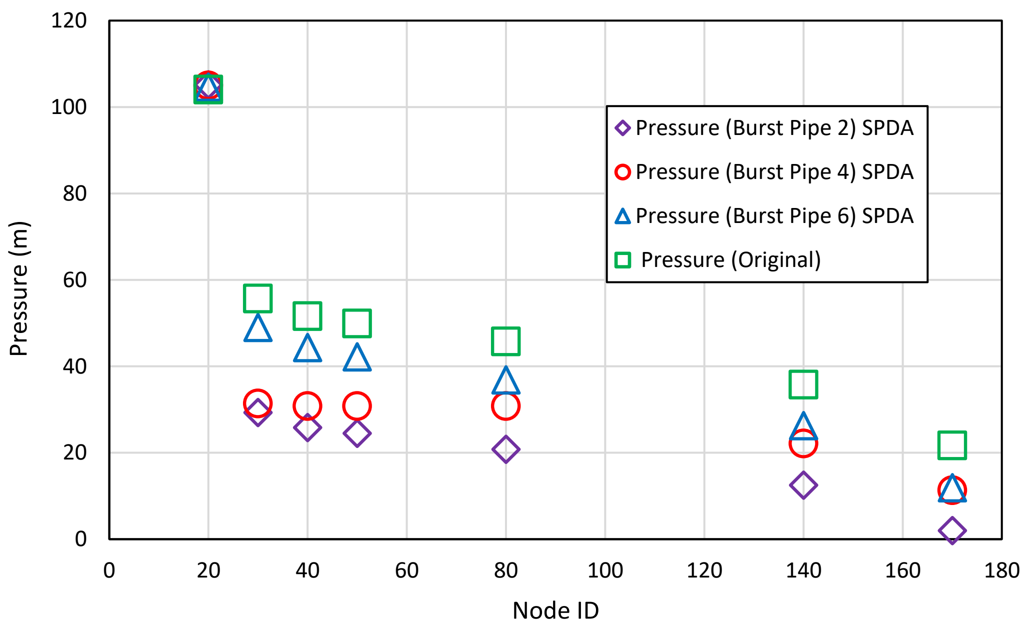

Figure III-5: The case study I: The pressure profile for route X semi pressure driven analysis (SPDA) for the original condition and burst pipes 2, 4 and 6.

2.1.3 The results analysis of semi pressure driven analysis (SPDA)

The SPDA approach is illustrated in Table B-5 (in Appendix B) and indicates where the total flow supplied to the WDS for the case where pipe 2 burst was decreased to 302.83 lps for the burst pipe

2 has WDS average pressure efficiency equal to 38.72 % compared with 6.25% for the DDA method. In the SPDA scenario for burst pipe 4, the total flow is equal to 318.45 lps and the pressure efficiency is 63.82 % compared with 6.8 % in the DDA. As well, the SPDA scenario for burst pipe 6 has a total flow of 347.49m. The average pressure efficiency was 74.1% compared with 27.64 % in the DDA.

2.1.4 The first case study results—Verification

Three different routes within the WDS were used to verify the results of the DDA, and SPDA approaches for the original WDS as well as the three scenarios for burst pipes 2, 4 and 6: route X, Y and Z2. Routes X, Y and Z2 start from the node near the source of the supply and are traced to the far nodes of the WDS as per flow direction to examine the impact of emergency/burst pipe on pressure and pressure efficiency for different nodes of the WDS [28]. Fig. III-2 and Fig. III-3 as well as Fig. III-4 and Fig. III-5 in addition to Fig. A-12 to Fig. A-15 (in Appendix A) demonstrate the verification of different routes for all of the scenarios.

2.1.4.1 For route X

Contained in Fig. III-4 is the pressure profile for the original WDS scenario in DDA from 20 m to 105 m, where the demand can be achieved. Fig. III-4 illustrates the pressure profile for the WDS scenario using DDA for burst pipes 2,4 and 6, which dropped from 105 to 0 m with 0 values for most of the nodes.

Fig. III-4 and Fig. III-5 illustrate the pressure profile for the WDS scenario for burst pipes 2, 4 and 6 using the SPDA approach that drops from 105 to 0 m with pressure in the range of 12 m to 25 m for most of the nodes. Both pressures in DDA and SPDA have the same trend, but the efficiency of the WDS is improved for burst pipe 2 from 6.25% in the DDA, Table B-2 (in Appendix B), to 38.72% in the SPDA Table B-5 (in Appendix B).

Comparable results are obtained for burst pipe 4 with an improved pressure efficiency of 63.82% using SPDA compared to DDA's pressure efficiency that is 6.8%. For the scenario analyzing the burst pipe 6 efficiency where the pressure is 27.24% in DDA, and that increased to 74.1% under the SPDA.

2.1.4.2 For route Y

Fig. B-12 and Fig. B-13 (in Appendix B) also illustrate the pressure profile for the WDS scenarios in DDA and SPDA, respectively, for burst pipes 2, 4 and 6. The same results are obtained as are described for the X route above.

2.1.4.3 For route Z2

Fig. A-14 and Fig. A-15 (in Appendix A) also illustrate the pressure profile for the WDS scenarios in DDA and SPDA, respectively, for burst pipes 2, 4 and 6. The same results are obtained as described for the X and Y routes.

2.2 The second case study

The model used is part of the El-Mustaqbal City water distribution system (WDS) was utilized for research into reliability in the context of a Middle Eastern environment in Egypt as is shown in Fig. III-6 to Fig. III-10 [29]. The number of junctions, reservoirs and pipes are 32, 1 and 44, respectively. In this scenario, there were no tanks, pumps, or valves. Finally, the flow was equal to 352.49 lps, and the pipes' diameters size ranged between 150 mm to 600 mm. The model has been applied using DDA in normal conditions and with SPDA for three emergency cases by removing pipes 2, 3 and 8 through individual scenarios in sequences as per Tables B-3 to B-4 (Appendix B).

2.2.1 The analysis of the second case study's results

The obtained pressure and consumption from running EPANET have been tabulated. Review this analysis in Tables B-3 to B-4 as well as in Tables B-8 to B-10 (in Appendix B).

Figure III-6: El-Mustaqbal City (Egypt) outline specified by red lines parameter map from Google Earth,

The result analysis for DDA and SPDA approaches during different scenarios of burst pipes 2, 3 and 8 have been demonstrated as examples for evaluation and verification as seen in the following sections.

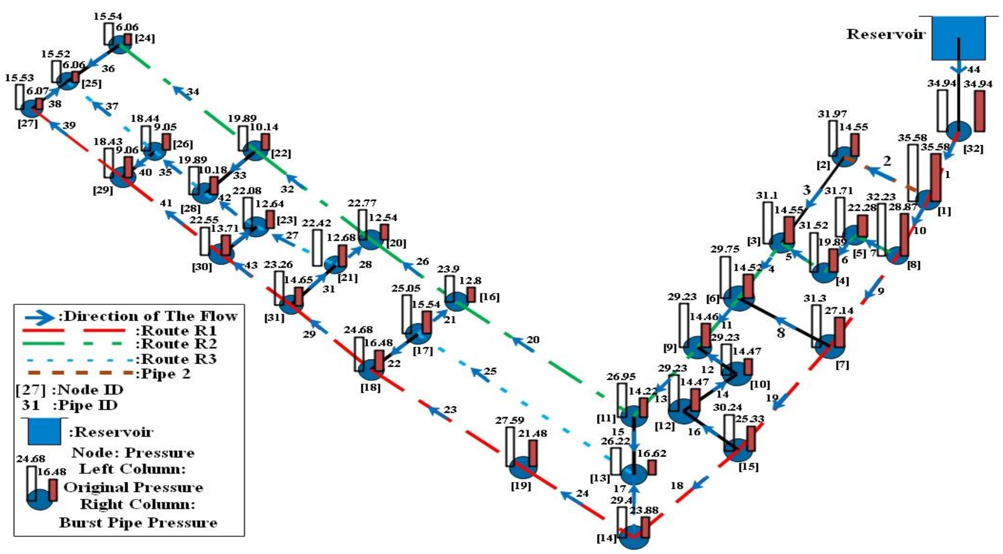

Figure III-7: The second case study with viewing pressure during the original condition and with the demand driven analysis (DDA) in burst pipe 2.

2.2.2 The results analysis of demand driven analysis (DDA)

The evaluation of the scenario results of the burst or removed pipe 2 indicates that the pipe has a water flow rate of 102.72 lps (see Table B-3 in Appendix B); a 300 mm diameter with a total supplied flow to the WDS of shown in Table B-4 (in Appendix B). Fig. A-16 (in Appendix A) shows that the DDA pressure is reduced dramatically compared with the pressure at the same nodes under the original model's condition. Furthermore, the efficiency for the case of burst or removed pipe 3 is 62.66 % while the flow rate passing through pipe 8, which is 150 mm in diameter, is equal to 9.17 lps as is shown in Tables B-3 to B-4 (in Appendix B). It is established, as well, that the pressure efficiency for pipe 8 is 99.36%.

2.2.3. The results analysis of semi pressure driven analysis (SPDA)

Shown in Table B-8 (Appendix B) is the result of the analysis of burst pipe 2. When the SPDA approach is applied the total flow supplied to WDS is equal to 320.82 lps, which is less than the original DDA total flow that is equal to 352.49 lps (Table B-3, in Appendix B). It is noted that for burst pipe 2 the SPDA average pressure efficiency is 79.68 % from (Tables B-8 to B-10, Appendix B). This demonstrates a significant huge improvement in comparison to the DDA for the same pipe burst that had WDS average pressure efficiency equal to 60.96% as is demonstrated in Table B-4 (in Appendix B).

Additionally, in the SPDA, the efficiency for the scenario of burst pipe 3 is 80.94% as is shown in Table B-9 (in Appendix B), which is more robust than the effeciency shown in the average pressure of the DDA at 62.66% in Table B-4 (in Appendix B). The SPDA approach for pipe 8 has the same pressure efficiency of DDA, that is equal to 99.36% as shown in Table B-10 (in Appendix B) for the SPDA and for the DDA due to the limitation of the flow rate in the pipe 8 that is 9.17 lps as shown in Table B-4 (in Appendix B), which is small in comparison with the total flow of 352.49 lps.

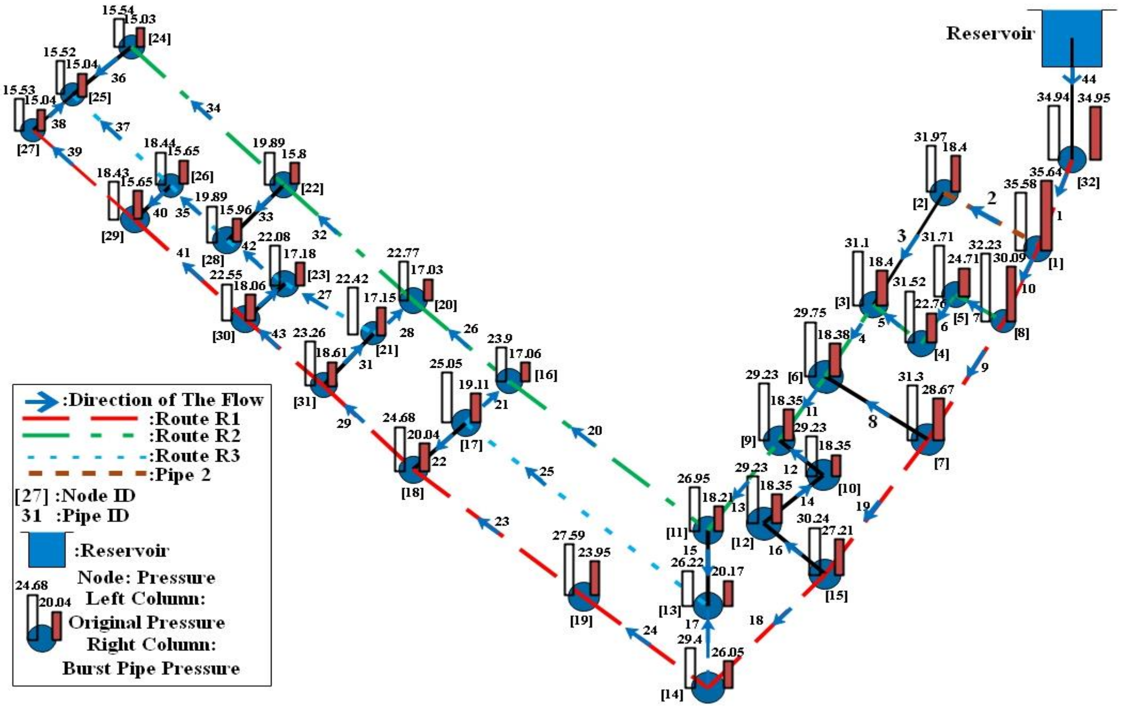

Figure III-8: The second case study with viewing pressure at the original condition and the semi pressure driven analysis (SPDA) in burst pipe 2.

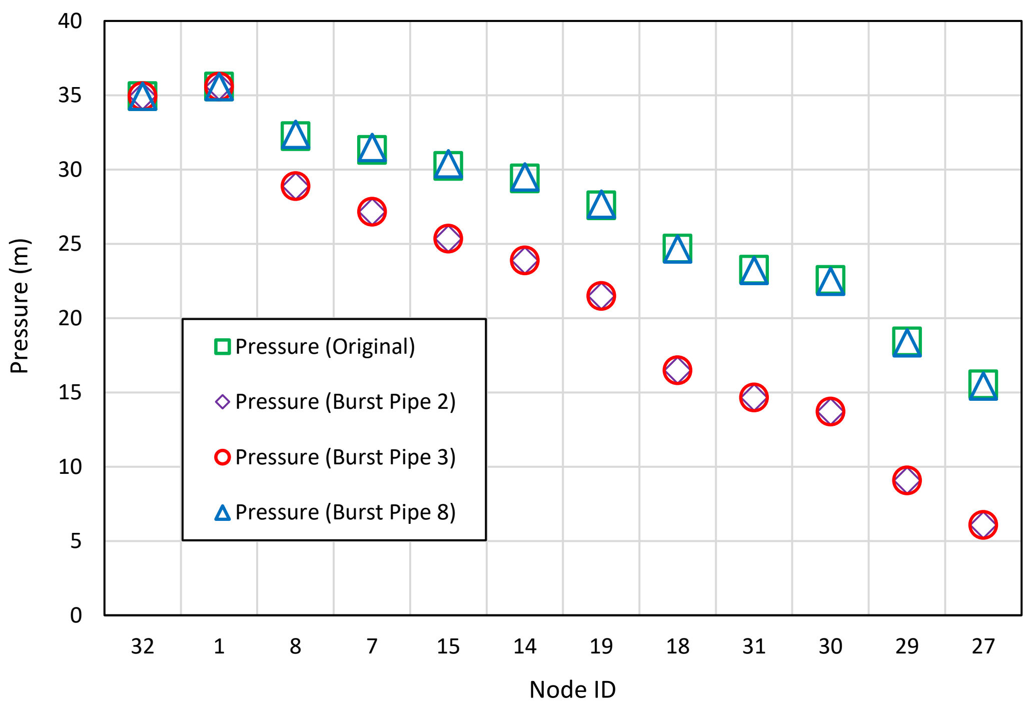

Figure III-9: The case study II: The pressure scenario in DDA for route R1.

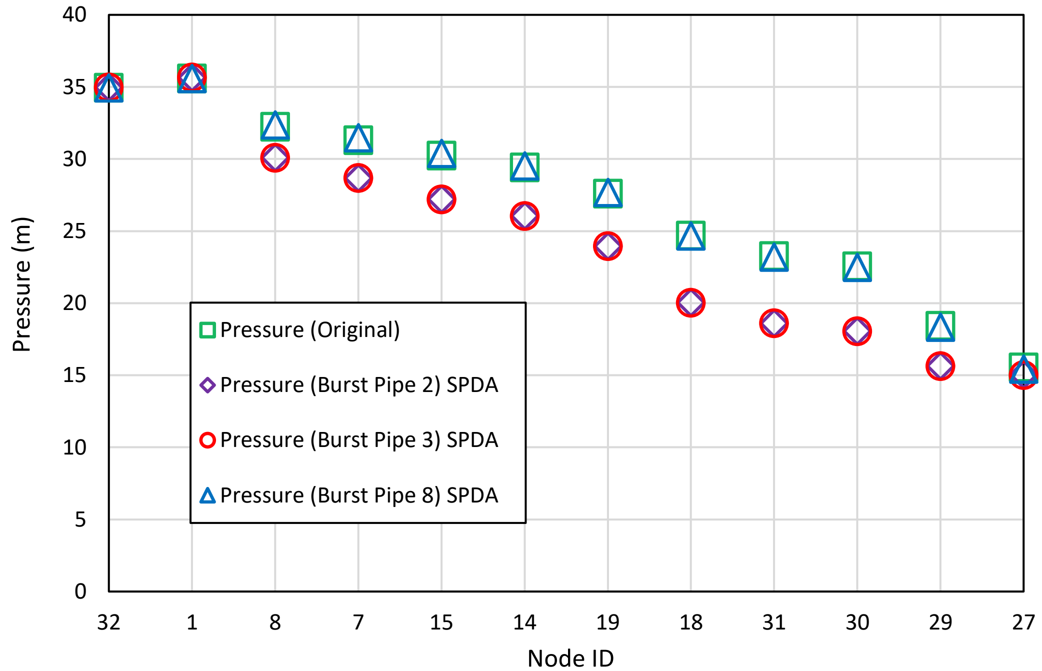

Figure III-10: The case study II: The pressure scenario for route R1 after applying SPDA method.

2.2.4 The second case study results—Verification

To verify the results of the DDA and SPDA approaches for the original WDS as well as for the three burst pipe scenarios (pipes 2, 3 and 8), three different routes within the WDS (R1, R2 and R3) were analyzed. The results are shown in Fig. III-9 and Fig. III-10 as well as in Fig. A-18 to Fig. A-19 (in Appendix A). These routes started from the node near the source of supply and traced to the far nodes, following the flow direction, of the WDS to examine the impact of emergency conditions on the pressure for different nodes in the WDS [19]. The y-axis represents the pressure in meter unit with range drops from 40 m to 5 m. The graph x-axis in the graph represents the node number in sequences and numbers. The graph illustrates the profile pressure in both the original WDS scenario in the DDA, and in the SPDA for burst pipes 2, 3 and 8.

2.2.4.1 For route R1

Fig. III-9 demonstrates the pressure profile for the original WDS scenario in which the DDA drops from 45 m to 5 m where it was shown that the demand could be supplied. The graph illustrates the pressure profile for the WDS scenario in the DDA for burst pipes 2, 3 and 8. The pressure profile drops from 45 m to 5 m with a low-pressure value for many nodes in the WDS. Fig. III-9 and Fig. III-10 demonstrate the pressure profile of WDS scenarios for burst pipes 2, 3 and 8 in the SPDA approach that drop from 40 m to 15 m for most of the nodes. Both the DDA and SPDA have the same trend, but the pressure efficiency of the WDS is improved. The pressure efficiency in the DDA for burst pipes 2 and 3 were 60.96% and 62.66%, respectively (see Table B-4 in Appendix B), while the efficiency of pressure in SPDA for burst pipes 2 and 3 are 79.68% and 80.94%, respectively, as is shown in Tables B-8 and B-9 (in Appendix B).

Fig. III-9 and Fig. III-10 illustrate the pressure profile for the WDS scenario for burst pipe 8 in DDA and SPDA that drops from 40 m to 5 m with pressure in the range of 35 m to 15 m for many of the nodes of the WDS. Both pressure profiles of the WDS have the same trend, and the efficiency is equal to 99.36% as is shown in Tables B-4 and B-8 (in Appendix B). The efficiency is equal, in both cases, because the flow rate in pipe 8 is small at 9.17 lps and it has a minor impact on the WDS when the pipe bursts. This result proves the strength and the accuracy of the SPDA for achieving reliable results.

2.2.4.2 For route R2

Fig. A-18 and A-19, as shown (in Appendix A), indicates route R2 for burst pipes 2, 3 and 8. It demonstrates the pressure profile for the original WDS scenario in the DDA and in the SPDA providing a comparable result to route R1.

2.2.4.3 For route R3

Fig. A-18 and Fig. A-19 (Appendix A) represents the same results and trends as found in routes R1 and R2 where the results indicate the low efficacy of burst pipes 2, 3 and 8 in the DDA approach. Fig. A-20 and Fig. A-21 (Appendix A) for route R3 signifies a similar result as in routes

R1 and R2 for the same burst pipes, that is 2, 3 and 8, in the SPDA approach. The verification and validation prove that the results are similar to the analysis of different scenarios like routes R1 and R2.

3.0 Conclusion

The purpose of this current study is to explore and clarify the difference between the demand-driven analysis (DDA) in original and emergency conditions, and during the semi-pressure driven analysis (SPDA) where demands may reach emergency levels. The two methods of approach are applied in the current research wherein the SPDA is applied for a more realistic reliability assessment of water distribution networks and the proposed methodology uses DDA results as iteratively starting point and proceeds using one of the most commonly used demand-driven software: EPANET. The EPANET hydraulic simulation model provided the simulation of the models for both normal and emergency conditions in water distribution system scenarios for two different case studies. The accuracy of the generated SPDA results has been verified using the hydraulic analysis results. The results demonstrate the weaknesses of DDA as it does not reflect the impact of a pressure drop on the node demand or the inability to quantify the deficiency of WDS performance. Involving the SPDA in research captures a realistic performance of the demand and related pressure at nodes. The nodal water supply is adjusted to satisfy the minimum nodal pressure requirement under the abnormal conditions, which arises when part of the water distribution system is closed for maintenance, rehabilitation, or because of an accident. The maximum of pressure for the water supply, while maintaining the nodal pressure, is 14 m. This amount is defined as the effective supply to guarantee the customers' demands are met. Reliability, in this present research, is defined as average pressure efficiency and it is the ratio of the amount supplied to meet the required pressure.

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5.0 References

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CHAPTER IV

Enhance the Reliability of Water Distribution System Utilizing the Smart Middle Eastern Application

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NOMENCLATURE

DDA	Demand Driven Analysis	OOTEN	Object Oriented Modification
D-W	Darcy Welsbach	PDA	Pressure Driven Analysis
EPS	Extended Period Simulation	H-W	Hazen-William
W-C	White Colebrook	WDS	Water Distribution System
M	Meter	EBT	Elevated Balanced Tank
LPS	Liter Per Second		

Keywords*:* Demand-Driven Analysis; Efficiency; EPANET; Hydraulic; Pressure Driven Analysis; Water Distribution System

1.0 Introduction

The pressure-driven analysis (PDA) models have become an essential tool for hydraulic analyses of water distribution system (WDS) under stress conditions. WDS modelling practice still relies mostly on the DDA calculations of steady and uniform flows in pressurized networks. DDA is used by almost all the traditional network hydraulic solvers, such as EPANET and KYPIPE [1]–[3]. When the pressure in a network drops, either due to a pipe or pump failure, or because of 'regular' intermittent supply caused by inadequate source capacity, the low pressure can affect demand. When this is about to happen, the hydraulic simulation should switch to more computationally analysis approaches. In a simplified approach, PDA models can be based on the principle of the emitter coefficient available

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in EPANET software [1]. If the minimum pressure requirement cannot be met, then only a fraction of the nodal demand can be satisfied. To satisfy this nodal demand, a relationship must be established between demand and pressure. A Semi Pressure Driven Analysis (SPDA) developed an algorithm for the network analysis that could circumvent the problem of spurious negative pressures due to forced demand conditions in the hydraulic analysis [6]. The technique called the Demand Driven Analysis Available Method (DDA-AM), which can be used for a more realistic reliability assessment of water distribution systems compared to pure DDA. The pressure sensitive demand implemented version of EPANET uses the object-oriented modification of EPANET known as OOTEN and utilizes the Emitter functionality of EPANET [6]. This was a command line tool that was not integrated into a graphical user interface. Furthermore, the new numerical algorithms have presented results to handle pressure driven analysis (PDA) in networks [7]. The EPANET 2.0 computational modified engines to implement pressure sensitive demand in network calculations [6],[8]. This is explained by an emitter formula which expressed that demand is proportional to a fractional power of the pressure (normally this power, $\alpha = 0.5$ for nozzles) in a way that is completely compatible with the existing user interface of the DDA EPANET standard.

1.1 The main objective and assumption

The present research seeks to evaluate, verify and compare the result of applying PDA methods that are SPDA, EPANET's normal emitter method, and EPANET's modified emitter method. Each is common reliability analysis methods that are modified to be more efficient in emergency or contingency scenarios of a WDS [9]. The results of the models will be compared with each other and to the conventional DDA to determine which method is more reliable, sensitive and time effective. Based on the selected reliable method results, the smart Middle Eastern solution to balance the reliable supply to WDS will be applied to allocate and design the proper WDS equipment. The elevated tanks will be added to WDS to eliminate the impact of the emergency conditions on the WDS and providing the reliable supply to every consumer in the network**.**

1.2 The applied assumptions

The assumptions of the current Chapter IV are the same assumption applied in Chapter III which are have been proven to be valid.

1.3 Theory of reliability

The mandatory part of the network reliability model is the phase during which the network's deficiencies are predicted under partially failed conditions. Consequently, once the pressure drops below the proposed threshold value, a shortfall begins in the volume of water flow that is delivered to consumers. The threshold pressure values are in the range of 14 m to 25 m, which can guarantee satisfactory service at all related taps in WDS [5]. The PDA simulation recognizes the weakness of DDA concerning nodal flows and heads which should be considered simultaneously to predict deficient network performances more accurately [12]. The concept of pressure driven demand can be compared to the discharge through an orifice, where h is the net head on the orifice, gravitational acceleration, A is the surface area of the orifice C is the shape factor of the orifice:

$$Q = CA\sqrt{2gh} \qquad (1)$$

The detailed comparison of various flow-head provides relationships, pressure driven approach, which is proposed by the researchers [13]. Typically, the relationship is expressed as *H*:

$$H_i = H_i^{min} + K_i Q_i^n \qquad (2)$$

Where H_i represents the actual head at demand node i , H_i^{min} is the minimum head below which the service becomes stopped, K_i is the resistance coefficient for node i, Q_i is the nodal discharge,and n is the exponent that theoretically and usually in practice takes values of 2.0 [14]. H_j^{min} is the threshold pressure head below, the outflow which at the node is unsatisfactory or 0. The concept of EPANET emitter coefficients uses a similar relationship as in Eq. (1). An emitter is modeled as a setup of a dummy pipe connecting the actual node with a dummy reservoir whose initial head equals to the nodal elevation, z. Hence, $H_i^{min} = z_i$.

To determine the unknown value of Q_i for any given nodal dead, Eq. 3 should be rearranged as:

$$Q_i = (\frac{H_i - H_i^{min}}{K_i})^{1/n} \tag{3}$$

When Q_i is equal to the required demand, Q_{req}, the value for H_i should equal to the desired head, H_{des}, in the node. It is the head that should be available if the demand at that node is to be satisfied in full. Hence:

$$Q_i^{red} = (\frac{H_i - H_i^{min}}{K_i})^{1/n} \rightarrow \frac{1}{K_i^{1/n}} = \frac{Q_i^{red}}{(H_i^{des} - H_i^{min})^{1/n}} \tag{4}$$

Finally, substituting K_i in Eq. 3 yields:

$$Q_i^{avl} = Q_i^{req} (\frac{H_i^{avl} - H_i^{min}}{H_i^{des} - H_i^{min}})^{1/n} \tag{5}$$

Where Q_i^{avl} is the discharge available for the head available at the node H_i^{avl}. Eq. (5) considers three possible situations:

1. $H_i^{avl} \leq H_i^{min} \rightarrow Q_i^{avl} = 0$
2. $H_i^{avl} < H_i^{min} < H_i^{des} \rightarrow 0 < Q_i^{avl} < Q_i^{req}$
3. $H_i^{avl} \geq H_i^{des} \rightarrow Q_i^{avl} = Q_i^{req}$

where the demand is fully dependent on pressure, such as an irrigation sprinkler system (ISS), the PDA relationship is explained by an emitter formula that states that the water demand is proportional to a fractional power of the pressure, this power for nozzles $\alpha = 0.5$ [16]. When there is no 'adequate' pressure, where the P_{ECUP} = the minimum threshold pressure required for the WDS to reach the water demand for each node, the demand depends on customer decided demand Q_o and the current pressure of the system (P) [17]. Therefore, all demand nodes of a network that have converted to a stable condition under realistic PDA and should satisfy the following:

1. For: $P > P_{ECUP}$, $Q = Q_o$

2. For: P < 0, Q = 0

3. For: 0 < P < P_{ECUP} , Q = KP^{α}

$$K_i = \frac{Q_{i,DD}}{ECUP^{\alpha}} \tag{6}$$

Where K is a proportionality constant, known as an emitter constant.

1.4 The emitter approaches

Full-featured and accurate hydraulic modelling is a prerequisite to creating an effective water quality modelling. EPANET contains a hydraulic analysis engine that can model the flow in the Pressure Dependent approach issuing from an emitter node (sprinkler heads) with an EPANET Normal Emitter Pressure Driven Analysis [18]. Emitter Exponent Power going to that pressure is raised when computing the flow through an emitter device. Emitters are devices associated with junctions that model the flow through a nozzle or orifice that discharges to the atmosphere [19]. Emitters are utilized to model flow by sprinkler procedures. This method is used to simulate the leakage in the main pipeline that connects to the junction for computing a fire flow available at some minimum residual pressure. EPANET handles emitters as a property of a junction, and not as an independent network element that can be utilized to compute the actual demand in PDA [19], [20]. The emitter coefficients were first introduced in EPANET to simulate the operation of fire hydrants or irrigation sprinkler system. By specifying the emitter coefficient, the demand node would turn into an emitter node. This is a node in which the demand will be adjusted based on the actual pressure in the system according to Eq. 5 [20], [21]. The default value for exponent α in EPANET is 0.5, which can be adjusted if necessary. Using the emitter approach gives a clear advantage while exploring the effects of pressure management on the leakage reduction in the system [22]. Furthermore, a node affected by an emitter is connected to the normal consumption node with a dummy pipe of low resistance.

1.5 The smart Middle Eastern technology solution

The smart Middle Eastern solution can be defined as the best practice application for the basics of the hydraulic theory in water distribution system by installing the required water system equipment such as: pump set; control valves; additional pipeline or elevated tank. The reliability assessment can lead to either one or all the smart solutions. The main objective of the smart solution is to supply the suitable quantity of water with an acceptable level of pressure for all nodes under the normal and emergency modes of supply, such as peak hourly demand or fire flow without further negative impact to WDS [13], [25]. There are many suitable smart solutions such as: installing additional pipelines with a large diameter size; providing an additional water source; constructing an additional pump station; building an automated control system; and constructing an elevated balance tank.

1.6 The criteria for selecting the suitable smart technology solution

The demand balancing tank enables demand management, assures water supply during system failures and reserves water for emergency situations such as firefighting, and allows for pump flow rate modulation. Tanks represent quite a small part of the whole network's cost. Nevertheless, they have a significant impact on the overall network performance. If the tanks are well designed and located, they may improve the overall network performance and reduce the total cost [26], [27]. It is stated that the design of an elevated tank involves the following decision variables: supply volume (balancing fire and emergency volumes) and hydraulic variables (maximum and minimum water levels). The design of the elevated tank should consider the operational variables (maximum, minimum and normal operational levels), and construction variables (shape, type, location and configuration of both the outlet and inlet pipes).

1.6.1 The design of the elevated balance tank

The tank volume is calculated with the assumption that is has a cylindrical shape [28]. This volume is consisting of four combined volumes (see Fig. A-7, in Appendix A). The model determines the maximum height level of the tank, the pipe diameters, the minimum water level, and initial water level at the beginning of the simulation [26], [29]. The optimization is constrained by minimum nodal pressure, maximum pipe unit head-loss, and tank inflow and outflow that preserve the demand balance in the network. The optimization process is done by generating many solutions through trial and error and then selecting the best solution based on the objective function [30], [31].

1.6.1.1 The SPDA approach

The SPDA method starts with the usual DDA, then identifies nodes that have insufficient pressure in the network, and that are not able to fully supply the demands of the outlet elevations served by specific node [34]. This identifies which of the remaining nodes are fully satisfactory regarding both pressure and demand values. For this purpose, the assumed modifications are made at each Pressure Deficient Node [5], [10], [35] as explained in Chapter III.

1.6.1.2 The emitter normal pressure driven analysis (ENPDA)

ENPDA is considered as a part of EPANET in the flow chart (see Fig. A-2, in Appendix A) [1].

1.6.1.3 The emitter UNESCO pressure driven analysis (EUPDA)

Another strong method to apply the pressure dependent analysis is the modified emitter

EPANET and the flow chart (see Fig. A-2, in Appendix A) [37].

1.7 The smart Middle Eastern technology approach (Fig. A-3 and Fig. A-4, in Appendix A)

1.7.1 Select the location and characteristics of elevated tank

1. At the node where the major impact in the demand and pressure happened.

2. At the low ground elevation but the elevation is higher than the value of threshold pressure.
3. To satisfy the minimum required pressure and the head loses.
4. To be able to supply WDS during peak period at least six hours during the emergency.
5. The size of the elevated tank is the summation of the following (Fig. A-5, in Appendix A):

i. Demand balancing volume = the summation of the difference between the average of low consumption and average supplied water during the period when the consumption rate is lower than the average supplied rate. Or;

ii. Demand balancing volume = the summation of the difference between the average high consumption and average supplied water during the period when the consumption rate is higher (peak) than the average supplied rate.

The design of the elevated tank volume will consider the largest volume of (i or ii):

a. Emergency volume for maintenance works (the leakage during the pipe failure events, or flow of firefighting) = 2* Demand Reduction * Maintenance Time *Peak factor.
b. 'Dead' volume (dead depth) to protect the tank from staying dry = 0.30 m.
c. Overflow depth to protect the tank against the overflow = 0.30 m.

2.0 Case Studies

Two different WDS are used to analyze both traditional hydraulic analysis DDA as well as three approaches to pressure dependent analysis PDA during the emergency condition. These two WDS have been used before in Chapter II and Chapter III. The proposed PDA approaches are Semi Pressure Driven Analysis (SPDA), EPANET-Normal Emitter Pressure Driven Analysis (ENPDA) (Fig. IV-1) and EPANET-UNESCO emitter pressure driven analysis (EUPDA). These reliability model approaches and conventional demand-driven analysis DDA model approach are demonstrated on a hypothetical example of water distribution system [38].

2.1 The first case study

The present WDS first case study is the same first case study was used in Chapters II and III as follows [39], [40]: The first case study has a single source node, three pumping stations, 16 demand nodes, and 35 links in (Fig. A-10, in Appendix A). This network is taken from previous research and modified according to the requirements of the current research [39].

2.1.1 The analysis of the first case study results

The obtained pressure and demand have been tabulated in Table B-1 (in Appendix B) with the complete analysis in (Tables B-5, B-6 and B-7, in Appendix B), and the percentage of the average pressure efficiency has been calculated. Pipes 2, 4 and 6, respectively, have been demonstrated as examples for evaluation and verification of the emergency scenarios since these three pipes carry the largest amount of flow in WDS, which considered as the worst-case analysis scenarios. The results analysis illustrates the pressure that occurs when applying three different reliability analyses SPDA, ENPDA and EUPDA along the traditional DDA.

2.1.1.1 For burst pipe 2

The reviewing of the SPDA illustrates that the total flow supplied to WDS for the case of burst pipe 2 in the WDS is 302.83 lps where the WDS average pressure efficiency is 38.72%. In Table B-5 (in Appendix B) the total flow passed in the ENPDA analysis is equal to 301.51 lps with the WDS average pressure efficiency is equal to 38.83%. Furthermore, the outcome results from EUPDA are like the other two reliable methods and the total flow as shown in Table B-5 (in Appendix B) is equal to 302.12 lps with an average pressure efficiency of 38.94%, which is very close to each other as a reliable solution.

2.1.1.2 For burst pipe 4

The review of the SPDA illustrates that the total flow supplied to the WDS for the case study of a burst pipe in the WDS is 318.45 lps where the WDS average pressure efficiency is 63.81%. In Table 3, the total flow passed in ENPDA analysis is equal to 329.3 lps with an average pressure efficiency of 45.16%. Furthermore, the outcome results from EUPDA are like the other two reliable methods, and the total flow is shown in Table B-6 (in Appendix B) and is equal to 332.69 lps with average pressure efficiency of 46.29%, which is very close to other reliable solutions.

2.1.1.3 For burst pipe 6

The reviewing of the SPDA illustrates that the total flow supplied to WDS for the case of the burst pipe 6 is 347.50 lps where the WDS average pressure efficiency is 74.04% in the SPDA. In the Table B-7 (in Appendix B) the total flow passed in ENPDA analysis is equal to 350.80 lps with a total efficiency of 61.01% for burst pipe 6. Moreover, the outcome results form EUPDA is like the other two reliable methods, and the total flow as shown in Table B-7 (in Appendix B) is equal to 355.48 lps with an average pressure efficiency of 64.16%, which is very close to other reliable solutions.

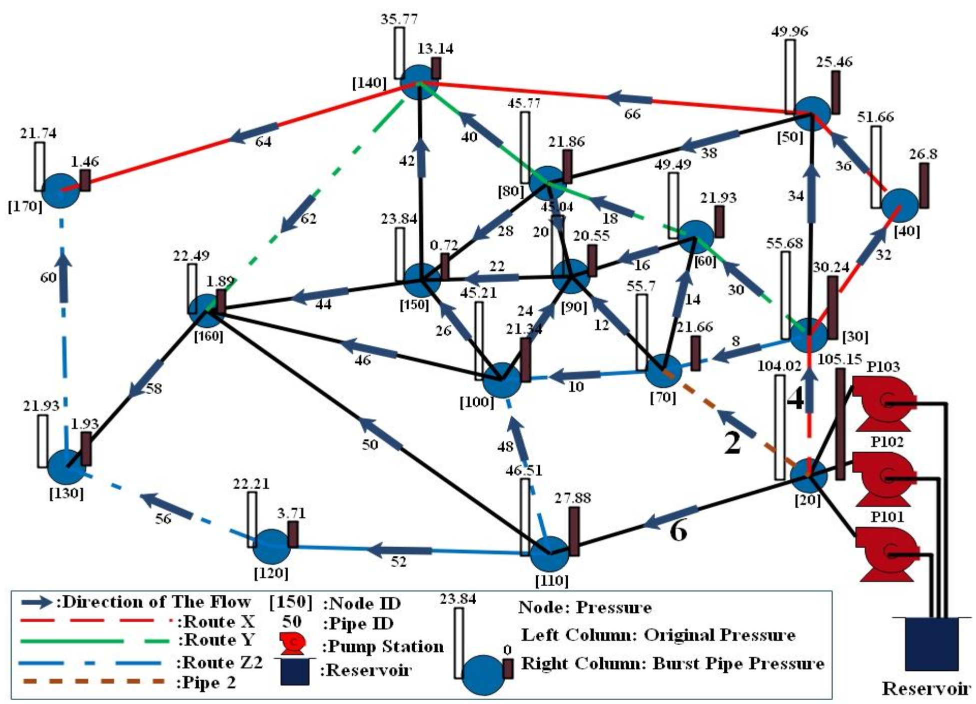

Figure IV-1: The first case study viewing pressure in original and ENPDA approach for burst pipe 2.

It can be stated that the three reliable PDA approaches provide for the analysis results that demonstrate that the approach is robust [41].

2.1.2 The first case analysis result—Verification

The validation has been carried out for three different routes within the WDS, and they are X, Y and Z2. Their validation is illustrated Fig. A-22 to Fig. A-26 (in Appendix A). These routes start from node (20), which is near the source of the water supply and traced to the far nodes of the WDS to examine the impact of the hydraulic grade line and consequently the pressure for the different nodes of WDS [44]. Fig. A-22 to Fig. A-26 (in Appendix A) illustrate the profile pressure in the WDS scenarios using DDA and the scenario for the burst pipes in SPDA, ENPDA and EUPDA of the specified pipes such as in the case of burst pipe 2, as is discussed in the following section.

2.1.2.1 For burst pipe 2 route X

In Fig. A-24 (in Appendix A) burst pipe 2 demonstrated the pressure profile for the original WDS scenario in DDA. The pressure profile in SPDA, ENPDA and EUPDA is in the range of pressure from 105 m to 0 m illustrating that most of the nodes had a pressure reading from 25 m to 14 m. The analysis shows that the pressure efficiency of the WDS in DDA equal to 6.25% is improved to 38.72% in SPDA, and improves to 38.83% in ENPDA and is found to improve to 38.94% in EUPDA. Table B-5 (in Appendix B) shows that ENPDA has an average value between that of the SPDA and the EUPDA. The same analysis approach is applicable for burst pipes 4 and 6, in accordance with the results shown in Tables B-6 and B-7 (in Appendix B), respectively.

2.1.2.2 For burst pipe 2 route Y

Fig. A-25 (in Appendix A) for burst pipe 2 demonstrates the pressure profile for the original WDS scenario in DDA. The graph also demonstrates SPDA, ENPDA and EUPDA in a range of pressures from ranging from 105 to 0 m illustrating that most of the nodes have pressure from 25 m to 14 m. The same is shown for pipe 4 and pipe 6, in Tables B-6 and B-7 (in Appendix B), respectively.

2.1.2.3 For burst pipe 2 route Z2

Fig. A-26 (in Appendix A**)** represents the same results and trends as both routes X and Y where the results have verified the efficiency of burst pipe 2. Fig. A-16 (in Appendix A) indicates comparable results like routes X and Y for the same burst pipe 2 for DDA, SPDA, ENPDA and EUPDA. Fig. A-26 (in Appendix A) shows that ENPDA has average values between the SPDA and that of EUPDA. The same analysis approach is applicable for pipes 4 and 6, as per the results are shown in Tables B-6 and B-7 (in Appendix B), respectively.

2.2 The second case study

Fig. III-6 in Chapter III shows the map of El-Mustaqbal City, Egypt. The model used is part of the El-Mustaqbal City Water Distribution Network, which was utilized for one of the reliability research studies [45]. The current and second WDS under study is case study two demonstrated in Chapter II and III of the present research.

2.2.1 The analysis of the second case study results

The obtained pressure and consumption for water demand results have been tabulated in Table B-3 (Appendix B), and the percentage of the average pressure efficiency has been calculated as is shown in Tables B-4, B-8 to B-10 (in Appendix B). Pipes 2, 3 and 8 have been demonstrated as examples for evaluation and verification since these three pipes carry out the largest and smallest amount of flow in the WDS. The hydraulic analysis of WDS illustrates the pressure in applying three different reliability analyses SPDA, ENPDA and EUPDA along the traditional DDA.

2.2.1.1 For burst pipe 2

The result of the analysis of burst pipe 2, (SPDA), has total flow supplied to WDS that equals 320.82 lps and the WDS average pressure efficiency is 79.68%. Moreover, for burst pipe 2, ENPDA has a WDS average pressure efficiency of 77.09% with a total flow 326.01 lps. EUPDA has pressure efficiency that is 76.66% with a total flow of 328.11 lps in Table B-8 (in Appendix B).

2.2.1.2 For burst pipe 3

The results for burst pipe 3, the SPDA condition, shows a total flow supplied to WDS equal to 320.94 lps and an average pressure efficiency equal to 80.94%. ENPDA has a WDS average pressure efficiency equal to 79.04% with a total flow of 323.93 lps. Also, EUPDA has a pressure efficiency equal to 80.73% with a total flow of 322.63 lps in Table B-9 (in Appendix B). It can be confidently stated that three reliable applied models are working with excellent pressure and flow efficiency.

2.2.1.3 For burst pipe 8

The analysis result of burst pipe 8, for all approaches SPDA, ENPDA and EUPDA as well as DDA, shows the same original flow supplied to the WDS is equal to 352.49 lps in Table B-10 (in Appendix B). The analysis result for burst pipe 8 indicates that it has the same average pressure efficiency equal to 99.36% for the different analysis approaches. This is because the flow pass through pipe 8 is equal to 9.17 lps, which is very small and has no impact on the water supply to the entire WDS where the total in flow is equal 352.49 lps.

2.2.2 The second case study result—Verification

The verification and validation have been carried out for three different routes within WDS (routes R1, R2 and R3) and this is shown in Fig. A-27 to Fig. A-31 (in Appendix A), all burst cases were exposed to different approaches such as DDA, SPDA, ENPDA and EUPDA. These routes (R1, R2 and R3) start from the node near the source of the supply and are directed to the far nodes of the WDS to examine the impact of the emergency condition on the pressure for different nodes in the WDS [32]. The figures illustrate the profile pressure in both original WDS scenario in DDA, and the WDS scenario for the burst pipe in SPDA, ENPDA and EUPD for specific pipes such cases of burst pipes 2, 3 and 8. Fig. A-27 to Fig. A31 (in Appendix A) are verified and validated by the obtained results as described in the following sections.

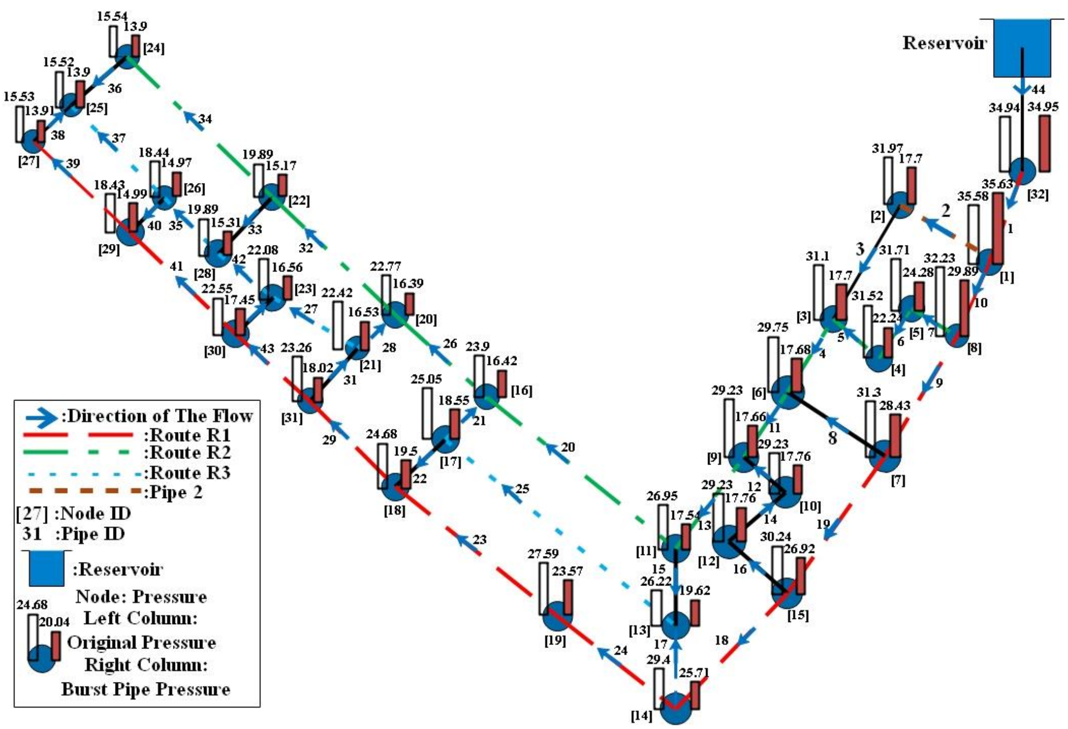

Figure IV-2: The second case study viewing pressure in original and ENPDA approach for burst pipe 2.

2.2.2.1 For burst pipe 2 route R1

Fig. A-29 (in Appendix A), illustrates the pressure profile for the WDS scenario for burst pipe 2 for SPDA, ENPDA and EUPDA in the range of 40 to 15 m, and in the range between 30 m to 15 m for most of the nodes of the WDS. The pressure in the DDA compared to SPDA, ENPDA and EUPDA has the same trend, but the efficiency of the WDS improved from 60.96% in DDA, in Table B-8 (in Appendix B), to 79.68% in SPDA, 77.09% in ENPDA and 76.66% in EUPDA.

Table B-8 shows that ENPDA had an average value between the SPDA and EUPDA. The same analysis applies to burst pipes 3 and 8, as shown in Tables B-9 and B-10 (in Appendix B).

2.2.2.2 For burst pipe 2 route R2

Fig. A-30 (Appendix A) illustrates the pressure profile for the WDS scenario for burst pipe 2 for approaches SPDA, ENPDA and EUPDA in the range from 40 m to 15 m, and with a range between 30 m to 15 m for most of the nodes of WDS. Route R2 has the same analysis as route R1 for all approaches DDA, SPDA, ENPDA and EUPDA. Also, the same analysis is applicable for burst pipes 3 and 8, etc., shown in the Tables B-9 and B-10 (in Appendix B).

2.2.2.3 For burst pipe 2 route R3

Fig. A-31 (Appendix A**)** represents the same results and trends as both routes R1 and R2 where the results are validated for the low efficiency of burst pipes 2, 3 and 8. Fig. A-33 (in Appendix A) indicates a similar result to that of route R1 and R2 for the same burst pipes 2, 3 and 8 in analysis approaches DDA, SPDA, ENPDA and EUPDA. In the same approach the same analysis is applicable for burst pipes 3 and 8, etc., as shown in Tables B-9 and B-10 (in Appendix B).

2.3 The selection of the proper PDA approach

The Semi Pressure Driven Analysis (SPDA) is utilizing partially the hydraulic theory since some nodes will not receive any water, which does not match the real-life site. The SPDA is both time and labour consuming. It should be noted that the current implementation of modified EPANET (EUPDA) has several disadvantages. First, in EUPDA, it is not possible to specify at the same time different emitter exponent values for different nodes or different demand categories. Another issue of importance is the inability of the model to accurately handle actual conditions as opposed to false negative pressure conditions such as unusually elevated node. In this situation, the model has options of zero demand and negative pressure. However, this is a complex situation that does not provide an easy solution within the current modified EPANET through the EUPDA model's approach. The last approach is the ENPDA that is a built-in function in the EPANET model for the simulation of irrigation sprinklers system and firefighting scenarios [52]. ENPDA has limited time consumption with the same accuracy of the original EPNET model. It is obvious that the three reliable applied model approaches are running with excellent efficiency. The analysis criteria are applied to find out and select the best reliable approach, among that of SPDA, ENPDA and EUPDA, to be adopted in the reliable and smart water distribution network approaches analysis. The best practice method will be selected to be used in the coming smart, reliable analysis. In Table IV-1 there is a comparison between the three reliable approaches based on six parameters as explained in the Table IV-1 related to the time consumed in the hydraulic analysis, used labour power, the exception of the negative pressure and exceeding demand value as well as the needs to modify the hydraulic analysis software.

Table IV-1: Assessment of the negative impacts parameters on the different applied PDA methods

No.	**Negative Impacts Parameter**	**SPDA**	**ENPDA**	**EUPDA**
1	Added virtual equipment like elevated tank and non-return valve	Applicable	N/A	N/A
2	Some nodes will not receive any demands	Applicable	N/A	N/A
3	The demand can exceed the original demand	Applicable	N/A	Applicable
4	The original EPANET model is modified	Applicable	Applicable	Applicable
5	Many iterations shall be applied	Applicable	N/A	N/A
6	Time consumption	Applicable	N/A	N/A
Assessment Results		**6 out of 6**	**1 out of 6**	**2 out of 6**

The data in Table IV-1 indicates that SPDA has the highest score (6 out of 6 of the applicable negative impact parameter) and the EUPDA has a second score (2 out of 6) available negative impact parameter. ENPDA is the approach that has the lowest score (applicable negative impact parameter (1 out of 6). The analysis result leads to the selection of ENPDA as the best reliable approach of the hydraulic analysis in all the situations especially in the emergency scenario for the reliability of any WDS since ENPDA has obtained a successful result from two different case studies.

3.0 The Smart Middle Eastern Engineering Technology Analysis

3.1 The first case study

In the first case study, the network was described for the analysis approach of PDA [27]. The smart solution was obtained by selecting the proper approach for the PDA, which is ENPDA. The size of the tank was set by the established assumption and criteria of the elevated balance tank (EBT) (see Fig. A-32, in Appendix A). The tank was designed considering the highest ground level is 36.50 m, the average losses is 14.65 m, and buffer head is 1.50 m to 3 m. As well the height of the tank is equal to the summation of all of the above plus threshold pressure, which equal to 65.50 m. The tank diameter for the worst-case analysis is 30 m. Two elevated balance tanks have been proposed to connect to the network. The criteria for the allocation of the tank was followed, and a trial and error procedure were applied. One tank was connected, in sequence, to the nodes 30, 40, 50, 60, 80 and 140, respectively, with elevation equal to 15.25 m to 24.40 m and the second tank was connected in sequence to nodes 100, 110, 120, 130, 150, 160 and 170, respectively. Trial and error criteria were applied with a diverse selection of tank locations until the proper locations were obtained. There is only one location for each tank where the criteria and design requirements have been achieved: nodes 60 and 110. The elevated tank is balanced for 24 hours/day. In other words, the volume of water inside the tank shall has kept the same volume at the end of each day until midnight. An additional challenge that was applied that was that the design of the elevated balanced tank was simulated to supply 110% of the ultimate demand of the system to ensure the high efficiency of the tank.

3.1.1 The validation results for adding an elevated balance tank (EBT) in the first case study

The result of the proposed additional EBT has been compared with the original model analysis before the burst pipes were simulated, and with the same analysis in the approach of ENPDA in all of the burst pipe cases such as in 2, 4 and 6. The verification will be discussed in the following sections.

3.1.1.1 For burst pipe 2

The WDS with EBT succeeded in supplying 403.77 lps equivalent to the original flow while the pressure driven ENPDA approach supplied 301.5 lps (see Table B-11, in Appendix B). Noted in Table B-11 (in Appendix B), the WDS with EBT achieved an average pressure equal to 19.80 m, while the original WDS had an average pressure equal to 19.25 m while the PDA through the ENPDA has only an average pressure equal to 9.55 m. The ENPDA analysis for burst pipes has pressure efficiency 38.83% while the smart solution EBT has a pressure efficiency of 100% equivalent to the original model, as noted in Table B-11 (in Appendix B).

3.1.1.2 For burst pipe 4

Table B-12 (in Appendix B) proves that the same result of burst pipe 2 is applicable where the WDS with EBT succeed in supplying 403.77 lps, which is equivalent to the original flow while the ENPDA supplied 329.3 lps. The WDS with the EBT achieved an average pressure equal to 19.80 m while the original WDS has 19.25 m, while ENPDA has only 10.44 m. The ENPDA analysis for burst pipes has a pressure efficiency equal to that of 45.16%, while the smart solution with EBT had 100% equivalency to the original model.

3.1.1.3 For burst pipe 6

Table B-13 (in Appendix B) proves that the same results for burst pipes 2 and 4 are obtained here as well that WDS with EBT succeeded in supplying 403.77 lps equivalent to the original flow, while the ENPDA can supply 350.80 lps. The WDS with the EBT achieved an average pressure equal to 19.80 m, while the original WDS had 19.25 m, and the ENPDA had achieved an average pressure of 13.54 m. ENPDA analysis for the burst pipe had a pressure efficiency of 61.01%, while a smart solution with EBT had 100% equivalent to the original model.

3.2 The second case study

In principle, the second case study was previously utilized in the analysis approach of PDA [27]. The size of the tank has been set by the established assumption and criteria of the smart solution and elevated balance selection Fig A-4, A-5 (Appendix A). The tank was designed while considering the highest ground level to be 15 m, the average losses is 4.5 m, and buffer head is 1.5 m to 3 m. Finally, the height of the tank is equal to the summation of all the above and to be equal to 46 m. The tank diameter for the ultimate case analysis is 40 m with one tank being selected in the network. The criteria for the allocation of the tank was followed, and trial and error procedures were applied. The trial and errors started with two tanks at different nodes. One tank had been selected based on the best result obtained from the trial and error methodology. The elevated tank was allocated to be balanced through 24 hours/day during both normal and emergency conditions. An additional challenge that was studied was that the tank was used to supply 110% of the ultimate supply to ensure the high efficiency of the EBT.

3.2.1 The validation for adding elevated balancing tank (EBT) in the second case study

The smart WDS analysis with the burst pipes has one additional elevated balance tank using EBT. The result of the proposed additional EBT has been compared with the original model analysis before the pipe burst and with the same analysis for the ENPDA approach in all burst pipes cases as in pipes 2, 3 and 8. The verification will be discussed in the following sections.

3.2.1.1 For burst pipe 2

In Table B-14 (in Appendix B) the WDS with the EBT succeeded in supplying 352.49 lps equivalent to the original flow, while the reliable ENPDA approach supplied 326.01 lps. The ENPDA for burst pipes has pressure efficiency of 77.09%, while the smart solution EBT has a pressure efficiency of 100% equivalent to the original model.

3.2.1.2 For burst pipe 3

From Table B-15 (in Appendix B) proves that the same result of burst pipe 3 is applicable here also that the WDS with EBT was successful in supplying 352.49 lps equivalent to the original flow while the ENPDA can supplement 323.93 lps. The ENPDA analysis for burst pipe showed a pressure efficiency of 79.04% while the smart solution with the EBT has 100% equivalence to the original model.

3.2.1.3 For burst pipe 8

From Table B-16 (in Appendix B) proves the same result found for burst pipes 2 and 3 and thus is applicable here. Also, the WDS with EBT succeeded in supplying 352.49 lps, which is equivalent to the original flow.

4.0 Discussion and conclusion

Reliability, in this research, is defined as an average pressure efficiency that is equal to a percentage of the available pressure to the required pressure. Four approaches methods are applied in the current research (DDA, SPDA, ENPDA and EUPDA). The SPDA approach is applied for more a realistic reliability assessment of water distribution networks. The proposed methodology uses demand-driven results as a starting point and proceeding in an iterative manner using one of the most commonly used demand-driven software, namely EPANET. The accuracy of the generated SPDA results has been verified and validated using the hydraulic analysis and evaluation of the energy [54]. EPANET has also been used in another approach of reliability analysis ENPDA [2]. ENPDA is utilizing the simple sprinkle emitter function in an original EPANT model that can be used for firefighting or irrigation simulation. In the current study, the available emitter node approach is used to draw very good quality reliable hydraulic model analysis in burst pipe cases. By specifying the emitter coefficient, the demand node would turn into an emitter node, in which the demand will be adjusted based on the actual pressure in the system.

The default value for EPANET's emitter exponent is $\alpha = 0.5$, which can be adjusted if necessary. The using of emitter exponent approach gives clear advantages while exploring the effects of pressure management on the leakage reduction in the system. Furthermore, EUPDA is another advanced pressure dependent analysis toward obtaining the accurate result of the reliable model analysis in an emergency [55]. Reform of EPANET menu for pressure-driven demand analysis, engaging 'Emitter Modeling of Demands,' is applied [6]. The revised version was designed to run in the same way as a normal EPANET network after developing an EPANET toolkit original application following the exact procedures of EPANET. The current implementation of modified EPANET (EPANET-UNSECO Emitter) has some disadvantages (EUPDA).

First, it is not possible to specify different emitter exponent values for different nodes or different demand categories like normal emitter analysis in the normal EPANET approach (ENPDA). ENPDA as a model has a strong approach and very low negative impact level compared to either the SPDA, or EUPDA approaches. ENPDA is also suitable because it is commonly available for the user of traditional EPANET.

Incorporating the elevated balancing tank at an appropriate location can decrease the total cost and increase the reliability of the network [27]. The criteria for the allocation of the tank is followed, and trial and error procedure were applied. The tank allocation achieved the criteria that the elevated tank was to be balanced through 24 hours per day, the volume of water inside the tank was the same at the end of every day at midnight.

5.0 Acknowledgement

I would like to thank my professors who supported me throughout the process to complete the present research and for their advice and guidance. I would also like to thank Mr. Rodney Bouchard of Union Water Supply System for his support and contributions to this work.

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CHAPTER V

Conclusions and Recommendations

1.0 Summary and Conclusions

The current study clarifies the limitations of demand-driven analysis for scenarios where demands may reach emergency levels. The EPANET hydraulic simulation model simulates both normal and emergency water distribution scenarios for two different WDS case studies. In Chapter II, the two case studies illustrate the demand-driven analysis (DDA) characteristics and standard performance in handling these emergency scenarios. There is a variation in the performance of the two different WDS during the original and emergency conditions when the DDA method was applied to their systems. The results of the two WDS show that the pressure profile for the burst pipe scenarios is lower than the original pressure profile while the original demand values were still supplied through the junctions, during the burst pipe, which is not reliable due to the drop in pressure under the minimum threshold pressure.

Chapter II concluded that the traditional hydraulic analysis is built on the concept of demand-driven analysis (DDA), where the nodal demands have to reach the consumer without consideration of the available pressure heads, which can drive the network to low or negative pressures that are less than the threshold pressure at the WDS. The result of the analysis recommended that pressure driven analysis (PDA) modelling should be applied to sample networks under burst pipe conditions to measure the ability of PDA modelling with the insufficiency of nodal pressure.

In Chapter III, the current study illustrates the difference between the demand-driven analysis (DDA) at the original and emergency conditions and the semi-pressure driven analysis (SPDA) where demands may reach emergency levels. The two methods of approaches are applied in the current research, DDA and SPDA. The SPDA is applied for more realistic reliability assessment of water distribution networks. The proposed methodology uses demand-driven analysis results as a starting point and proceeding in an iterative manner using one of the most commonly used demand-driven software, namely EPANET. The EPANET hydraulic simulation model represented the analysis in both normal and emergency conditions in water distribution system scenarios for two different cases studies and approaches.

In Chapter III, the accuracy of the generated SPDA results has been verified and validated. Involving the SPDA in the research provides the realistic performance of the demand and related pressure at nodes. The nodal water supply is adjusted to satisfy the nodal pressure requirement under the abnormal condition, which arises when part of the water distribution system is closed for maintenance, rehabilitation, or because of an accident. The maximum pressure for the water supply while maintaining the nodal pressure is 14 m is defined as the effective supply to guarantee the customers' convenience.

In Chapter IV, reliability, in the present study, is defined as average pressure efficacy and it is the percentage of the supplied to the required pressure. Four analysis methods are applied including the accuracy of the generated SPDA results which has been verified and validated. In Chapter IV, EPANET has also been used in another approach of reliability analysis ENPDA. ENPDA is utilizing the simple sprinkle emitter function in an original EPANT model that can be used for firefighting or irrigation system but in the current studies used to draw very good quality reliability model. Emitter coefficients were introduced early in EPANET to simulate the operation of fire hydrants or irrigation sprinkles. By specifying the emitter coefficient, the demand node would turn into an emitter node. Using the emitter approach gives clear advantages while exploring the effects of pressure management on the leakage reduction in the system.

In Chapter IV, furthermore, EUPDA is another advanced pressure dependent analysis towards obtaining the accurate result of the reliable model analysis in an emergency secnrios. Reform of EPANET menu for pressure-driven demand analysis, engaging Emitter Modeling of Demands is produced. EUPDA is the revised version to run in the same way as a normal EPANET network after developing the EPANET-toolkit original application following the exact procedure of EPANET. The current implementation of modified EPANET by UNSECO has some disadvantages. First, it is not possible to specify different emitter exponent values for different nodes or different demand categories like normal emitter analysis in a normal EPNAT 'ENPDA' approach. In Chapter IV, ENPDA is a method that has a strong approach and a very low negative impact level compared to SPDA and EUPDA. ENPDA is also suitable because it is commonly available for the user of traditional EPANET. The ENPDA can be considered as the best practice approach to resolve the reliability analysis issue and even if it is not a new method it does utilize certain existing embedded functions of the traditional EPANET.

In Chapter IV, trial and error criteria was applied with different alternative selections until the proper results are obtained by choosing only the proper number of the tanks at the proper node/location. The elevated tank is allocated where the inflow and outflow will be balanced through 24 hours/day. In other words, the volume of water inside the tank will have the correct volume at the end of each day at midnight. An additional challenge has been studied that the tank is used to supply 110% of the ultimate supply and this worst case is to ensure the high efficiency of the tank. The study succeeded in improving the efficiency of the smart Middle East solution for the WDS performance, which can be applied for any similar WDS.

2.0 Recommendations

It is recommended to extend the application of the current study of applying the reliability analysis using EPANET hydraulic model with ENPDA approach for one of the municipalities within the Great Lakes area in Canada. Where ENPDA reliability approach shall be applied, it is recommended to utilize the existing elevated tanks to achieve the smart water supply solution. The recommendation will extend to include the pressure regulation by introducing the flow control valves in the analysis.

It is also recommended to study the possibility to create and apply multiplication (correction) factor to calculate the nodal demand during emergency cases. The correction factor shall be a function of the flow and pressure as well as related geometry functions as the difference in ground elevation. This correction factor can achieve the reliability analysis of WDS with short processing time to improve the performance of the WDS.

APPENDIX A : FIGURES

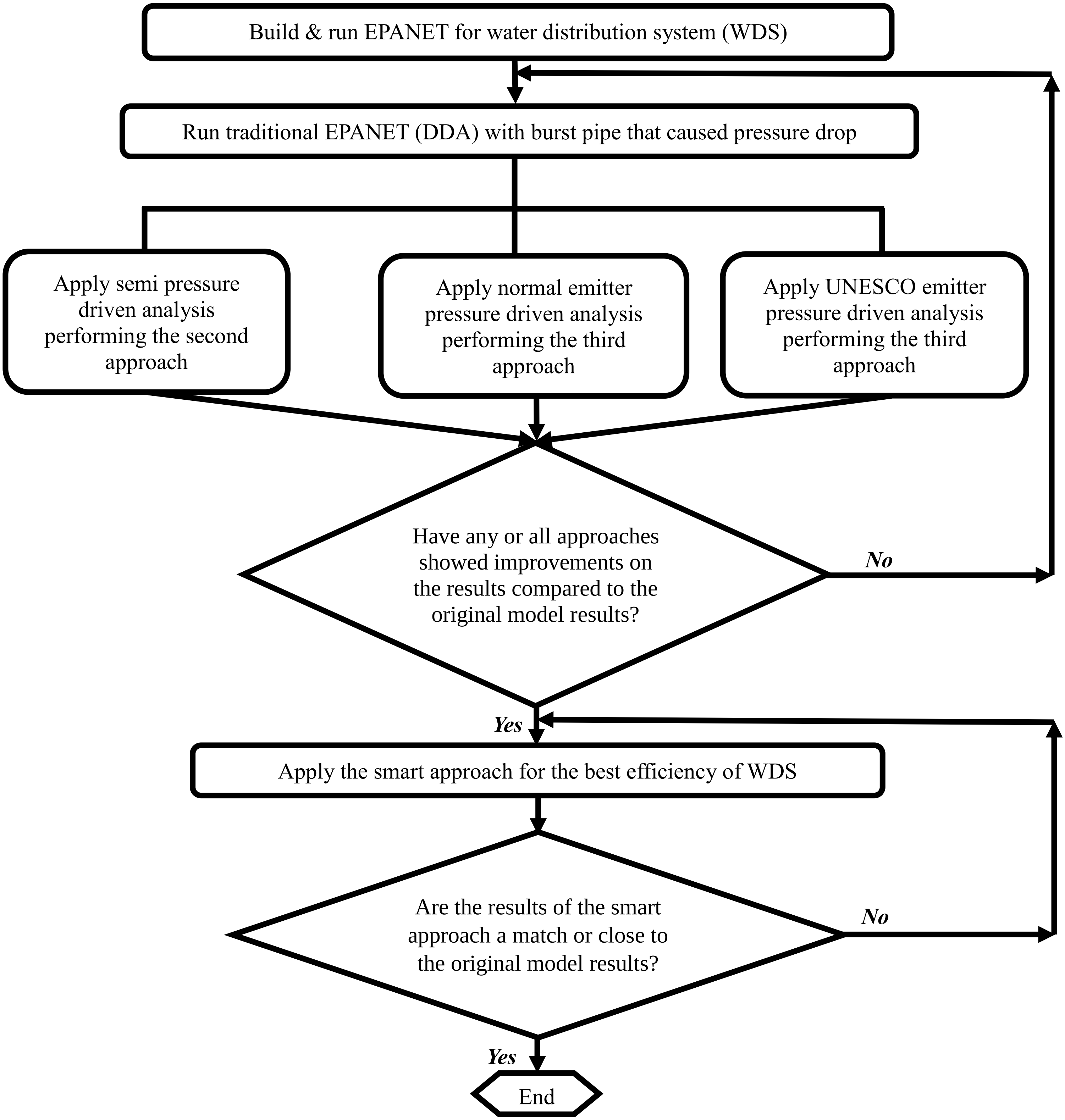

Figure A-1: The flow chart of the pipes networks research modelling approaches

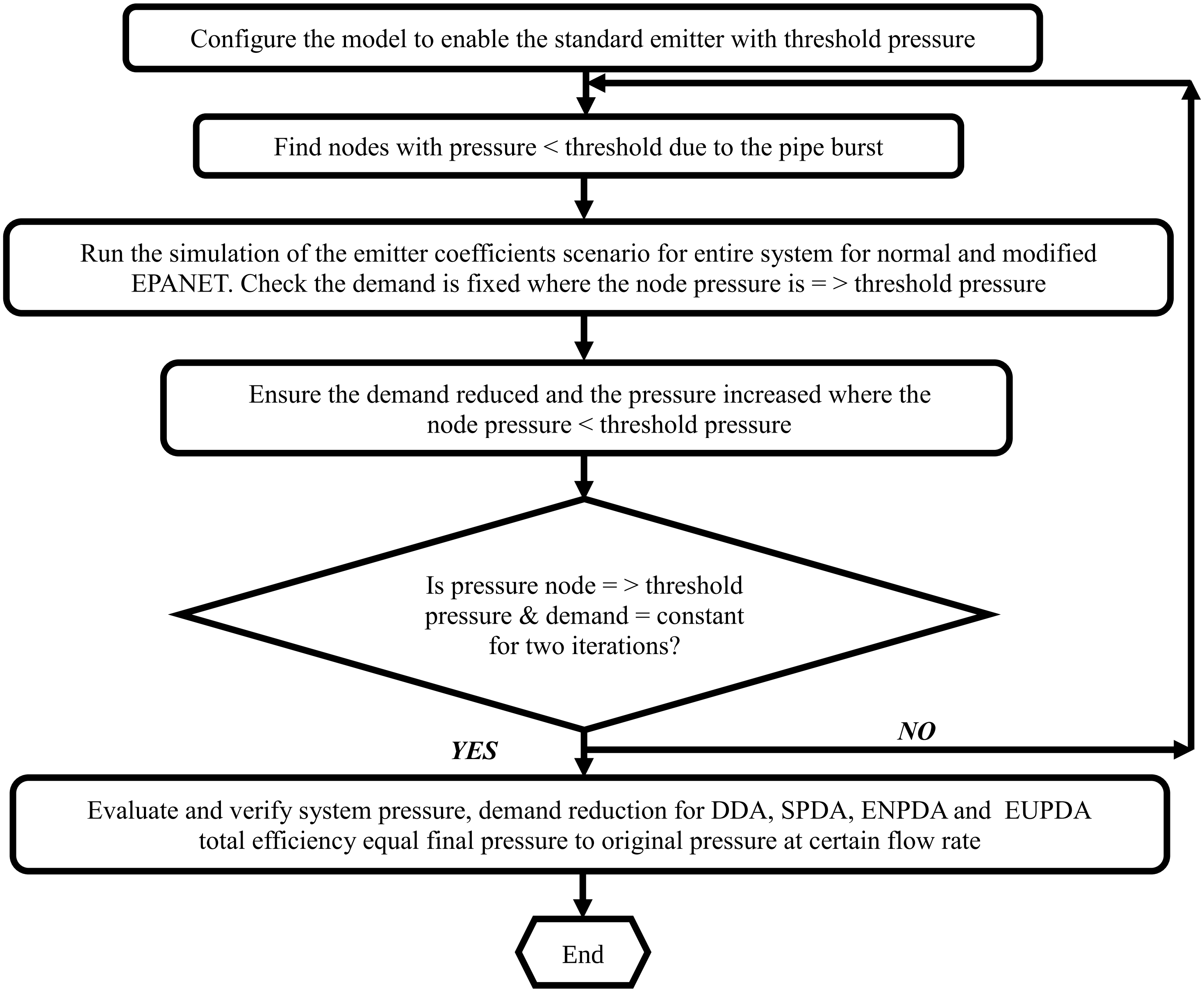

Figure A-2: The flow chart of the pipes networks analysis of emitter driven approaches for normal and UNESCO (ENPDA and EUPDA) algorithms

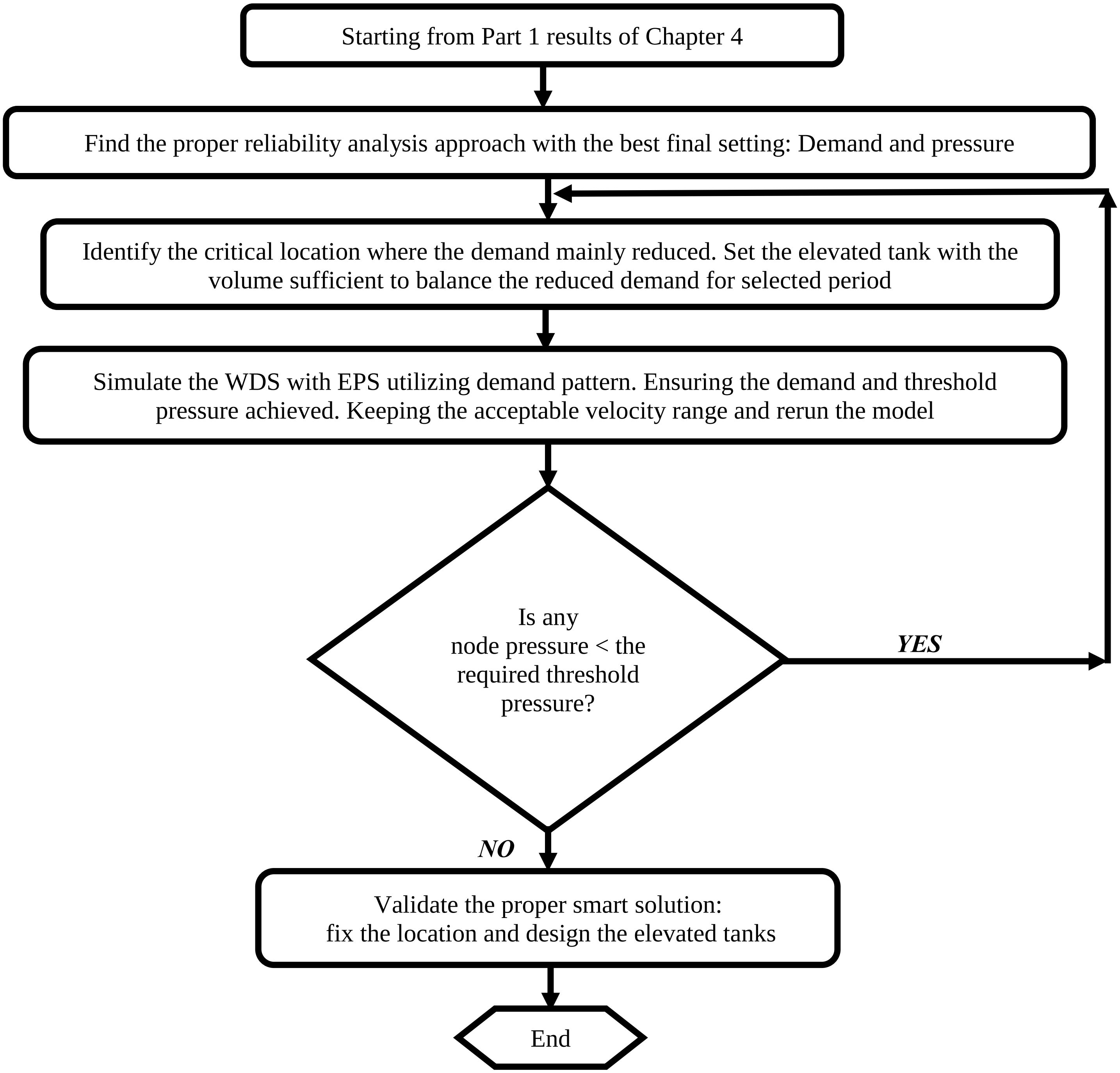

Figure A-3: The smart Middle Eastern elevated balance tank (EBT) for determining reliability of water supply algorithm.

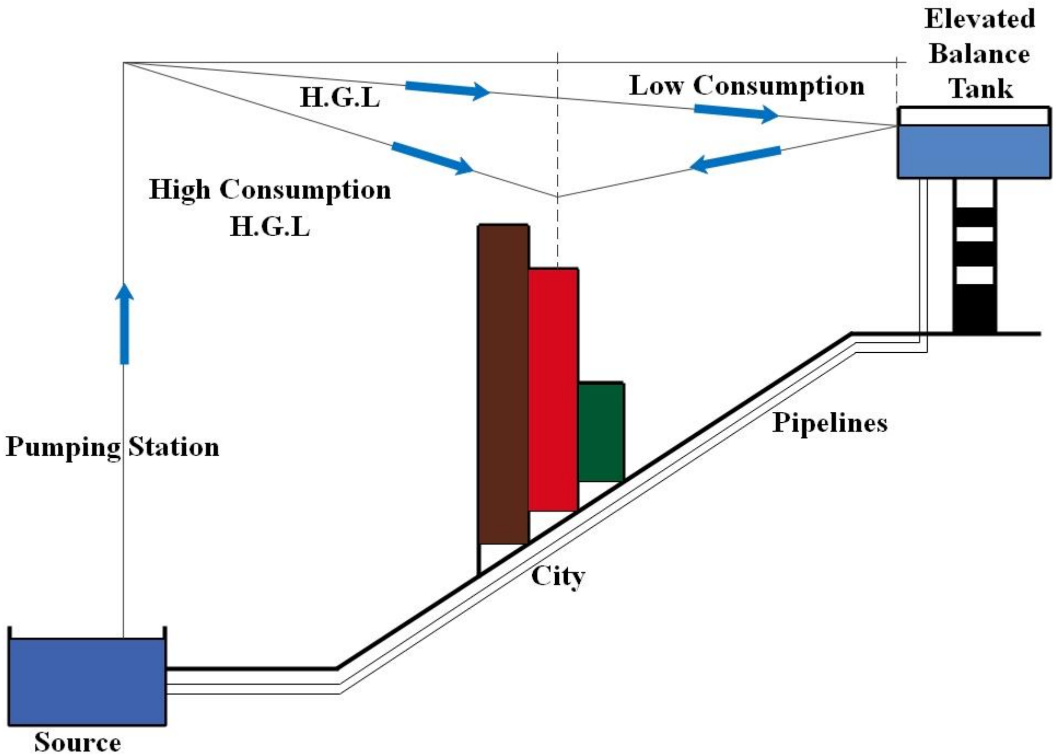

Figure A-4: The elevated balance tank hydraulic grade line.

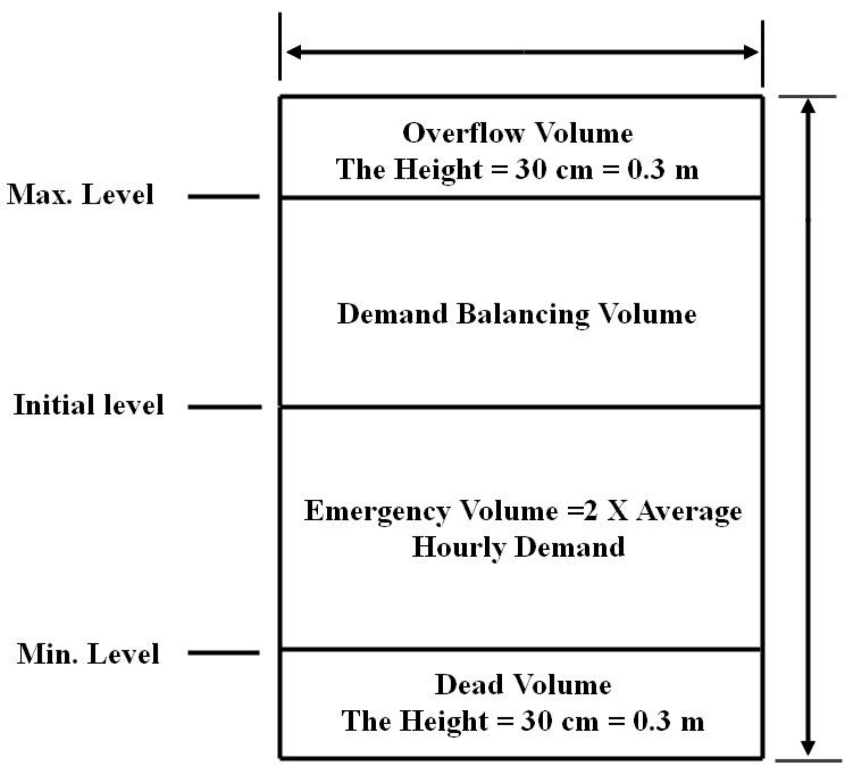

Figure A-5: The elevated balance tank required volume.

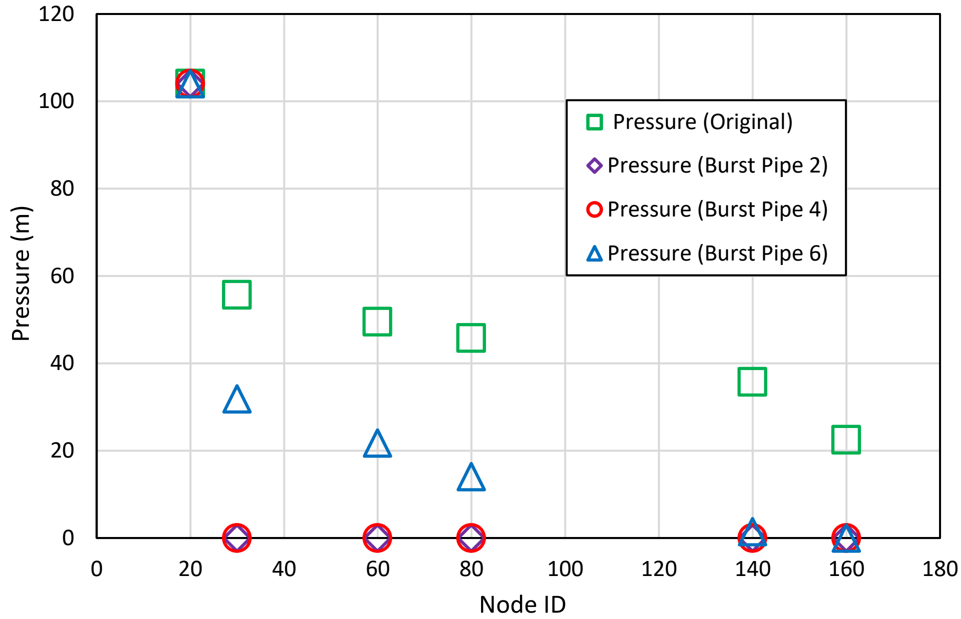

Figure A-6: The case study I: The pressure route Y for original and burst pipes 2, 4 and 6.

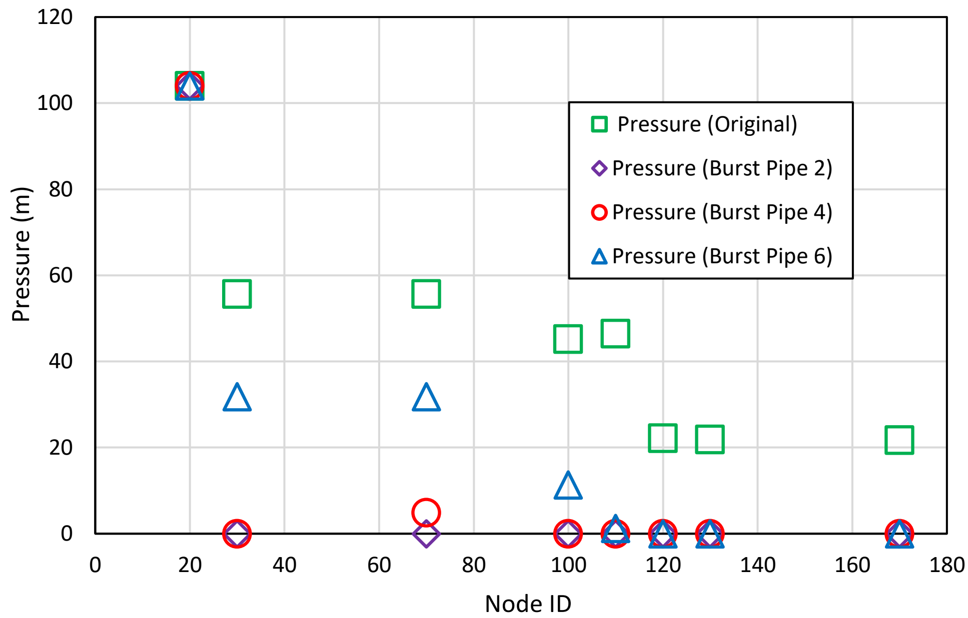

Figure A-7: The case study I: The pressure route Z2 for original and burst pipes 2, 4 and 6.

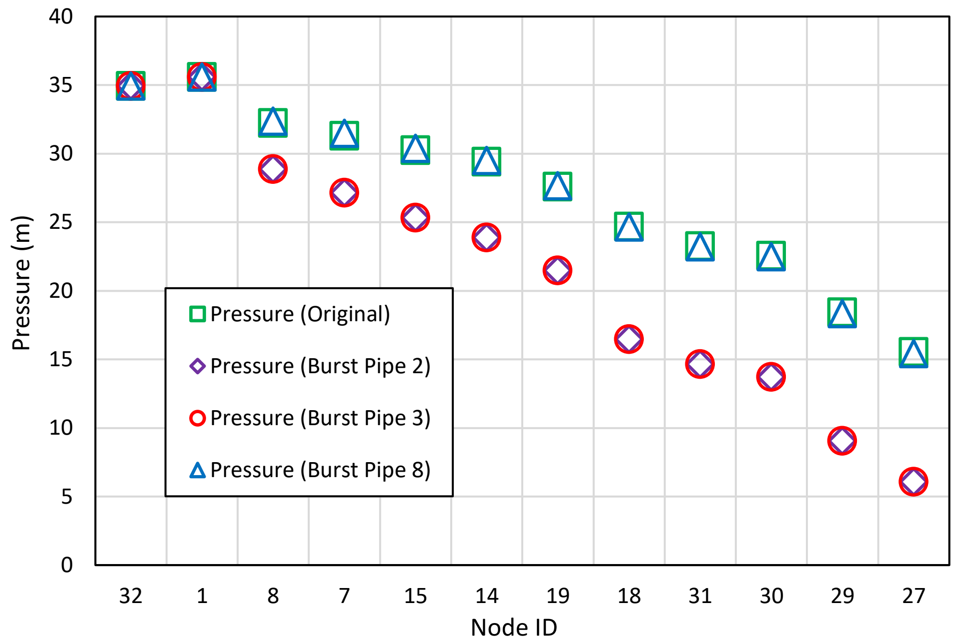

Figure A-8: The case study II: The pressure route R2 for original and burst pipes 2, 3, and 8.

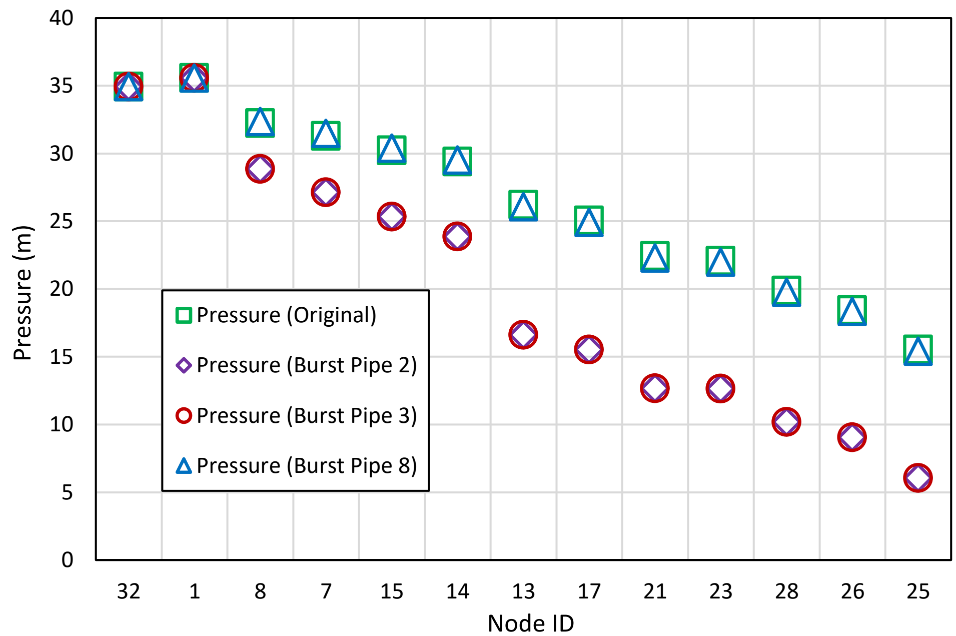

Figure A-9: The case study II: The pressure route R3 for original and burst pipes 2, 3 and 8.

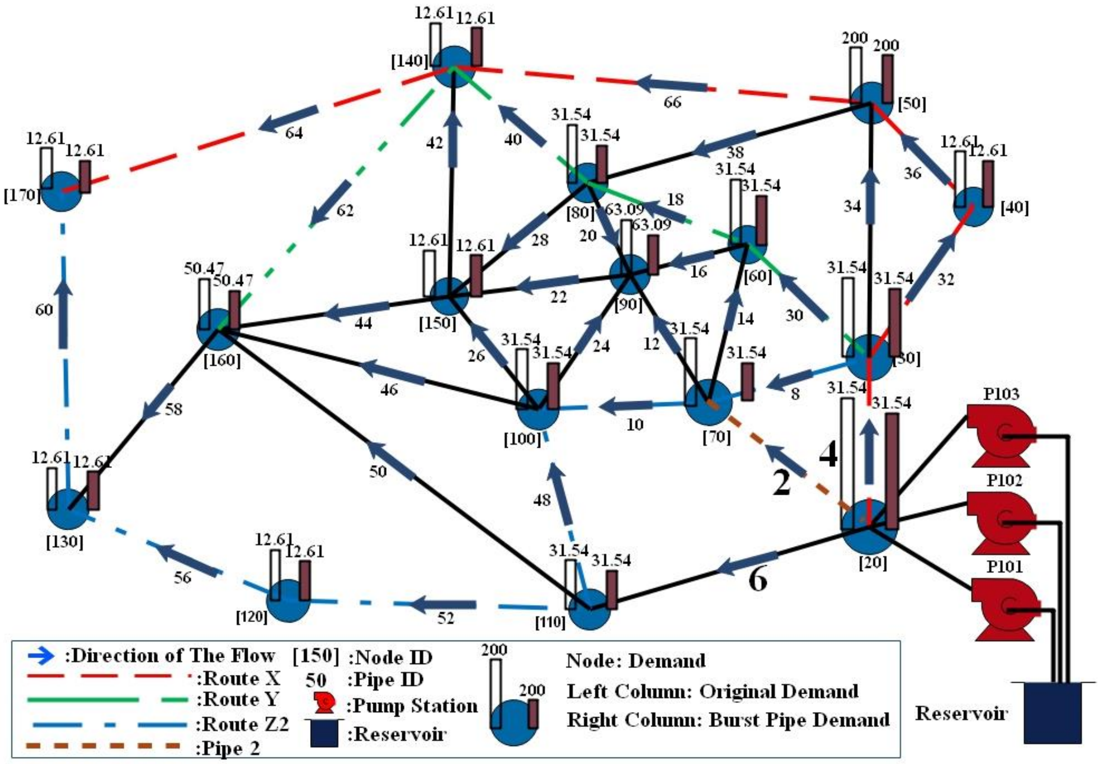

Figure A-10: The first case study Network 2 with viewing base demand at the original and burst pipe 2 conditions in DDA.

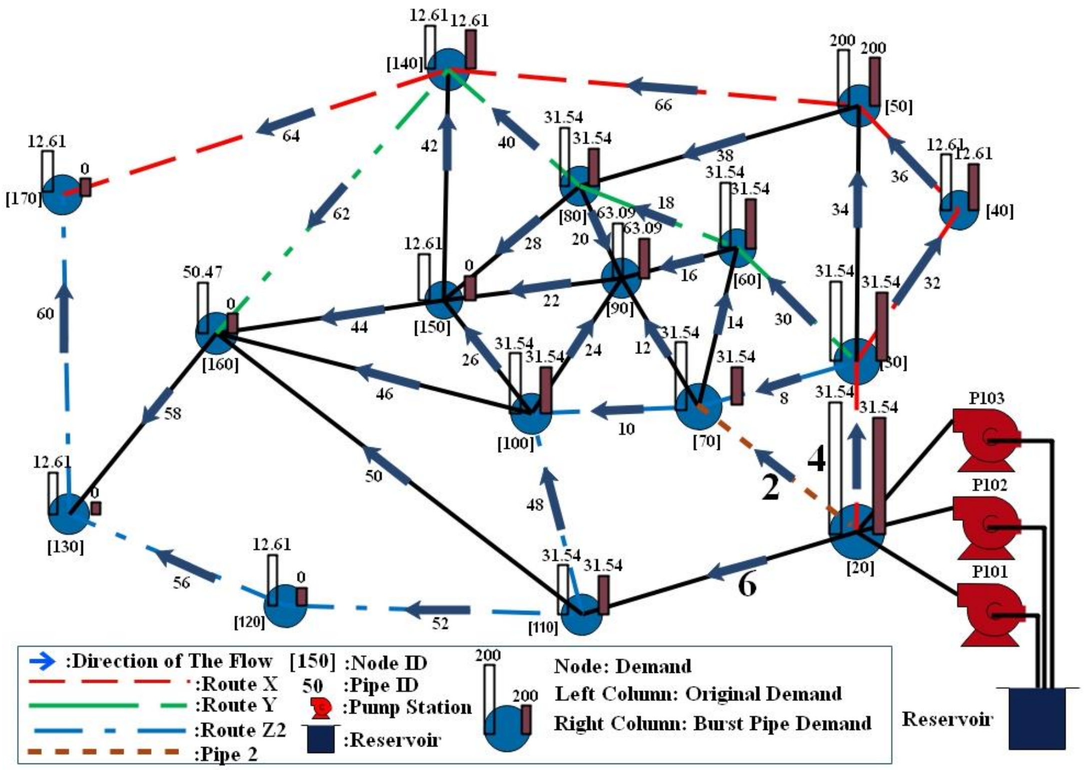

Figure A-11: The first case study Network 2 with viewing base demand in original and after applying the semi pressure driven analysis in burst pipe 2 in SPDA.

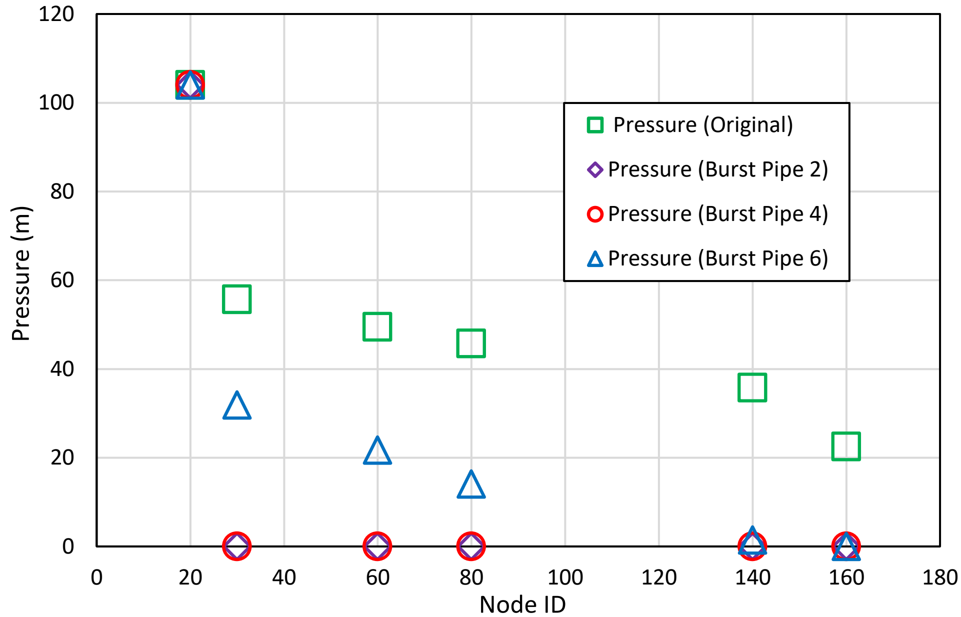

Figure A-12: The case study I: The pressure profile for route Y by DDA for the original and burst pipes 2, 4 and 6.

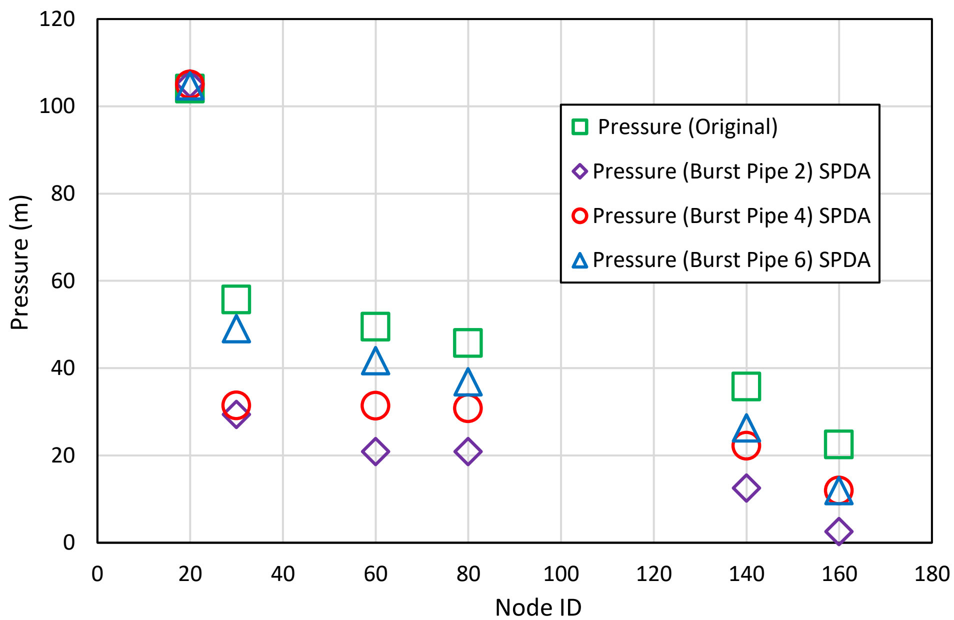

Figure A-13: The case study I: The pressure profile for route Y by the semi pressure driven analysis for original condition and burst pipes 2, 4 and 6.

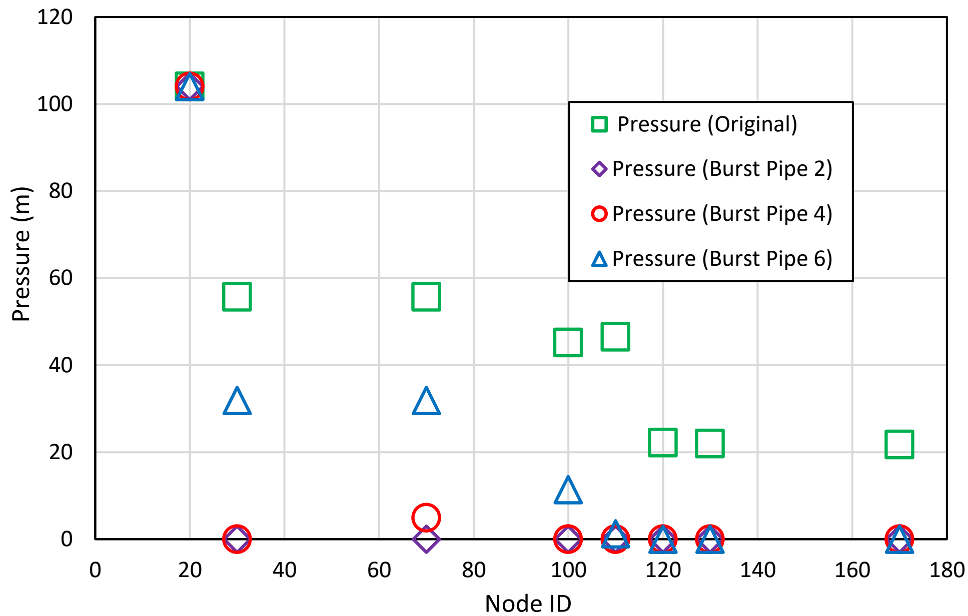

Figure A-14: The case study I: The pressure profile for route Z2 by the demand driven analysis for the original condition and burst pipes 2, 4 and 6.

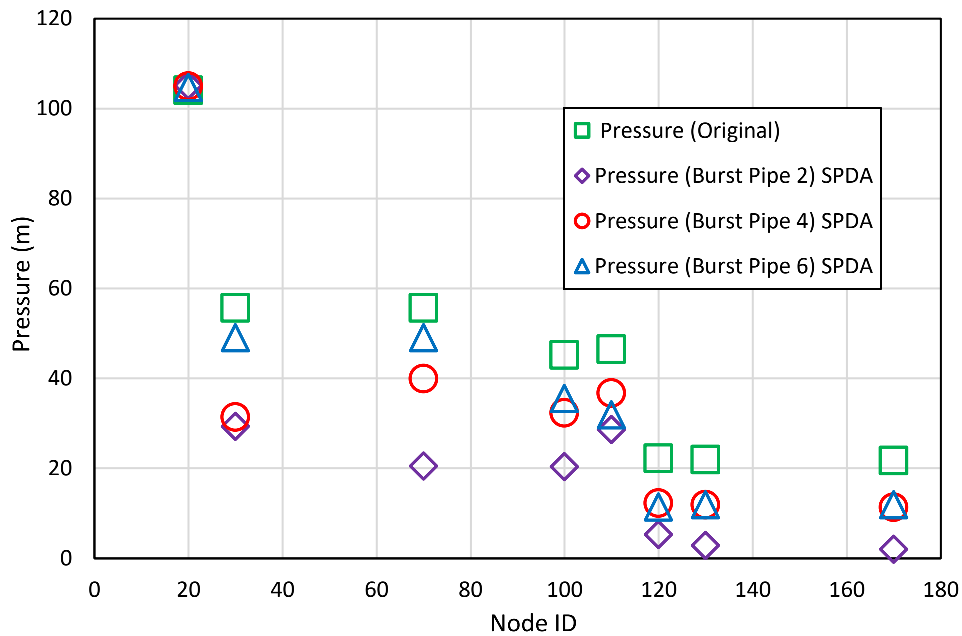

Figure A-15: The case study I: The pressure profile for route Z2 by the semi pressure driven analysis for original condition and burst pipes 2, 4 and 6.

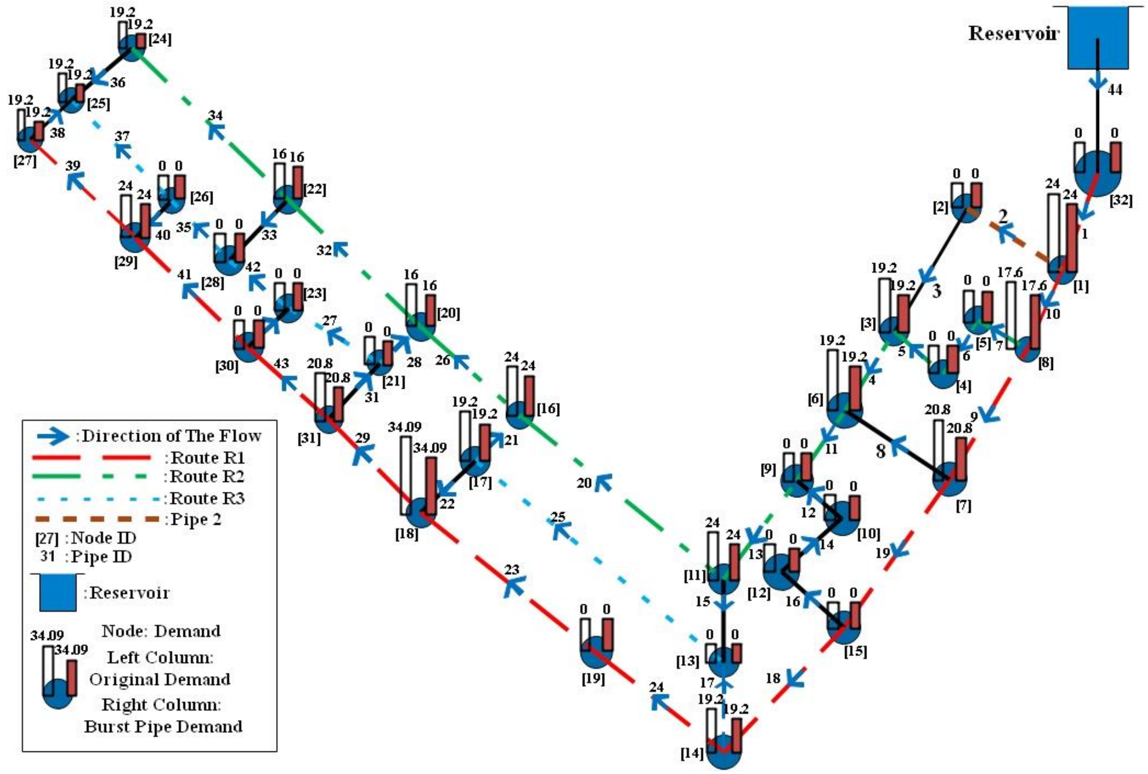

Figure A-16: The second case study El-Mustaqbal City network with viewing base demand at the original and burst conditions at pipe 2 in DDA.

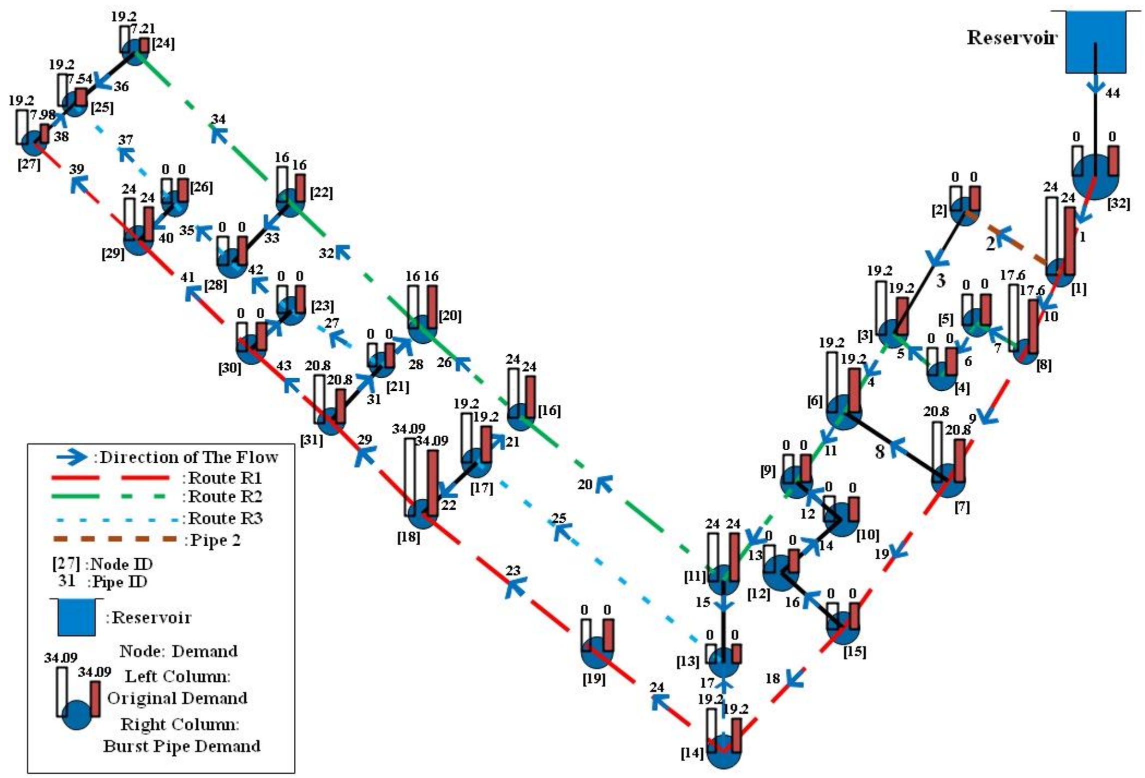

Figure A-17: The second case study El-Mustaqbal City network with viewing base demand at the original and burst conditions pipe 2 in SPDA.

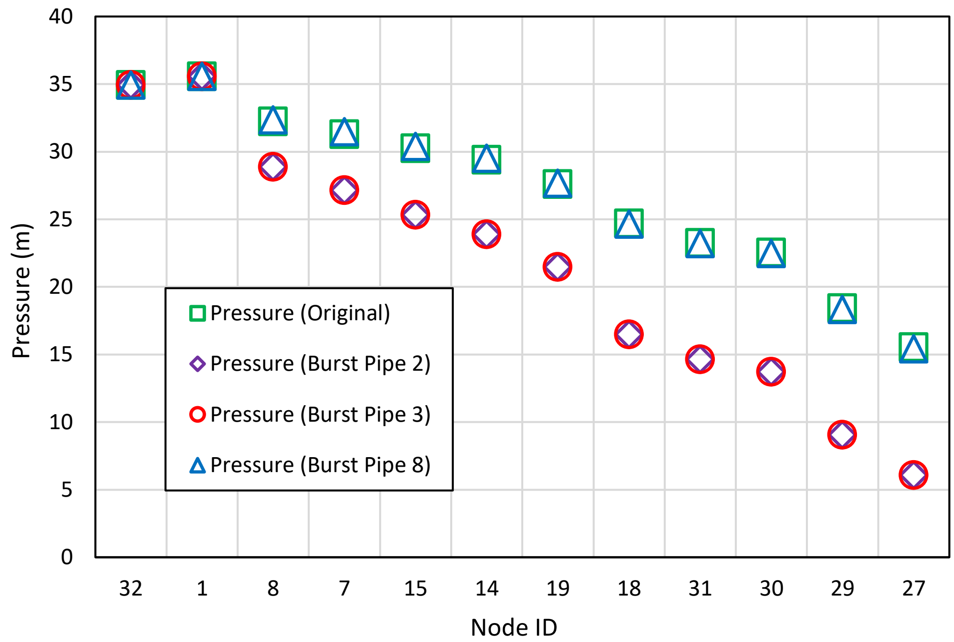

Figure A-18: The case study II: The pressure scenario for route R2 nodes.

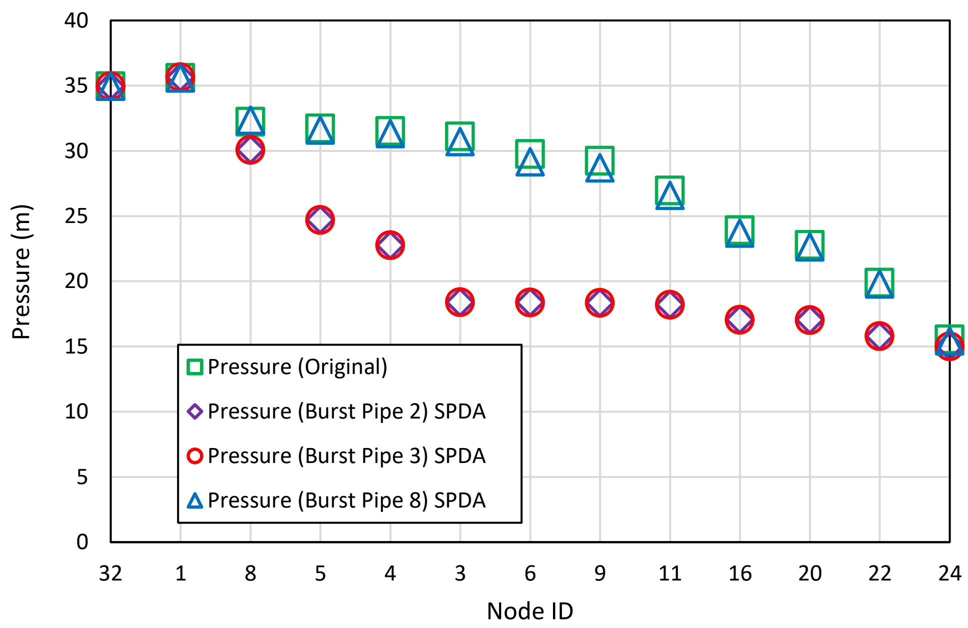

Figure A-19: The case study II: The pressure scenario for route R2 nodes after applying SPDA approach.

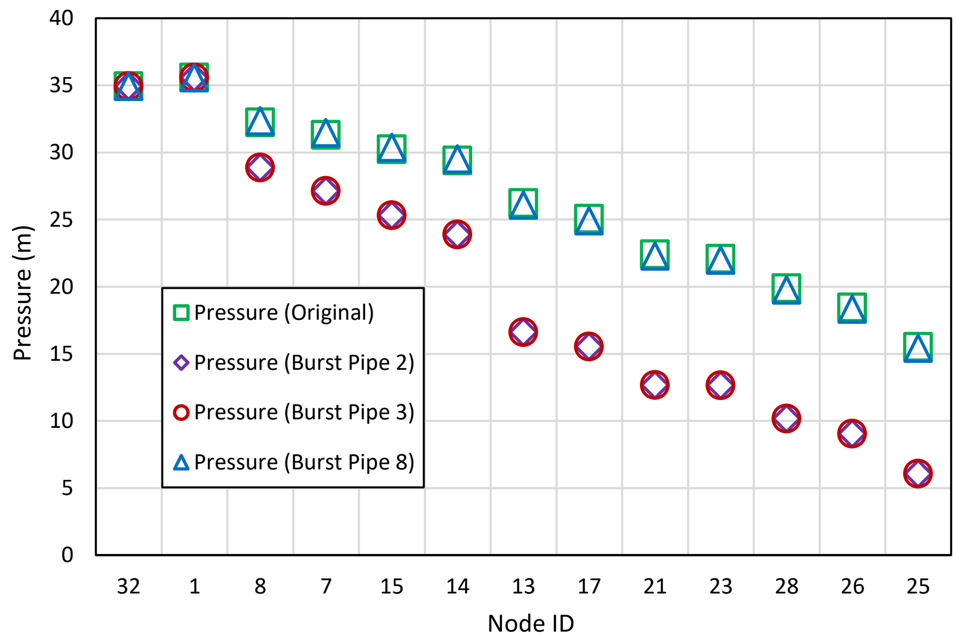

Figure A-20: The case study II: The pressure scenario for route R3 nodes.

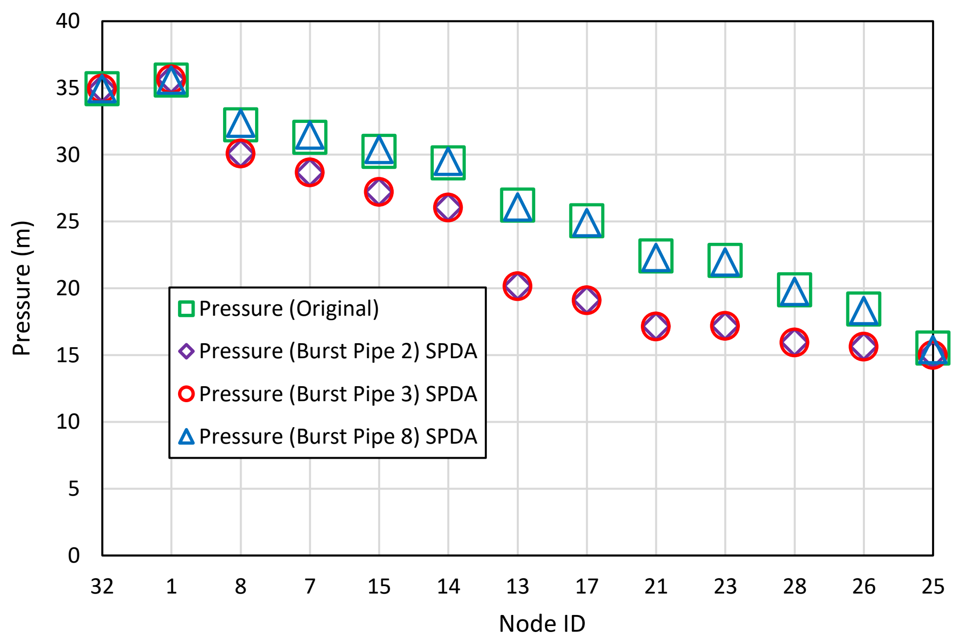

Figure A-21: The case study II: The pressure scenario for route R3 nodes after applying SPDA approach.

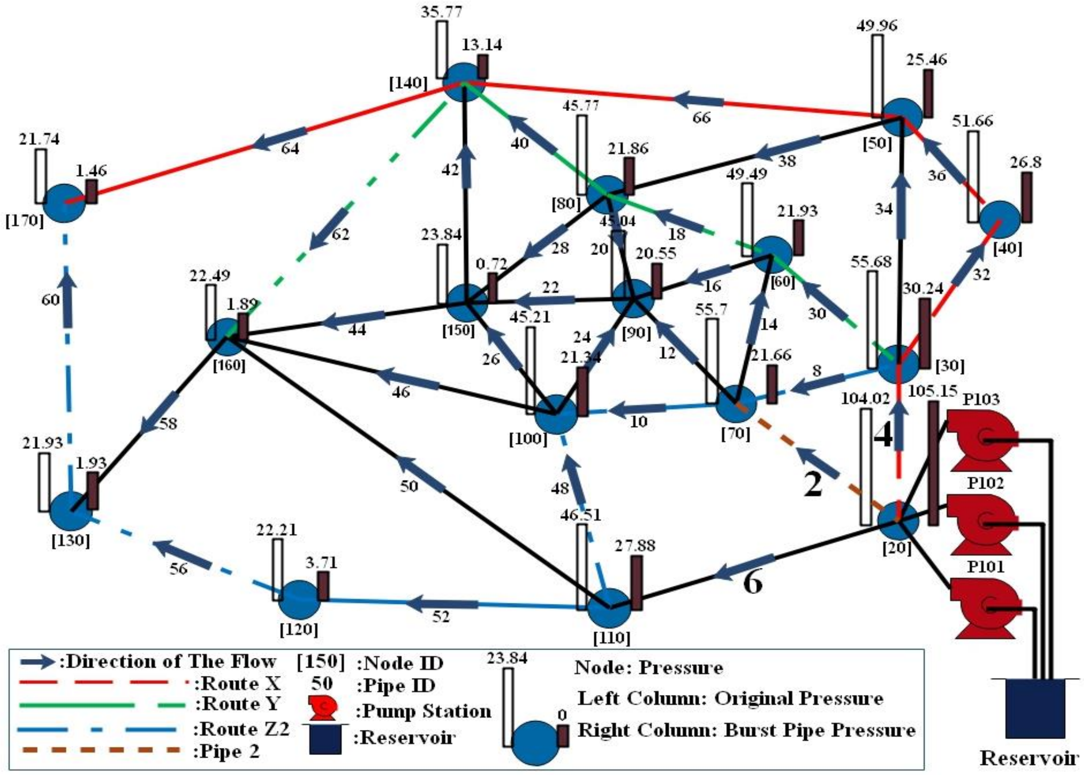

Figure A-22: The first case study Network 2 with viewing pressure at the original and after applying the emitter normal pressure driven analysis (ENPDA) in burst pipe 2.

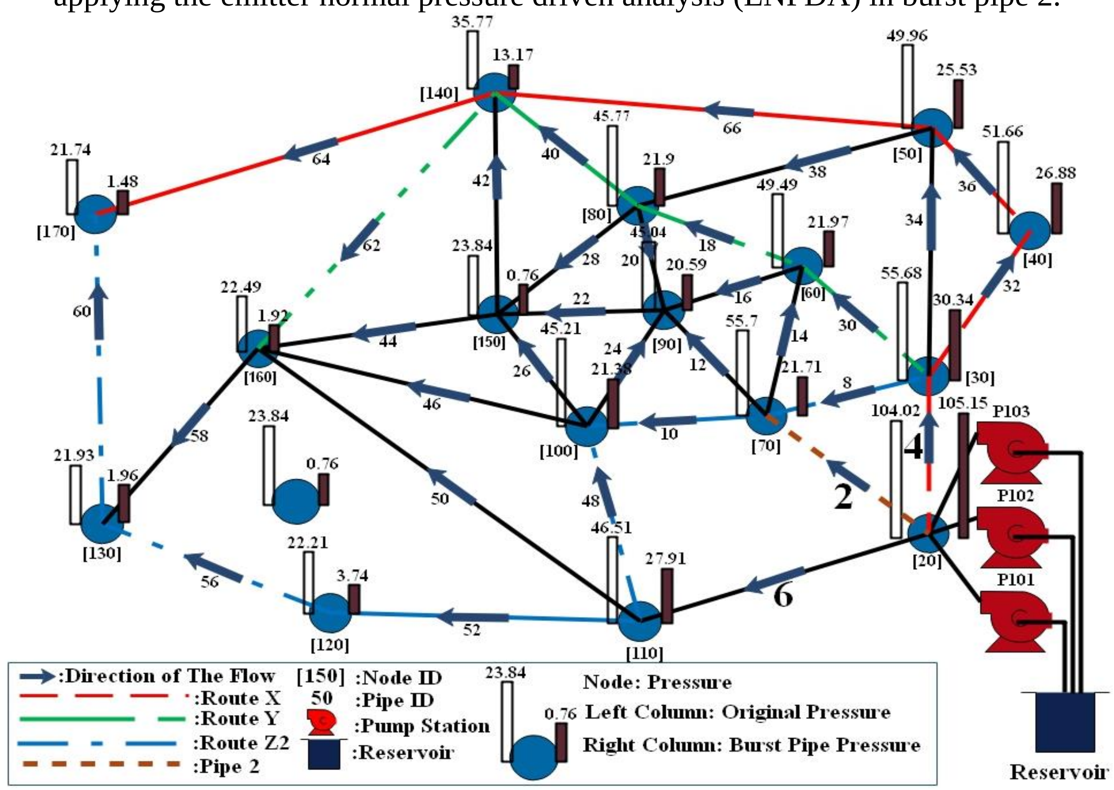

Figure A-23: The first case study Network 2 with viewing pressure at the original and after applying the emitter normal pressure driven analysis (EUPDA) in burst pipe 2.

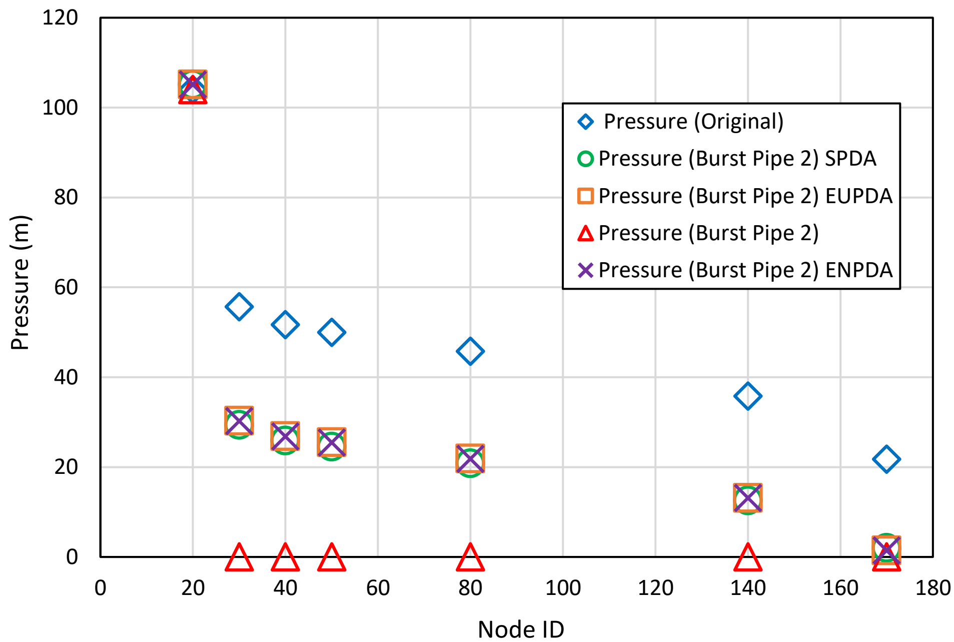

Figure A-24: The case study I: Network 2 with viewing pressure in original, SPDA, ENPDA and EUPDA after burst pipe 2 route X.

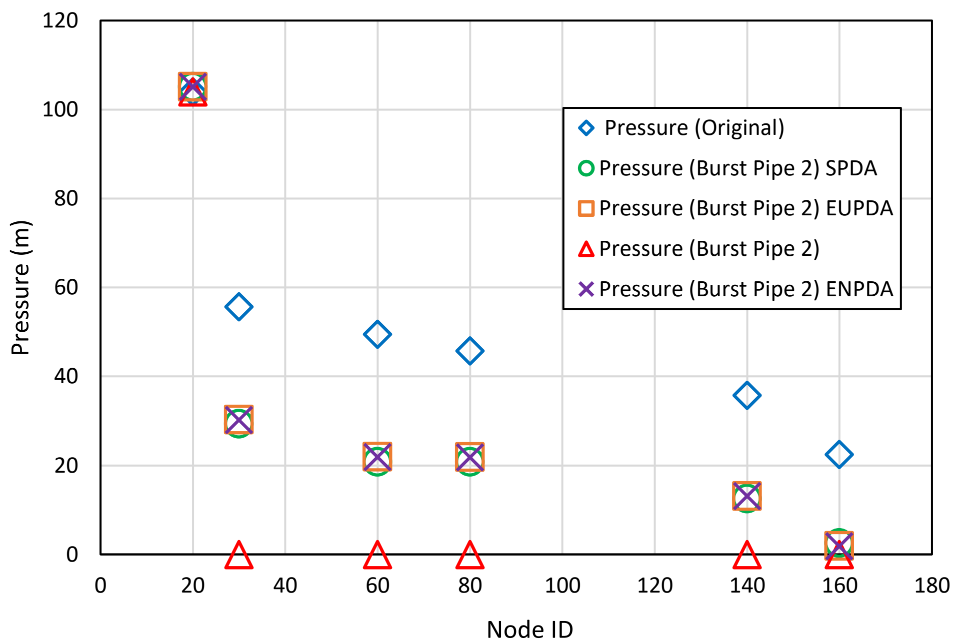

Figure A-25: The case study I: Network 2 with viewing pressure in original, SPDA, ENPDA and EUPDA after burst pipe 2 route Y.

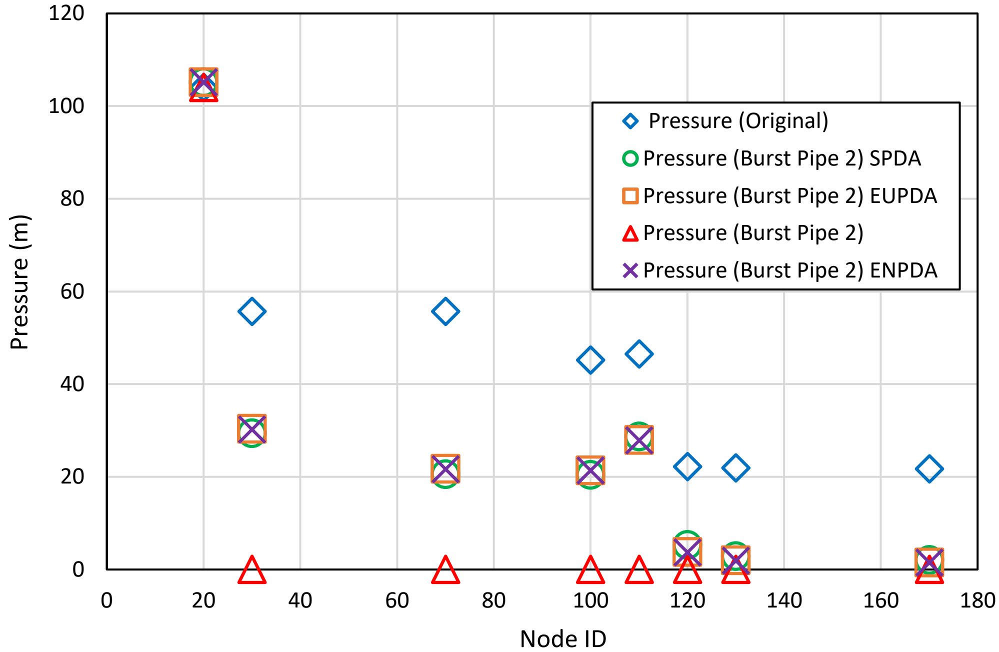

Figure A-26: The case study I: Network 2 with viewing pressure in original, SPDA, ENPDA and EUPDA after burst pipe 2 route-Z2.

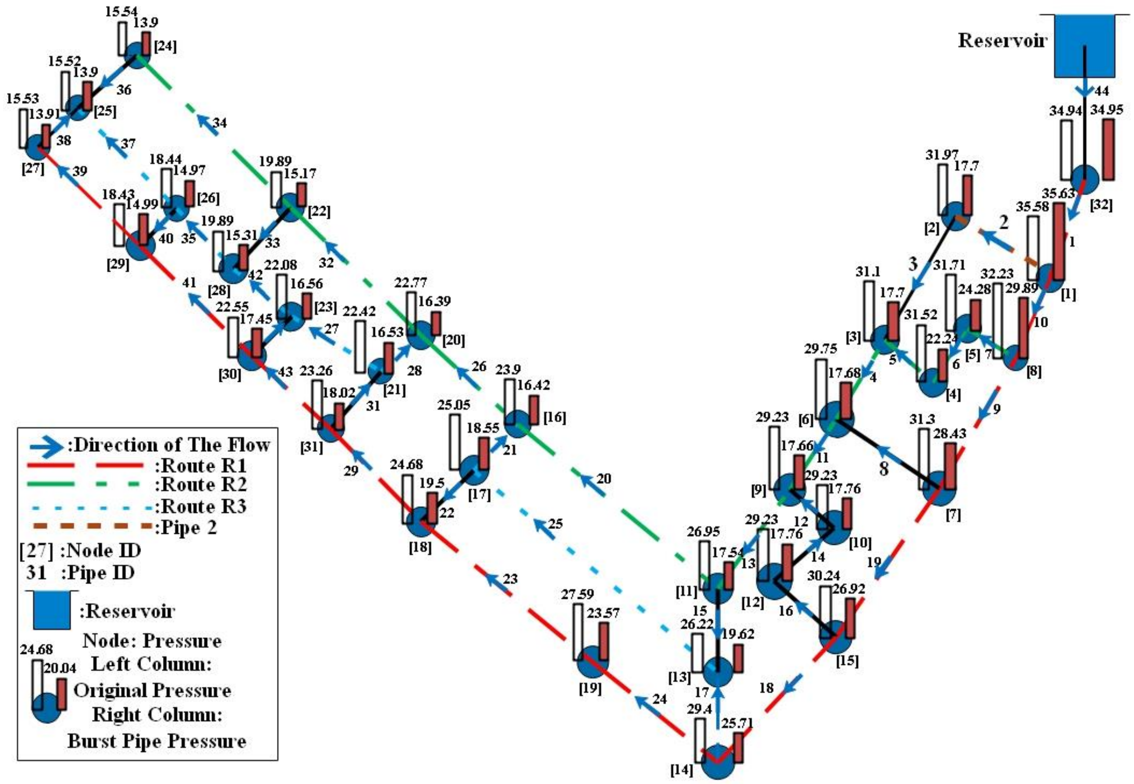

Figure A-27: The second case study in original and emitter normal pressure driven analysis (ENPDA) approach with viewing pressure after burst pipe 2.

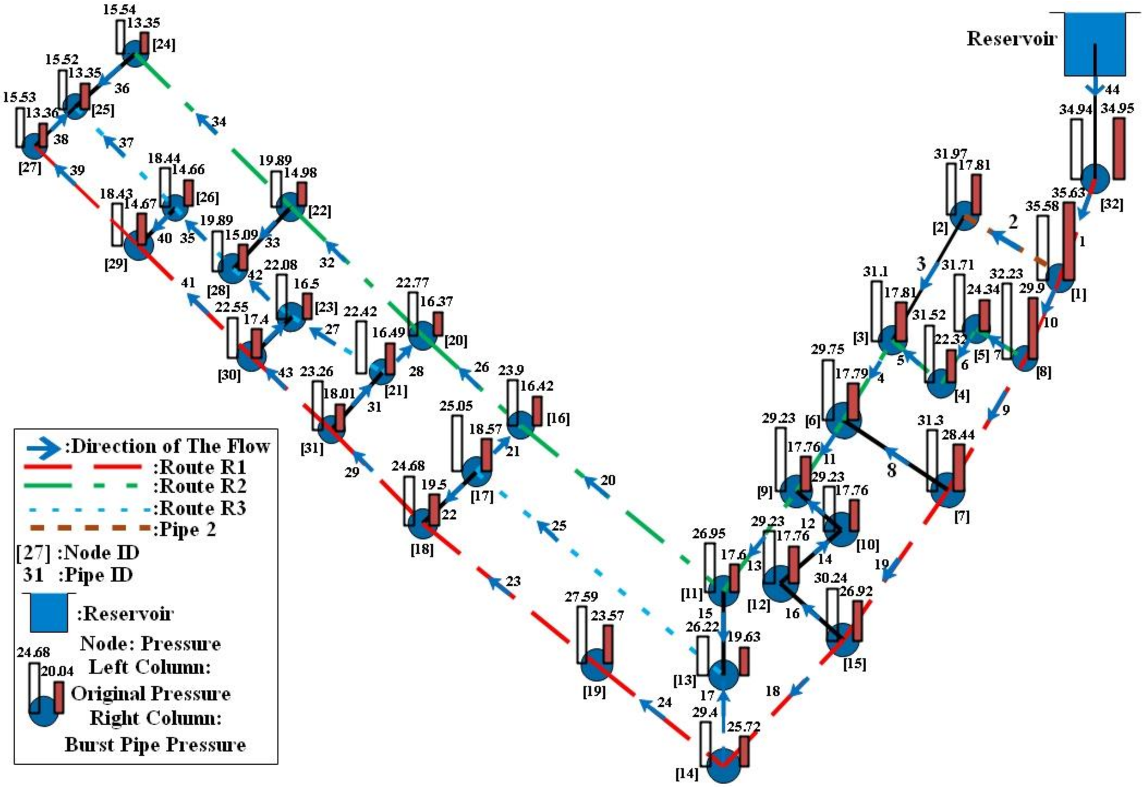

Figure A-28: The second case study in original and emitter UNESCO pressure driven analysis (EUPDA) approach with viewing pressure after burst pipe 2.

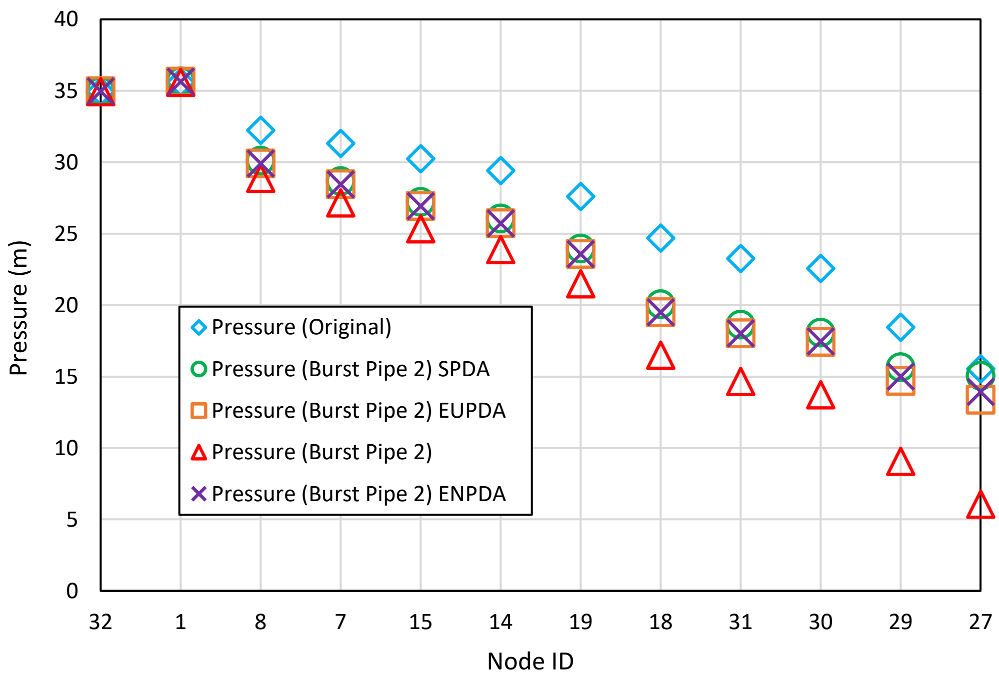

Figure A-29: The case study II: El-Mustaqbal City network with viewing pressure in original, SPDA, ENPDA and EUPDA after burst pipe 2 route-R1.

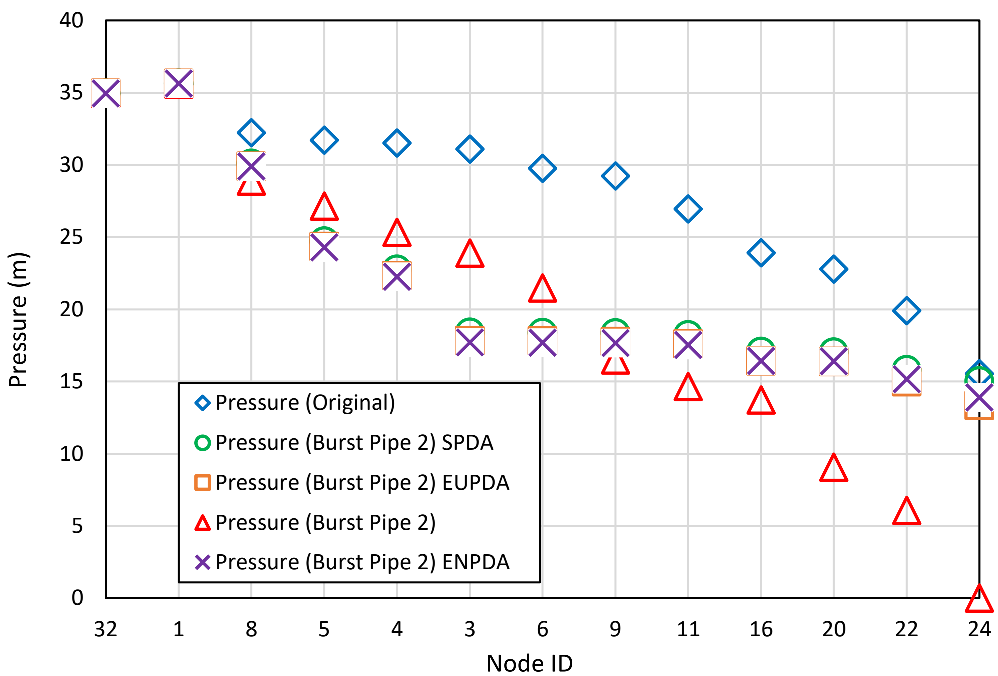

Figure A-30: The case study II: El-Mustaqbal City network with viewing pressure in original, SPDA, ENPDA and EUPDA after burst pipe 2 route-R2.

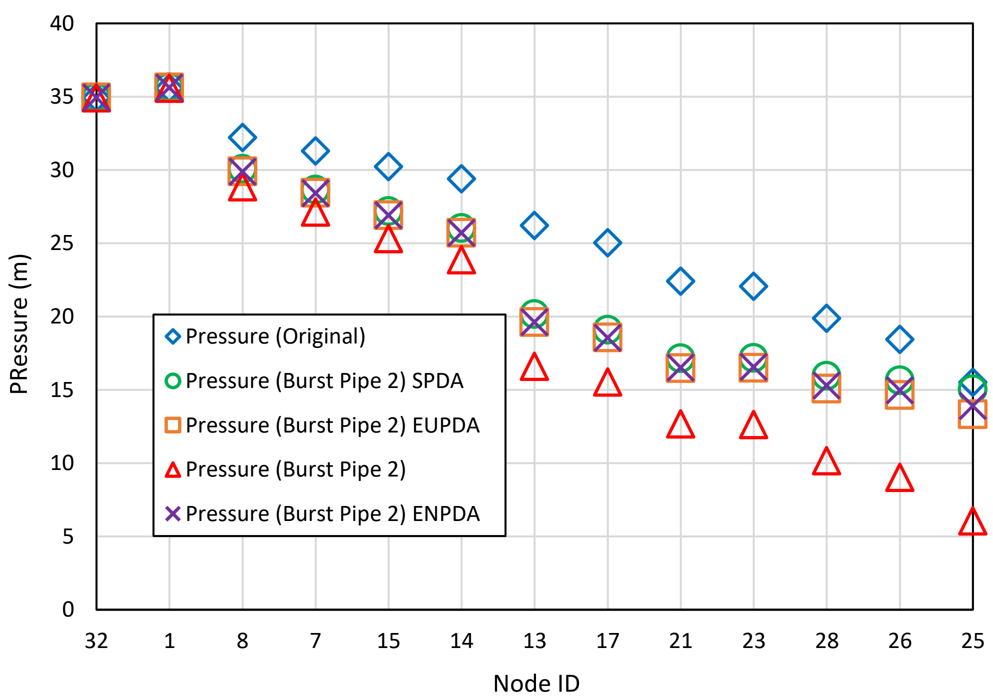

Figure A-31: The case study II: El-Mustaqbal City network with viewing pressure in DDA, SPDA, ENPDA and EUPDA after burst pipe 2 route R3.

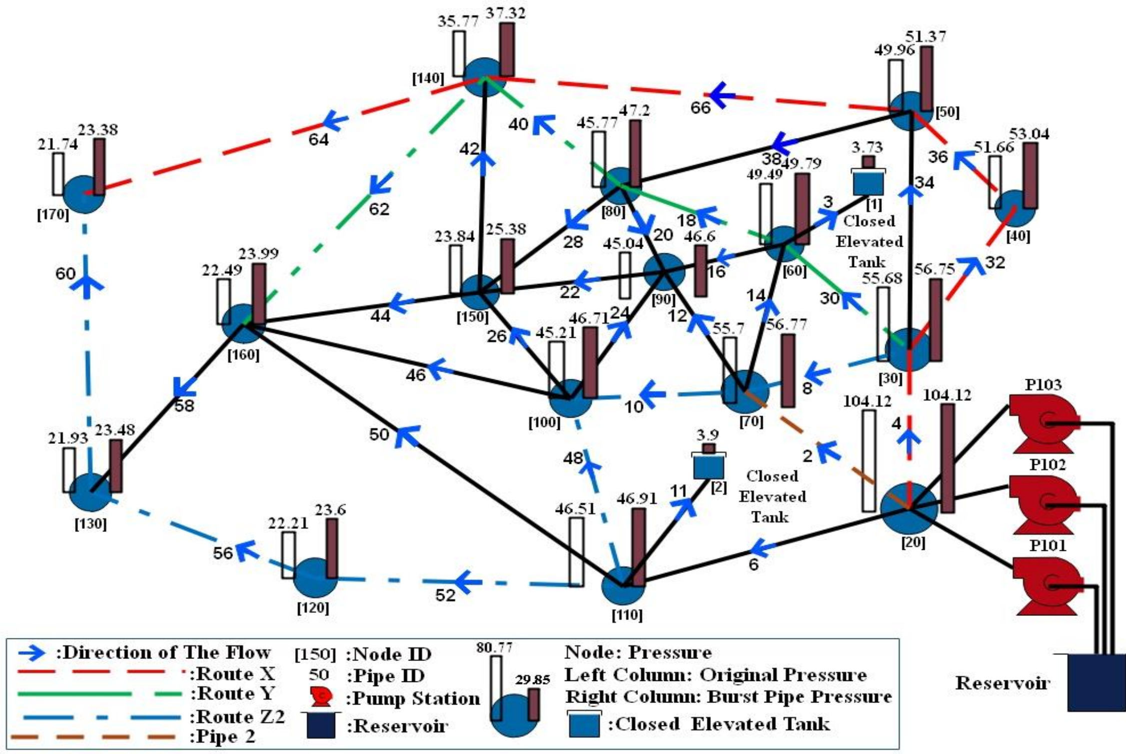

Figure A-32: The first case study: Network 2 pressure results routes X, Y and Z2 at original and elevated balance tanks at burst pipe 2.

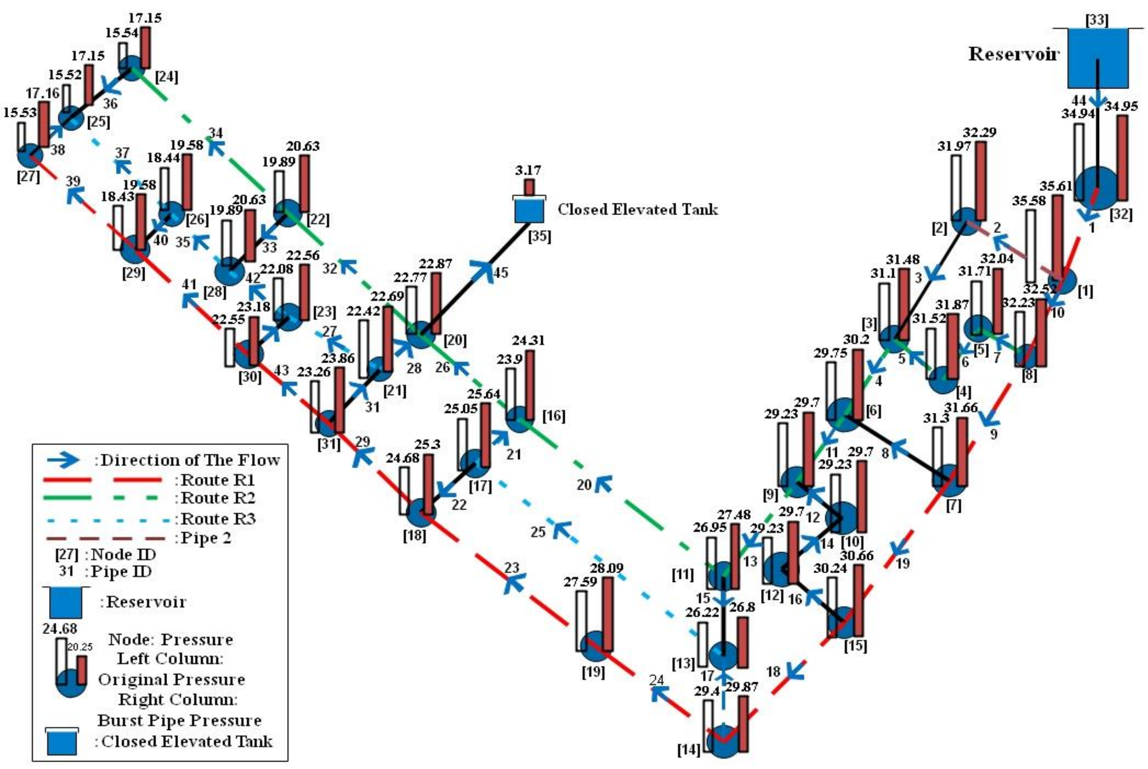

Figure A-33: The second case study: El-Mustaqbal City network pressure results routes R1, R2 and R3 at burst pipe 2 and the elevated balance tank (EBT).

APPENDIX B : TABLES

Table B-1: The first case study for the network pipelines

Link ID	Length	Diameter	Flow	Velocity	Unit Head Loss	Friction Factor	Status
	m	mm	lps	m/sec	m/km		
Pipe 2	3657.6	406.2	159.75	1.23	10.98	0.058	Open
Pipe 4	3657.6	304.8	128.53	1.75	10.98	0.021	Open
Pipe 6	3657.6	304.8	83.94	1.14	13.54	0.06	Open
Pipe 8	2743.2	304.8	-1.30	0.01	0.01	0.113	Open
Pipe 10	1828.8	304.8	-53.36	0.73	5.85	0.065	Open

Table B-2: The first case study pressure efficiency for burst pipe scenarios

Node ID	Original Model		Burst Pipe 2			Burst Pipe 4			Burst Pipe 6		
	Base Demand	Pressure	Base Demand	Pressure	P eff.	Base Deman	Pressur e	P eff.	Base Deman	Pressur e	P eff.
	lps	m	lps	m	%	lps	m	%	lps	m	%
20	**31.54**	104.02	**31.54**	104.02	**100**	**31.54**	104.02	**100**	**31.54**	104.02	**100**
30	**12.61**	55.68	**12.61**	0	**0**	**12.61**	0	**0**	**12.61**	31.86	**75.64**
40	**12.61**	51.66	**12.61**	0	**0**	**12.61**	0	**0**	**12.61**	25.51	**70.27**
50	**12.61**	49.96	**12.61**	0	**0**	**12.61**	0	**0**	**12.61**	22.17	**66.61**
60	**31.54**	49.49	**31.54**	0	**0**	**31.54**	0	**0**	**31.54**	21.75	**66.29**
70	**31.54**	55.70	**31.54**	0	**0**	**31.54**	4.91	**29.69**	**31.54**	31.86	**75.63**
80	**31.54**	45.77	**31.54**	0	**0**	**31.54**	0	**0**	**31.54**	14.08	**55.46**
90	**63.09**	45.04	**63.09**	0	**0**	**63.09**	0	**0**	**63.09**	12.33	**52.32**
100	**31.54**	45.21	**31.54**	0	**0**	**31.54**	0	**0**	**31.54**	11.38	**50.17**
110	**31.54**	46.51	**31.54**	0	**0**	**31.54**	0	**0**	**31.54**	1.24	**16.32**
120	**12.61**	22.21	**12.61**	0	**0**	**12.61**	0	**0**	**12.61**	0	**0**
130	**12.61**	21.93	**12.61**	0	**0**	**12.61**	0	**0**	**12.61**	0	**0**
140	**12.61**	35.77	**12.61**	0	**0**	**12.61**	0	**0**	**12.61**	1.48	**20.34**
150	**12.61**	23.84	**12.61**	0	**0**	**12.61**	0	**0**	**12.61**	0	**0**
160	**50.47**	22.49	**50.47**	0	**0**	**50.47**	0	**0**	**50.47**	0	**0**
170	**12.61**	21.74	**12.61**	0	**0**	**12.61**	0	**0**	**12.61**	0	**0**
			P eff. %		**6.25**	P eff. %		**6.80**	P eff. %		**27.6**

Table B-3: The second case study for the network pipelines

Link ID	Length	Diameter	Flow	Velocity	Unit Head loss	Friction Factor	Status
	m	mm	lps	m/sec	m/km		
Pipe 2	328	300	100.82	1.43	10.61	0.031	Open
Pipe 3	80	300	100.82	1.43	10.61	0.031	Open
Pipe 8	341.7	150	9.17	0.52	3.66	0.04	Open
Pipe 10	288	400	227.67	1.81	11.81	0.028	Open

Table B-4: The second case study pressure efficiency for burst pipe scenarios

Node ID	Original Model		Burst Pipe 2			Burst Pipe 3			Burst Pipe 8		
	Base Demand	Pressure	Base Demand	Pressure	P eff.	Base Demand	Pressure	P eff.	Base Demand	Pressure	P eff.
	lps	m	lps	m	%	lps	m	%	lps	m	%
32	0	34.94	0	34.94	100	0	34.94	100	0	34.94	100
1	24	35.58	24	35.58	100	24	35.58	100	24	35.58	100
8	17.6	32.23	17.6	28.87	89.57	17.6	28.87	89.57	17.6	32.36	100
7	20.8	31.3	20.8	27.14	86.70	20.8	27.14	86.71	20.8	31.48	100
15	0	30.24	0	25.33	83.76	0	25.33	83.76	0	30.39	100
14	19.2	29.4	19.2	23.88	81.22	19.2	23.88	81.22	19.2	29.51	100
19	0	27.59	0	21.48	77.85	0	21.48	77.85	0	27.67	100
18	34.09	24.68	34.09	16.48	66.77	34.09	16.48	66.77	34.09	24.65	99.88
31	20.8	23.26	20.8	14.65	62.98	20.8	14.65	62.98	20.8	23.2	99.74
30	0	22.55	0	13.71	60.79	0	13.71	60.8	0	22.48	99.69
29	24	18.43	24	9.06	49.15	24	9.06	49.16	24	18.33	99.46
27	19.2	15.53	19.2	6.07	39.08	19.2	6.07	39.09	19.2	15.43	99.36
2	0	31.97	0	14.55	45.51	0	35.58	100	0	31.66	99.03
3	19.2	31.1	19.2	14.55	46.78	19.2	14.55	46.78	19.2	30.7	98.71
6	19.2	29.75	19.2	14.52	48.80	19.2	14.52	48.81	19.2	29.16	98.02
9	0	29.23	0	14.46	49.47	0	14.46	49.47	0	28.69	98.15
11	24	26.95	24	14.22	52.76	24	14.22	52.76	24	26.59	98.66
16	24	23.9	24	12.8	53.55	24	12.8	53.56	24	23.69	99.12
20	16	22.77	16	12.54	55.07	16	12.54	55.07	16	22.63	99.39
22	16	19.89	16	10.14	50.98	16	10.14	50.98	16	19.78	99.45
24	16	15.54	16	6.06	38.99	16	6.06	39	16	15.43	99.29
5	0	31.71	0	22.28	70.26	0	22.28	70.26	0	31.6	99.65
4	0	31.52	0	19.89	63.10	0	19.89	63.1	0	31.32	99.37
17	19.2	25.05	19.2	15.54	62.03	19.2	15.54	62.04	19.2	24.92	99.48
21	0	22.42	0	12.68	56.55	0	12.68	56.56	0	22.3	99.46
23	0	22.08	0	12.64	57.24	0	12.64	57.25	0	21.98	99.55
25	19.2	15.52	19.2	6.06	39.04	19.2	6.06	39.05	19.2	15.42	99.36
26	0	18.44	0	9.05	49.07	0	9.05	49.08	0	18.34	99.46
28	0	19.89	0	10.18	51.18	0	10.18	51.18	0	19.77	99.40
13	0	26.22	0	16.62	63.38	0	16.62	63.39	0	26.08	99.47
12	0	29.23	0	14.47	49.50	0	14.47	49.5	0	28.69	98.15
10	0	29.23	0	14.47	49.50	0	4.98	49.5	0	28.69	98.15
			P eff. %		**60.96**	P eff. %		**62.66**	P eff. %		**99.36**

Table B-5: The case study I: The pressure efficiency analysis in DDA, SPDA, ENPDA and EUPDA for burst pipe 2

Node ID	Original		Burst			Semi Pressure Driven Analysis			Normal Emitter Driven Analysis			UNESCO Emitter Driven Analysis		
	Base Demand	Pressure	Base Demand	Pressure	P eff.	Base Demand	Pressure	P eff.	Base Demand	Pressure	P eff.	Base Demand	Pressure	P eff.
	lps	m	lps	m	%	lps	m	%	lps	m	%	lps	m	%
20	31.54	104.02	31.54	104.02	100	31.54	105.14	100	31.54	105.15	100	31.54	105.15	100
30	12.61	55.68	12.61	0	0	12.61	29.38	52.76	12.61	30.24	54.31	12.61	30.34	54.48
40	12.61	51.66	12.61	0	0	12.61	25.89	50.12	12.43	26.80	51.88	12.45	26.88	52.036
50	12.61	49.96	12.61	0	0	12.61	24.55	49.13	12.12	25.46	50.97	12.14	25.53	51.111
60	31.54	49.49	31.54	0	0	31.54	20.85	42.13	28.12	21.93	44.30	28.15	21.97	44.392
70	31.54	55.70	31.54	0	0	31.54	20.53	36.85	27.95	21.66	38.88	27.98	21.71	38.975
80	31.54	45.77	31.54	0	0	31.54	20.86	45.57	28.07	21.86	47.75	28.10	21.90	47.846
90	63.09	45.04	63.09	0	0	63.09	19.24	42.71	54.46	20.55	45.64	54.51	20.59	45.72
100	31.54	45.21	31.54	0	0	31.54	20.39	45.10	27.74	21.34	47.20	27.77	21.38	47.3
110	31.54	46.51	31.54	0	0	31.54	28.66	61.63	31.54	27.88	59.95	31.73	27.91	60
120	12.61	22.21	12.61	0	0	0	5.31	23.90	4.63	3.71	16.73	4.64	3.74	16.85
130	12.61	21.93	12.61	0	0	0	2.86	13.08	3.34	1.93	8.836	3.36	1.96	8.96
140	12.61	35.77	12.61	0	0	12.61	12.53	35.02	8.70	13.14	36.73	8.72	13.17	36.83
150	12.61	23.84	12.61	0	0	0	0	0	2.04	0.72	3.03	2.09	0.76	3.21
160	50.47	22.49	50.47	0	0	0	2.66	11.86	13.23	1.89	8.43	13.33	1.92	8.55
170	12.61	21.74	12.61	0	0	0	2.10	9.67	2.90	1.46	6.72	2.93	1.48	6.85
	403.78	**43.56**	**403.78**	**6.49**	**6.25**	**302.83**	**21.31**	**38.72**	**301.51**	**21.61**	**38.83**	**302.13**	**21.64**	**38.94**

Table B-6: The case study I: The pressure efficiency analysis in DDA, SPDA, ENPDA and EUPDA for burst pipe 4

Original		Burst			Semi Pressure Driven Analysis			Normal Emitter Driven Analysis			UNESCO Emitter Driven Analysis		
Base Demand	Pressure	Base Demand	Pressure	P eff.	Base Demand	Pressure	P eff.	Base Demand	Pressure	P eff.	Base Demand	Pressure	P eff.
lps	m	lps	m	%	lps	m	%	lps	m	%	lps	m	%
403.78	**43.56**	**403.78**	**7.77**	**6.8**	**318.45**	**31.27**	**63.81**	**329.30**	**23.70**	**45.16**	**332.70**	**24.10**	**46.29**

Table B-7: The case study I: The pressure efficiency analysis in DDA, SPDA, ENPDA and EUPDA for burst pipe 6

Original		Burst			Semi Pressure Driven Analysis			Normal Emitter Driven Analysis			UNESCO Emitter Driven Analysis		
Base Demand	Pressure	Base Demand	Pressure	P eff.	Base Demand	Pressure	P eff.	Base Demand	Pressure	P eff.	Base Demand	Pressure	P eff.
lps	m	lps	m	%	lps	m	%	lps	m	%	lps	m	%
403.78	**43.56**	**403.78**	**17.35**	**27.64**	**347.50**	**34.93**	**74.09**	**350.80**	**30.63**	**61.01**	**355.49**	**31.75**	**64.16**

Table B-8: The case study II: The pressure efficiency analysis in DDA, SPDA, ENPDA and EUPDA for burst pipe 2

Node ID	Original		Burst			Semi Pressure Driven Analysis			Normal Emitter Driven Analysis			UNESCO Emitter Driven Analysis		
	Base Demand	Pressure	Base Demand	Pressure	P eff.	Base Demand	Pressure	P eff.	Base Demand	Pressure	P eff.	Base Demand	Pressure	P eff.
	lps	m	lps	m	%	lps	m	%	lps	m	%	lps	m	%
32	**0**	34.94	**0**	34.94	**100**	**0**	34.95	**100**	**0**	34.95	**100**	**0.01**	34.95	**100**
1	**24**	35.58	**24**	35.58	**100**	**24**	35.64	**100**	**24**	35.63	**100**	**24**	35.63	**100**
8	**17.6**	32.23	**17.6**	28.87	**89.57**	**17.6**	30.09	**93.36**	**17.6**	29.89	**92.73**	**17.6**	29.9	**92.77**
7	**20.8**	31.3	**20.8**	27.14	**86.70**	**20.8**	28.67	**91.59**	**20.8**	28.43	**90.83**	**20.8**	28.44	**90.86**
15	**0**	30.24	**0**	25.33	**83.76**	**0**	27.21	**89.98**	**0**	26.92	**89.02**	**0.01**	26.92	**89.02**
14	**19.2**	29.4	**19.2**	23.88	**81.22**	**19.2**	26.05	**88.60**	**19.2**	25.71	**87.44**	**19.2**	25.72	**87.48**
19	**0**	27.59	**0**	21.48	**77.85**	**0**	23.95	**86.80**	**0**	23.57	**85.42**	**0.01**	23.57	**85.42**
18	**34.09**	24.68	**34.09**	16.48	**66.77**	**34.09**	20.04	**81.19**	**34.09**	19.5	**79.01**	**34.09**	19.5	**79.01**
31	**20.8**	23.26	**20.8**	14.65	**62.98**	**20.8**	18.61	**80.00**	**22.8**	18.02	**77.47**	**20.8**	18.01	**77.42**
30	**0**	22.55	**0**	13.71	**60.79**	**0**	18.06	**80.08**	**0**	17.45	**77.38**	**0.01**	17.4	**77.16**
29	**24**	18.43	**24**	9.06	**49.15**	**24**	15.65	**84.91**	**19.13**	14.99	**81.33**	**19.68**	14.67	**79.59**
27	**19.2**	15.53	**19.2**	6.07	**39.08**	**7.98**	15.04	**96.84**	**10.81**	13.91	**89.56**	**12.12**	13.36	**86.02**
2	**0**	31.97	**0**	14.55	**45.51**	**0**	18.4	**57.55**	**0**	17.7	**55.36**	**0.01**	17.81	**55.70**
3	**19.2**	31.1	**19.2**	14.55	**46.78**	**19.2**	18.4	**59.16**	**20.82**	17.7	**56.91**	**19.2**	17.81	**57.26**
6	**19.2**	29.75	**19.2**	14.52	**48.80**	**19.2**	18.38	**61.78**	**20.81**	17.68	**59.42**	**19.2**	17.79	**59.79**
9	**0**	29.23	**0**	14.46	**49.46**	**0**	18.35	**62.77**	**0**	17.66	**60.41**	**0.01**	17.76	**60.75**
11	**24**	26.95	**24**	14.22	**52.76**	**24**	18.21	**67.56**	**24**	17.54	**65.08**	**24**	17.6	**65.30**
16	**24**	23.9	**24**	12.8	**53.55**	**24**	17.06	**71.38**	**23.59**	16.42	**68.70**	**23.8**	16.42	**68.70**
20	**16**	22.77	**16**	12.54	**55.07**	**16**	17.03	**74.79**	**15.8**	16.39	**71.98**	**15.79**	16.37	**71.89**
22	**16**	19.89	**16**	10.14	**50.98**	**16**	15.8	**79.43**	**13.56**	15.17	**76.26**	**14.03**	14.98	**75.31**
24	**16**	15.54	**16**	6.06	**38.99**	**7.21**	15.03	**96.71**	**8.98**	13.9	**89.44**	**10.08**	13.35	**85.90**
5	**0**	31.71	**0**	22.28	**70.26**	**0**	24.71	**77.92**	**0**	24.28	**76.56**	**0.01**	24.34	**76.75**
4	**0**	31.52	**0**	19.89	**63.10**	**0**	22.76	**72.20**	**0**	22.24	**70.55**	**0.01**	22.32	**70.81**
17	**19.2**	25.05	**19.2**	15.54	**62.03**	**19.2**	19.11	**76.28**	**19.2**	18.55	**74.05**	**19.2**	18.57	**74.13**
21	**0**	22.42	**0**	12.68	**56.55**	**0**	17.15	**76.49**	**0**	16.53	**73.72**	**0.01**	16.49	**73.55**
23	**0**	22.08	**0**	12.64	**57.24**	**0**	17.18	**77.80**	**0**	16.56	**75**	**0.01**	16.5	**74.72**
25	**19.2**	15.52	**19.2**	6.06	**39.04**	**7.54**	15.04	**96.90**	**10.81**	13.9	**89.56**	**12.09**	13.35	**86.01**
26	**0**	18.44	**0**	9.05	**49.07**	**0**	15.65	**84.86**	**0**	14.97	**81.18**	**0.01**	14.66	**79.50**
28	**0**	19.89	**0**	10.18	**51.18**	**0**	15.96	**80.24**	**0**	15.31	**76.97**	**0.01**	15.09	**75.86**
13	**0**	26.22	**0**	16.62	**63.38**	**0**	20.17	**76.92**	**0**	19.62	**74.82**	**0.01**	19.63	**74.86**
12	**0**	29.23	**0**	14.47	**49.50**	**0**	18.35	**62.77**	**0**	17.66	**60.41**	**0.01**	17.76	**60.75**
10	**0**	29.23	**0**	14.47	**49.50**	**0**	18.35	**62.77**	**0**	17.66	**60.41**	**0.01**	17.76	**60.75**
	352.49	**25.87**	**352.49**	**16.40**	**60.96**	**320.82**	**20.47**	**79.68**	**326.01**	**19.88**	**77.09**	**328.11**	**19.82**	**76.66**

Table B-9: The case study II: The pressure efficiency analysis in DDA, SPDA, ENPDA and EUPDA for burst pipe 3

Original		Burst			Semi Pressure Driven Analysis			Normal Emitter Driven Analysis			UNESCO Emitter Driven Analysis		
Base Demand	Pressure	Base Demand	Pressure	P eff.	Base Demand	Pressure	P eff.	Base Demand	Pressure	P eff.	Base Demand	Pressure	P eff.
lps	m	lps	m	%	lps	m	%	lps	m	%	lps	m	%
352.49	**25.879**	**352.49**	**17.06**	**62.66**	**320.94**	**20.99**	**80.94**	**323.93**	**20.60**	**79.04**	**322.63**	**20.83**	**80.73**

Table B-10: The case study II: The pressure efficiency analysis in DDA, SPDA, ENPDA and EUPDA for burst pipe 8

Original		Burst			Semi Pressure Driven Analysis			Normal Emitter Driven Analysis			UNESCO Emitter Driven Analysis		
Base Demand	Pressure	Base Demand	Pressure	P eff.	Base Demand	Pressure	P eff.	Base Demand	Pressure	P eff.	Base Demand	Pressure	*P eff.*
lps	m	lps	m	%	lps	m	%	lps	m	%	lps	m	*%*
352.49	**25.87**	**352.49**	**25.73**	**99.36**	**352.49**	**25.53**	**99.36**	**352.49**	**25.73**	**99.36**	**352.49**	**25.73**	***99.36***

Table B-11: The case study I: The pressure efficiency analysis in DDA, ENPDA and EBT for burst pipe 2

Node ID	Original		Normal Emitter Driven Analysis			Elevated Tank Results Analysis		
	Base Demand	Pressure	Base Demand	Pressure	P eff.	Base Demand	Pressure	P eff.
	lps	m	lps	m	%	lps	m	%
20	**31.54**	104.02	**31.54**	105.15	**100**	**31.54**	104.12	**100**
30	**12.61**	55.68	**12.61**	30.24	**73.69**	**12.61**	56.75	**100**
40	**12.61**	51.66	**12.43**	26.80	**72.03**	**12.61**	53.04	**100**
50	**12.61**	49.96	**12.12**	25.46	**71.39**	**12.61**	51.37	**100**
60	**31.54**	49.49	**28.12**	21.93	**66.56**	**31.54**	49.79	**100**
70	**31.54**	55.70	**27.95**	21.66	**62.36**	**31.54**	56.77	**100**
80	**31.54**	45.77	**28.07**	21.86	**69.1**	**31.54**	47.20	**100**
90	**63.09**	45.04	**54.46**	20.55	**67.56**	**63.09**	46.60	**100**
100	**31.54**	45.21	**27.74**	21.34	**68.7**	**31.54**	46.71	**100**
110	**31.54**	46.51	**31.54**	27.88	**77.43**	**31.54**	46.92	**100**
120	**12.61**	22.21	**4.63**	3.71	**40.9**	**12.61**	23.60	**100**
130	**12.61**	21.93	**3.34**	1.93	**29.72**	**12.61**	23.48	**100**
140	**12.61**	35.77	**8.70**	13.14	**60.61**	**12.61**	37.32	**100**
150	**12.61**	23.84	**2.04**	0.72	**17.42**	**12.61**	25.38	**100**
160	**50.47**	22.49	**13.23**	1.89	**29.03**	**50.47**	23.99	**100**
170	**12.61**	21.74	**2.90**	1.46	**25.93**	**12.61**	23.38	**100**
	403.78	**43.56**	**301.51**	**21.60**	**38.83**	**403.78**	**44.77**	**100**

Table B-12: The case study I: The pressure efficiency analysis in DDA, ENPDA and EBT for burst pipe 4

Original		Normal Emitter Driven Analysis			The Elevated Tank Results Analysis		
Base Demand	Pressure	Base Demand	Pressure	P eff.	Base Demand	Pressure	P eff.
lps	m	lps	m	%	lps	m	%
403.78	**43.56**	**329.30**	**23.70**	**45.16**	**403.78**	**44.85**	**100**

Table B-13: The case study I: The pressure efficiency analysis in DDA, ENPDA and EBT for burst pipe 6

Original		Normal Emitter Driven Analysis			The Elevated Tank Results Analysis		
Base Demand	Pressure	Base Demand	Pressure	P eff.	Base Demand	Pressure	P eff.
lps	m	lps	m	%	lps	Psi	%
403.78	**43.56**	**350.80**	**30.63**	**61.01**	**403.78**	**44.77**	**100**

Table B-14: The case study II: The pressure efficiency analysis in DDA, ENPDA and EBT for burst pipe 2

Node ID	Original		Normal Emitter Driven Analysis			Elevated Balance Tank Results Analysis		
	Base Demand	Pressure	Base Demand	Pressure	P eff.	Base Demand	Pressure	P eff.
	lps	m	lps	m	%	lps	m	%
32	**0**	34.94	**0**	34.95	**100**	**0**	34.95	**100**
1	**24**	35.58	**24**	35.63	**100**	**24**	35.61	**100**
8	**17.6**	32.23	**17.6**	29.89	**92.74**	**17.6**	32.53	**100**
7	**20.8**	31.3	**20.8**	28.43	**90.83**	**20.8**	31.66	**100**
15	**0**	30.24	**0**	26.92	**89.02**	**0**	30.67	**100**
14	**19.2**	29.4	**19.2**	25.71	**87.45**	**19.2**	29.87	**100**
19	**0**	27.59	**0**	23.57	**85.43**	**0**	28.09	**100**
18	**34.09**	24.68	**34.09**	19.5	**79.01**	**34.09**	25.3	**100**
31	**20.8**	23.26	**22.8**	18.02	**77.47**	**20.8**	23.87	**100**
30	**0**	22.55	**0**	17.45	**77.38**	**0**	23.19	**100**
29	**24**	18.43	**19.13**	14.99	**81.33**	**24**	19.59	**100**
27	**19.2**	15.53	**10.81**	13.91	**89.57**	**19.2**	17.16	**100**
2	**0**	31.97	**0**	17.7	**55.36**	**0**	32.29	**100**
3	**19.2**	31.1	**20.82**	17.7	**56.91**	**19.2**	31.48	**100**
6	**19.2**	29.75	**20.81**	17.68	**59.43**	**19.2**	30.2	**100**
9	**0**	29.23	**0**	17.66	**60.42**	**0**	29.7	**100**
11	**24**	26.95	**24**	17.54	**65.08**	**24**	27.49	**100**
16	**24**	23.9	**23.59**	16.42	**68.7**	**24**	24.32	**100**
20	**16**	22.77	**15.8**	16.39	**71.98**	**16**	22.88	**100**
22	**16**	19.89	**13.56**	15.17	**76.27**	**16**	20.64	**100**
24	**16**	15.54	**8.98**	13.9	**89.45**	**16**	17.16	**100**
5	**0**	31.71	**0**	24.28	**76.57**	**0**	32.05	**100**
4	**0**	31.52	**0**	22.24	**70.56**	**0**	31.87	**100**
17	**19.2**	25.05	**19.2**	18.55	**74.05**	**19.2**	25.65	**100**
21	**0**	22.42	**0**	16.53	**73.73**	**0**	22.7	**100**
23	**0**	22.08	**0**	16.56	**75**	**0**	22.57	**100**
25	**19.2**	15.52	**10.81**	13.9	**89.56**	**19.2**	17.16	**100**
26	**0**	18.44	**0**	14.97	**81.18**	**0**	19.59	**100**
28	**0**	19.89	**0**	15.31	**76.97**	**0**	20.64	**100**
13	**0**	26.22	**0**	19.62	**74.83**	**0**	26.81	**100**
12	**0**	29.23	**0**	17.66	**60.42**	**0**	29.7	**100**
10	**0**	29.23	**0**	17.66	**60.42**	**0**	29.7	**100**
	352.49	**25.87**	**326.01**	**19.88**	77.1	**352.49**	**26.47**	**100**

Table B-15: The case study II: The pressure efficiency analysis in DDA, ENPDA and EBT for burst pipe 3

Original		Normal Emitter Driven Analysis			Elevated Balance Tank Results Analysis		
Base Demand	Pressure	Base Demand	Pressure	P eff.	Base Demand	Pressure	P eff.
lps	m	lps	m	%	lps	m	%
352.49	**25.87**	**323.93**	**20.60**	**79.04**	**352.49**	**26.45**	**100**

Table B-16: The case study II: The pressure efficiency analysis in DDA, ENPDA and EBT for burst pipe 8

Original		Normal Emitter Driven Analysis			Elevated Balance Tank Results Analysis		
Base Demand	Pressure	Base Demand	Pressure	P eff.	Base Demand	Pressure	P eff.
lps	m	lps	m	%	lps	m	%
352.49	**25.87**	**352.49**	**25.73**	**99.35**	**352.49**	**26.35**	**99.98**

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