Strategic valve locations in a water distribution system

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Dissertation Submitted to the Faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
in
Civil and Environmental Engineering

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May 6, 2005
Blacksburg, Virginia

Keywords: Water Distribution System, Valve, Segment, Matrix Algorithm, Simulation, Failure Analysis, Performance Indicators

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ABSTRACT

Valves play a critical role in a water distribution system for subsystem isolation and flow or pressure control. Among them, subsystem isolation is required to repair or to rehabilitate a broken component and can be done by closing adjacent valves. To evaluate the role of valves, the concept of "Segment" is necessary. A segment consists of a set of pipes and nodes isolated together by closing adjacent valves when a pipe fails. An efficient algorithm to identify segments in a water distribution system is proposed. In addition, when a segment is isolated, an additional subsystem may be disconnected from water sources by the segment isolation. It is a topological unintended isolation. In addition, a hydraulic failure, in terms of pressure types of failures at demand nodes should be considered. These three account for the failure impact of a pipe.

Placing valves efficiently improves the reliability of a water distribution system. However, the valve reliability itself is not 100%. Therefore, valve failure consequence should be explored in determining the locations of valves. For this purpose, three methodologies, namely segment-valve matrix algorithm, decision tree approach and simulation are proposed. Another consideration for placing valves is a strategic valving rule, namely N and (N-1) valving rules. Using a formulation for

node reliability in terms of failing valves, the reliability difference between the two valving rules is evaluated. We also employ a mixed N and (N-1) valving rule. Another strategic valving rule, a segment size reducing approach minimizing the number of affected customers is proposed.

The developed algorithms are utilized to build software, the Strategic Valve Management Model, to solve practical problems. The methodology is applied to three real water distribution systems.

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1. INTRODUCTION

1.1 Problem description

Recent concerns regarding protecting, identifying, isolating, redundant routing and dewatering of subsystems of water distribution networks have led to the realization of the importance of valves in these systems. Most valves serve two purposes namely, flow and pressure control and isolating subsystems due to breakage or contaminant containment. In this thesis, valves are considered from the point of view of subsystem isolation.

When a water main is required to be closed, in general it is necessary to close several other pipes in addition to the broken pipe itself. The number and extent of the other pipes to be closed depend on the distribution of adjacent valves. This set of pipes is defined as a segment. Typically, we can group the problem into analysis and planning categories. In the analysis mode we evaluate the system performance based on the existing valves at their given locations. In a planning mode we determine the optimal locations for valves for maximum control within budgetary restrictions. It is also likely that an existing system of valves may be reinforced with a new set of valves to improve the performance of the system. Clearly, to conduct these analyses a set of performance measures is essential. For example, this set may include duration of down time, number of customers affected and demand shortage (in terms of flow and pressure) and direct and indirect costs. The last aspect should consider emergencies such as fires, ability to reroute the flows, and withdrawal from alternate sources including water tanks and dewatering after containment. Even though the problem is quite complex in general terms, certain trends can be discerned. The transmission pipelines will always qualify to be critical pipes affecting the performance measures significantly; based on the looping involved, blocking a few laterals might not significantly impact the performance measures; provision of secondary sources such as well fields, equalizing tanks, and another provider improves redundancy and performance measures. Therefore, the issue is trading off cost and labor against higher performance measures.

Another issue to consider is the possible forcing of contaminants into the distribution system. Because the distribution system is pressurized, such intrusions will require establishing high energy heads say, through pumping. This requirement of higher energy heads may serve to detect such intrusions. The containment is established with the aid of valves and subsequent dewatering through the sewer system or by other suitable means of draining.

1.2 Objectives

The objectives of this thesis are to:

1) Develop an algorithm for identifying valves that need to be closed to isolate a segment (subsystem) of a water distribution system.
2) Develop a methodology for assessing the impact of valve failure on flow containment.
3) Develop performance measures to assess the impact of isolated segments.
4) Perform sensitivity analyses of alternative valve configuration in a simulation framework to assess general criteria for valve placement.
5) Develop a decision support tool using the developed algorithms to delineate the segments of a network.

1.3 Organization of the thesis

In chapter 2, a detailed literature review pertaining to valve placement and subsystem isolation is given. In chapter 3, a new algorithm for identifying valves that can isolate a selected pipe is proposed. Also, a breadth first search algorithm is suggested for delineating source-destination connectivity. Chapter 4 contains detailed description on hydraulic simulation analysis to assess the impact of isolating segments. Chapter 5 presents a complete enumeration technique for capturing the uncertainty present in valve operation. Because the number of configurations is extremely large, two strategies based on stochastic simulation are also offered in chapter 5. In chapter 6, a methodology for strategic locations for placement of valves is presented. The chapter takes into consideration the trade-off between reliability for flow containment and the number of valves at a node. To evaluate the performance of the system, seven performance indicators are presented in chapter 7. Chapter 8 presents extensive results for a reasonably sized network using the proposed methodologies. Chapter 9 contains results for two real water systems. These applications clearly illustrate the lack of sufficient number of valves in real systems and the utility of the techniques developed in this dissertation. Chapter 10 presents key points of this research and areas for future work.

2. LITERATURE REVIEW

In this section we provide a review of papers related valve location strategies for water distribution systems.

Goulter et al. (2000) present a comprehensive review of issues involved in reliability analysis. A repeated theme in this paper [also see Khomsi et al. (1996)] is the de-emphasis in recognizing simultaneous occurrence of two or more failures due to very small probability of such an event. Bouchart and Goulter (1991) presented a model to select a set of valve locations to minimize demand volume deficit. They assumed that the volume deficit was due only to the failed pipe and the impact on the rest of the network was ignored. Nevertheless, this paper established the importance of valve positioning in improving the performance measure.

Walski (1993) defined a segment as the portion of the network that can be isolated by closing valves. Such a segment will be a single pipe only if that pipe has two valves located at its upstream and downstream ends. Otherwise, isolation of a pipe will require closing valves on other pipes as well; thus formed segment may be comprised of adjacent pipes and nodes. Walski (1993) further suggested visualizing the network made up of nodes representing the segments and arcs representing the valves. This diagram helps in visualizing how segments merge as valves fail. Walski (2002) compared fire flow simulation results pertaining to modeling outages by blocking individual pipes versus segments. The primary conclusion is that connections to large mains should be valved well so that during an outage on a smaller line the large main will not become part of a segment. Also, not all pipe failures affect the system performance in terms of fire flow. Walski's approach requires identifying segments based on valve locations and performing simulations to assess the performance measures.

It is noted that in the above discussion we have assumed that valves will be operable when needed. Hoff (1996) addresses practical considerations related to valve maintenance, selection, storage, and installation. Whittaker (1997) describes potential problems in identifying, selecting, operating, monitoring, and record keeping of valves. He describes how two UK utilities joined with an electronic company to install a data logger capsule in a valve head. This capsule holds and displays information on that valve such as valve number, type of valve and main, percentage open, direction to open, and normal operational position. Skousen (1997) is a comprehensive reference on valve selection, type, and sizing. It also addresses the various problems associated with valves and costing.

Ysusi (2000) has provided a comprehensive review of water distribution system design. He groups valves into four major categories, namely: (1) isolation valves to separate subsystems (2) control valves for pressure and flow control (3) blow off valves to drain water from unwanted build up and (4) air release and vacuum prevention valves. In this thesis we exclusively focus on the isolation valves which primarily consist of gate valves and butterfly valves. Skousen (1998) and Hammer and Hammer (2001) provide details on the valves. Ysusi (2000) also discusses positioning of the valves. He states that the valves are typically placed at junctions. The preferred practice is to install one less valve than the number of pipes at a junction called the “(N-1) valve rule”. This will require at most 6 valves to be closed to isolate a pipe connecting two cross junctions. An ideal system will require two valves for each pipe located at its ends called the “N valve rule”. With the N valve rule at each junction, every incident pipe is valved at that junction. For large diameter transmission pipelines, isolation valves should be installed at selected intervals. He also states that unless valves are exercised at regular time intervals (at least once a year; more often, for aggressive water), they may become inoperable.

Ozger and Mays (2004) recommend a rule of thumb that no more than four valves should require closing to isolate a pipe. They also point out the complexity involved in finding optimal locations for valves in terms of the number of permutations to consider. Goulter et al. (2000) provide a detailed review of reliability analysis for water distribution systems including valve location analysis. In addition to the N and (N-1) valve rules, valves should be provided at all critical points such as each hydrant lateral and end of each city block.

In general, there is no widely accepted definition for reliability of a water distribution system. Mays addresses two different reliability definitions for a water distribution system: mechanical reliability and hydraulic reliability (Mays, 1996). The mechanical reliability is defined as the ability of distribution system components to provide continuing and long-term operation without the need for frequent repairs modifications, or replacement of component or subcomponents. The hydraulic reliability is defined as the ability of a water distribution system to provide sufficient water flow at demand nodes with adequate water pressure head. Based on these definitions, many researchers suggest methodologies to evaluate or to improve the reliability of a water distribution system.

Su et al. (1987) provide a clear methodology for addressing pipe failures in terms of minimal cut sets. A minimal cut sets is a set that contains elements such that all of them should fail for losing connectivity; survival of even a single member of a minimum cut set will ensure connectivity (Billinton and Allan, 1983). For each pipe failure, they identify the nodes that fail to satisfy the pressure requirements. Then for each node, pipes that induce the pressure failure are identified as the minimal cut set. They consider simultaneous failure of two or more pipes and state that such simultaneous failures have very small probability of occurrence. Using a relationship between the pipe diameter and its failure probability, iterations are performed to improve the reliability of pipes by changing their diameters. While this paper does not consider the role of the valves, it does invoke the seminal idea of paths and demand failures.

The minimal cut set is also used to estimate the mechanical reliability by Yang et al. (1996). They suggest mechanical reliability to be more appropriate than the hydraulic reliability in estimating the reliability of a water distribution system (WDS). They determined the connectivity of sources and nodes based on a fixed flow direction and the minimum cut-sets. To identify the minimum cut sets for a source-demand pair from candidate sets, a hydraulic simulation process was used based on the fixed flow direction. While simulating a candidate set, they removed all links in the candidate set without considering the possibility of the isolation of those links. As stated before, the actual isolation of links is carried out by closing valves. Thus, their assumption is true only if there are two valves at each end of links and the valves work. For this reason, if the availability of valves and actual links to be isolated including the unintended isolation, the number of the minimum cut-sets may be increased and the reliability of the system will be decreased.

Another approach to estimate a pipe failure impact and the reliability is suggested by Jowitt el al. (1993). They assume that the abnormal conditions of distribution systems are caused by a failure of any network component such as a pipe. Then, they predict failure consequences in terms of the number of demand nodes which don't have sufficient water flow with adequate hydraulic pressure head under the abnormal condition. Bouchart and Goulter (1991) address the role of valves directly and provide critical discussions on the role of the valves. They state the non-existence of demand nodes in real water distribution systems and rather continuous distribution of demand along pipelines. Therefore, to reduce the failure impact, valves should be placed minimizing the distance between them. Clearly, issues related to installation, maintenance, personnel, hydraulic performance, corrosion and water quality arise when a large number of valves at least in theory can be installed. In their paper, they assume that each pipe has valves at its ends (n-valve rule).

Valve placement clearly depends on measures used to assess their performance. Deb et al. (1995) developed a methodology to quantify the performance of water distribution systems. They surveyed and interviewed water distribution utilities in North America, foreign countries, and other distribution utilities such as gas, electric, and telephone. In addition, they conducted an expert workshop. Based on the collected data from these activities, they recommended the concept of the performance evaluation criteria for water distribution systems. Their criteria are divided by three categories: Adequacy, Dependability, and Efficiency. Adequacy refers to the delivery of an acceptable quantity and quality of water to customer. Dependability is defined as the measure of the ability of the distribution system to consistently deliver an acceptable quantity and quality of water. Efficiency is defined as how well water and energy are utilized. To assess the three criteria, they specified the performance measures for each criterion such as pressure, flow and water quality for Adequacy, service interruption and main breaks for Dependability and unaccounted-for water and pumping efficiency for Efficiency. Those performance measures are used to quantify the system performance. Moreover, they provided a stepwise procedure to evaluate the performance measures.

Coelho (1995) divided his book into four main chapters: performance in water distribution and assessment frame work, hydraulic performance, water quality performance, and reliability performance. In each section, the basic concepts and examples are provided. Marques and Monteiro (2001) reported their recent case study performed in Portugal to apply performance indicators to water distribution systems. Because each water utility has its own characteristics and the complexity of the system, there is no systematic way to assess the system for better management and operation. The authors developed 50 indicators and divided them into five groups: structural indicators, operational indicators, water and service quality indicators, personnel indicators, and economic indicators (see Table 2-1). Unfortunately, these indicators do not cover valves.

In the power plant industry, Jones and Tenera (1998) state that a comprehensive valve practice includes design practice as well as maintenance. Appropriate valve design assures the reliability of valves and the system. If any valve requires repairing, the valve maintenance practice is considered to have failed. Kovan (2000) reports a valve maintenance practice adopted by Siemens one of the largest service providers for the nuclear power plant industry. This practice is targeted to improve the safety of the plant. Their valve maintenance practice consists of three stages: design calculation, design evaluation, and monitoring and maintenance. Among them, early monitoring system to detect change in the valve condition is a key to reduce the risk and the cost of maintenance. Karjalainen (2001) states that valve maintenance and exercising programs should be carried out for assuring operability of emergency valves. The cost of the program can be expensive exceeding $1 million per year for manual exercising program at certain plants. An automated, stand-alone testing and monitoring system for emergency valves can be installed for real time monitoring resulting in cost saving.

For good valve maintenance program conducted by a real water utility, Shea (1990) reports the Boston Water and Sewer Commission's valve program. Before the valve maintenance program was initiated, crew routinely exercised large valves and most of the small valves were not maintained routinely. The author addresses the needs for the maintenance program:

- Water loss: when a pipe break occurs, inoperable valves result in the loss of considerable amount of water.
- Property damage: claims can be as expensive as the cost of one year maintenance program.
- Staff time: inoperable valves result in wastage of crew time looking for other operable valves to arrest the flow instead of repairing.

The program consists of the following:

- Raise casting to grade
- Clean access tube and exercise valve
- Repair packing leaks
- Replace valves
- Provide temporary by-pass piping

Temporary by-pass piping is necessary not to interrupt water service to important customers such as hospitals. The valve inventory should be updated and computerized in the form of GIS for better future maintenance.

AWWARF and KIWA (2001) report common valve problems and solutions. Problem prevention strategies are also given. The reliable valve is defined as the one that: (1) can be found and identified under all weather conditions, (2) can be operated and (3) works properly. Detailed documentation of valve failures is crucial for evaluating and improving the maintenance program. The report also states that 87% of valves in water distribution systems are used for isolation or sectioning. Based on several utility and county guidelines, the following practices are noted. Valves shall be placed at intersection of water mains, at hydrants and at fittings associated with the valve installation, at a reducer a valve should be placed in the smaller pipe within 20 feet of the reducer; spacing should be less than 500 ft in business area, less than 800 ft in other areas; number of valves should be at least two valves at a T-intersection and three at a cross-intersection; and no more than four valves should be closed for segment isolation.

Table 2-1
50 performance indicators (Marques and Monteiro, 2001)

Groups	Indicators
Structural Indicators	▪ The supply coverage (%) ▪ Water abstraction capacity (%) ▪ Water abstraction (%) ▪ Customers density (person / km) ▪ Storage tanks capacity (days) ▪ Materials (%) ▪ Diameters (%) ▪ Age pipes (years) ▪ Volume per type of customer (%) ▪ Per capita consumption (1 day^{-1} $cu.^{-1}$) ▪ Water consumption peak factors ▪ Customer enlargement (%) ▪ Network rehabilitation (%) ▪ Public taps density (number / km)

Table 2-1 continued

Operational indicators	▪ The meter reading frequency (number / year) ▪ Billing per meter reader (number / year) ▪ Inspection and maintenance of systems ▪ Water billed (%) ▪ Network efficiency (m^3 / day / km) ▪ Replaced meters (%) ▪ Pipe length per vehicle (km / # vehicle) ▪ Losses per pipe length (Liter / hr / km) ▪ Losses per customers (Liter / day / cu.) ▪ Failures per pipe length (number / 100 km / year) ▪ Interruption of supply
Water quality and quality of service delivered	▪ Disinfected water (%) ▪ Treated water (%) ▪ Number of yearly quality analysis (%) ▪ Violations of water quality analysis (%) ▪ Customers' complaints (number / 10^{-1} cu.) ▪ Response to complaints (days)
Personnel indicators	▪ Employee per activity (%) ▪ Qualification of employees (%) ▪ Absenteeism (%) ▪ Training (hours / employee / year) ▪ Employees per water produced (number / $10^5 m^3$ / year) ▪ Employees per customer (number / 10^3 cu.) ▪ Employees per pipe length (number / 10^2 km)

Table 2-1 continued

Economic indicators	▪ Average water charges ($ / m^3) ▪ Average income ($ / m^3) ▪ Income per type of customer (%) ▪ Cost composition per type of cost (%) ▪ Running costs composition per type of cost (%) ▪ Income per employees ($ / employee) ▪ Investment per pipe length ($ / km / year) ▪ O&M cost per water produced ($ / 10^5 m^3 / year) ▪ O&M cost per customer ($ / 10^5 cu.^{3}) ▪ O&M cost per pipe length ($ / 10^2 km) ▪ Debt equity ratio ▪ Liquidity indicator (current ratio) ▪ Return of equity

3. CHARACTERIZATION OF SEGMENTS

3.1 Segment of a network

In the conventional Link-Node representation as shown in Figure 3-1, we denote pipes as links and aggregate demand points as nodes. Figure 3-1 consists of 7 nodes, numbered 1 through 5 and two water sources, reservoir and tank, 8 pipes denoted by P1, P2,…, P8, and 9 valves denoted by V1, V2,…, V9. In most previous studies, a broken pipe is considered as an isolated link and removed. After the removal, further network analysis is carried out without the link to assess the effect of the pipe failure. In reality, however, the adjacent pipes to the broken pipe may need to be closed as well to repair the broken pipe. When valves are distributed throughout the network, Walski (1993) suggested a segment as the portion of the network that should be isolated to conduct repairs on a pipe. Based on the location and the number of the valves, the number of pipes in a segment varies. Figure 3-2 shows the segments associated with the pipes of network of Figure 3-1. When pipe P2 fails, segment S2 made up of pipe P2 and P4 must be closed to conduct repairs on P2. Because pipe P8 has two valves, segment S5 is just pipe P8. Segment S3 associated with pipe P7 affects pipe P4 dependent on the location of the valve 3. With the segment isolation, hydraulic condition of the network due to the pipe failure can be analyzed correctly. Repair of a broken pipe involves closing a set of valves to isolate the associated segment. In Figure 3-1 to isolate pipe P3, we need to close three valves, V1, V2 and V4. With this combination of valves closing, not only pipe P3 is closed but also pipe P5 is closed. To simulate this situation correctly, both pipes P3 and P5 must be removed from the network. It is clear that pipe P3 and pipe P5 belong to the same "Segment" so that the segment as a whole should be removed from the network. In this study we define a "Segment" as the set of pipes and nodes isolated by adjacent valves. For the sample network in Figure 3-1, eight segments are found as shown in Figure 3-2. Walski (2002) studied this case and presented the difference between the results of isolating just a single pipe and the associated segment for fire flow. While Walski suggested the need for segment analysis, he did not propose a method for finding the segments. In this study, we present an efficient algorithm for finding the segment. We also note that the network is completely covered by the union of segments. Therefore, we can also represent a network by the segments as nodes and valves as links as shown in Figure 3-3. We provide a matrix representation for the segment-valve diagram. We also offer a technique how to exploit the segment-valve matrix to identify the failure paths (given in chapter 5).

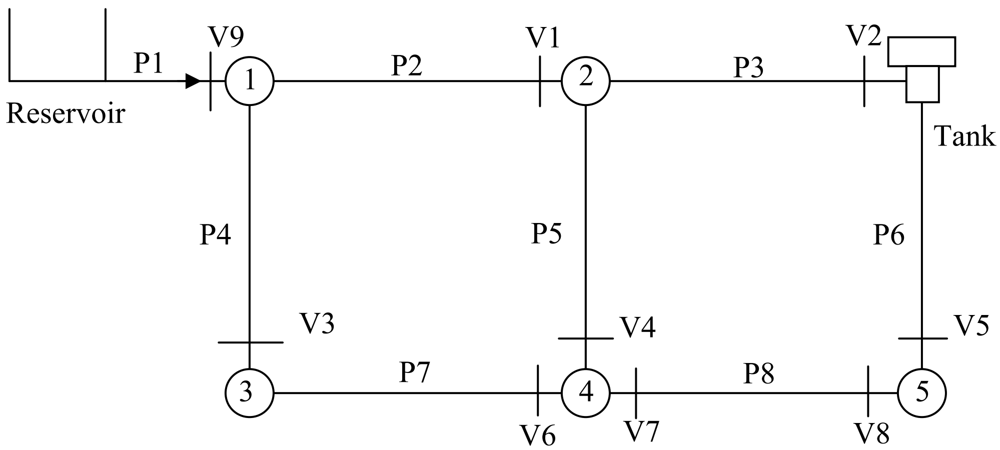


Figure 3-1 Example network

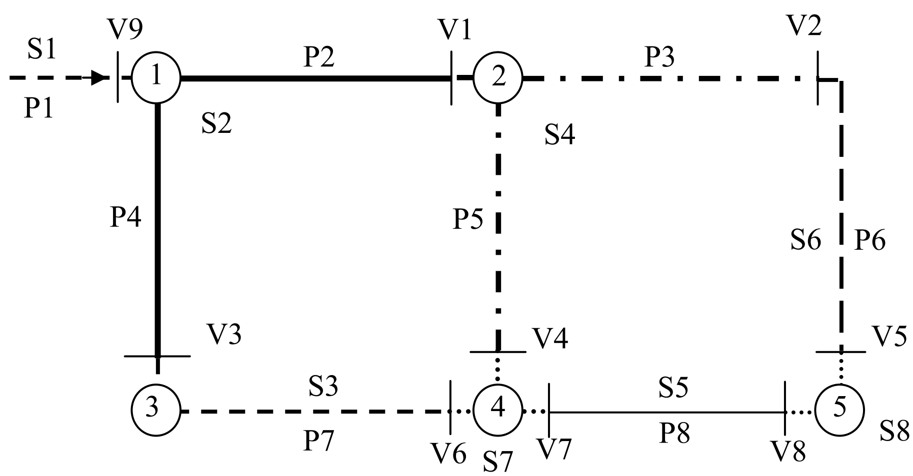


Figure 3-2 Segment delineation

3.2 Node Segments and nodes within segments

In Figure 3-2, we observe two special segments, S7 and S8, which consist of just one node each namely node 4 and node 5 surrounded by valves. As shown in Figure 3-2, three pipes, P5, P7, and P8 meet at node 4 and valves are placed on all of them. We name this type of segment "Node segment" which consists of a node but no pipe belonging to it. Isolating a node singly may refer to a major appurtenance failure such as a pump. In the normal mode of pipe failures, isolating both the segments S5 and S6 also isolates the node segment S8 corresponding to node 5. However, these pipes serve as the feeders and carriers of flow into and out of node 5. Therefore, when these pipes fail, node 5 will not deliver any demand called unintended isolation to be discussed later. Consider pipe P7 (segment S3) alone to fail. If both valves V3 and V6 function, we can isolate pipe P7 singly. However, segment S6 also traps node 3. Assigning a zero demand to node 3 will also result in zero flow for pipe P4. That is, isolating a node calls for isolating all pipes that are incident to that node regardless of whether the incident pipes belong to the segment or not. It is due to the position of valve V3 on pipe P4. If instead, valve V3 had been located on pipe P7 near node 3, node 3 can be served even when pipe P7 is repaired. Now consider pipe P8 (segment S5) failure. If valves V7 and V8 function properly, we can isolate just pipe P8 alone and its end nodes 4 and 5 can be served well. However, if the valve V7 is inoperable, then pipe P8 failure results in closing valves V4 and V6 which merges node 4 and pipe P8 or segments S5 and S7. However, inclusion of segment S7 corresponding to node 4 also forces zero flow in pipes P5 and P7, of which both are incident to node 4. The above discussion clearly illustrates the crucial role of the nodes. In reality, however even after node 4 is isolated consumers along pipes P5 and P7 will be able to obtain water unlike consumers on pipe P8 who will not receive water at all. In conclusion, we state that whenever a node is a part of a segment, all incident pipes to that node will have zero flow. That is, in a hydraulic simulator such as EPANET, we need to close all incident pipes to a node that is contained within a segment. A detailed discussion is given in chapter 4.

3.3 Segment-Valve Representation

As given in Walski (1993), the node-arc representation of a network can be considered to have a dual representation in terms of segments and valves. Every valve is shared by adjacent segments. This is important since this adjacency relationship permits us to represent the pipe network using only segments as nodes and valves as links without the regular nodes and pipes. The network shown in Figure 3-1, has segment-valve representation as shown in Figure 3-3. From the segment-valve diagram, it is easier to analyze segment merging as valves fail. Failure of valve V9 leads to the merging of the segments S1 and S2. Failure of valves V7 and V8, calls for the merger of the segments S8, S5, and S7.

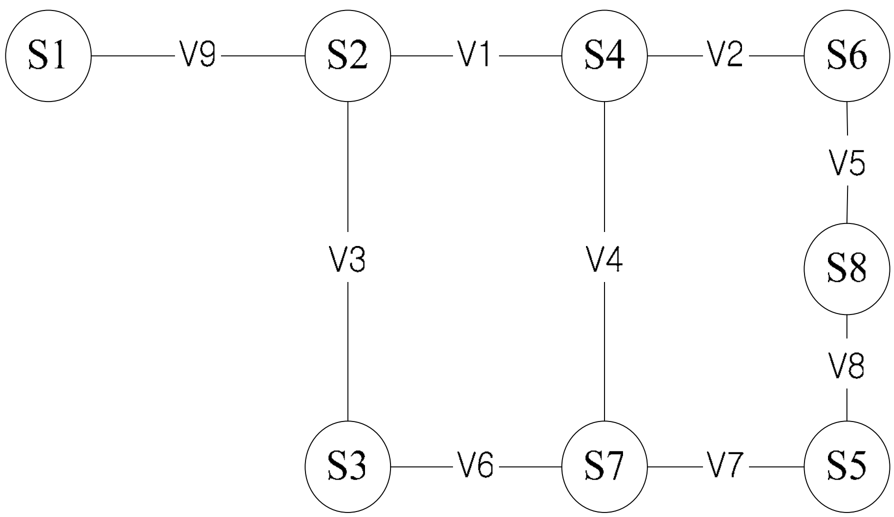


Figure 3-3 Segment-Valve Diagram

3.4 Analytical Basis of Strategic Valve Management Model (SVMM)

In this section a matrix algorithm for delineating segments is developed. This algorithm is utilized in the interactive computer software, Strategic Valve Management Model (SVMM) to solve practical problems.

3.4.1 Network Representation

In developing the segment-finding algorithm, a network in terms of node-arc incidence matrix is represented. The algorithm is described with the aid of the example shown in Figure 3-4. The corresponding node-arc incidence matrix is shown as Table 3-1. The rows contain the nodes 1, 2, … , 15. The columns represent the pipes P1, P2, …, P20. In Figure 3-4, pipe P1 is incident with nodes 1 and 2, and therefore, in column P1 "1"s are put for nodes 1 and 2 and 0s elsewhere. Similarly, all other columns are filled in. It is observed that the node-arc representation easily accommodates parallel links as opposed to a node-node adjacency matrix representation.

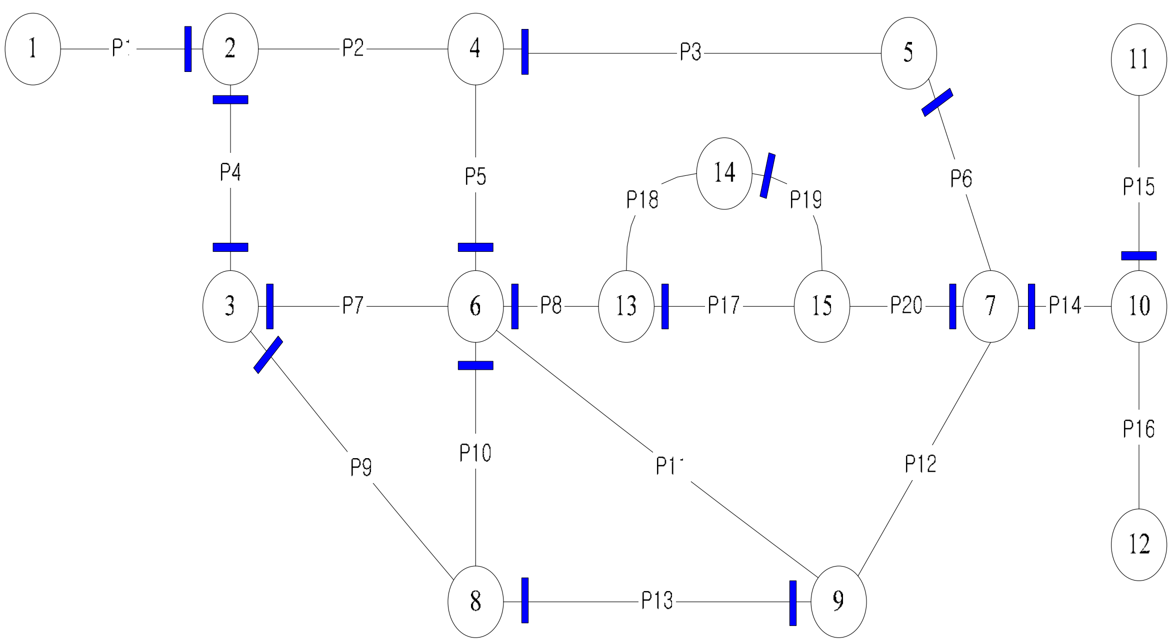


Figure 3-4 Representative pipe network

Table 3-1
Node-Arc matrix (A matrix) for the sample network in Figure 3-4

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P 10	P 11	P 12	P 13	P 14	P 15	P 16	P 17	P 18	P 19	P 20
N1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N2	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N3	0	0	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
N4	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N5	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N6	0	0	0	0	1	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0
N7	0	0	0	0	0	1	0	0	0	0	0	1	0	1	0	0	0	0	0	1
N8	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	0	0
N9	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0
N10	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0
N11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
N12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
N13	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	0	0
N14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
N15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1

The node-arc matrix implies two important properties: the number of pipes incident at a node, and the two end nodes of a pipe. Because each pipe has two end nodes, there are two "1"s in each column so the summation of each column is 2. By the row summation, the number of pipes incident at a node is determined. For example, in the row of node N8, there are three "1"s and it means three pipes incident at node N8. These properties can be expressed as:

- The row summation: the number of pipes emanating from node i

$$\textit{The number of pipes incident at node } i = \sum_{j=1}^{m} C_{ij} \qquad (3\text{-}1)$$

Where, C_{ij} = 1 if pipe j is incident with node i, j, otherwise zero

m: total number of pipes (total number of columns)

- The column summation: two ending nodes for a pipe should be 2

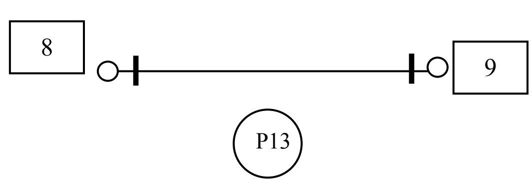
$$\textit{Summation of column } j = \sum_{i=1}^{n} C_{ij} = 2 \qquad (3\text{-}2)$$

Where, n = total number of rows (nodes)

The second property may be used for verifying data input because it must be 2 for all pipes.

3.4.2 Valve Location Representation

Using the network representation shown in Table 3-1, the valve location matrix representation can be formulated as given in Table 3-2. Due to the characteristics of a water main network, the pipes in a water distribution system are undirected. An undirected pipe is incident with its two end nodes. In Figure 3-4, pipe P13 is incident with nodes 8 and 9. As shown in the valve location matrix Table 3-2, we place a “1” in row 8 of column P13 only if there is a valve on P13 next to node 8. A “1” in a cell of the valve location matrix indicates that there is a valve immediately adjacent to the row node on the column pipe. Because P13 has valves next to both nodes 8 and 9, we have “1”s in both rows 8 and 9 for column P13.



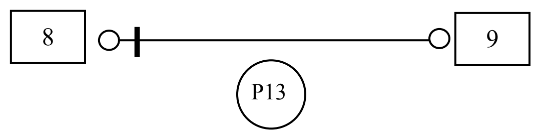
Therefore, the valve location entries for pipe P13 are

Node	P13
8	1
9	1

Table 3-2
Valve location matrix (B matrix) for the sample network in Figure 3-4

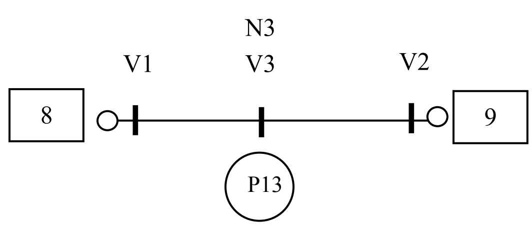
	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20
N1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N2	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N3	0	0	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
N4	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N5	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N6	0	0	0	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0
N7	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
N8	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
N9	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
N10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
N11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
N14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
N15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

A “1” for node 8 and P13 means a valve is next to node 8. Of course, the same concept is applied for node 9 and P13. If there is no valve next to node 9 on pipe 13, the diagram and the matrix entries are modified as shown below:



Node	P13
8	1
9	0

Consider a set of three valves on pipe P13 as shown below:



The question arises how an intermediate valve V3 on pipe P13 is represented. In reality, as shown in Figure 3-5, one will consider V3 only if there is a positive demand between nodes 8 and N3 and N3 and 9 so that fewer customers will be affected. This leads to a positive demand for (artificial) node N3. In such cases we can treat N3 as one of the regular nodes in the node-arc incidence matrix and valve V3 representation fits well within the valve location matrix. The only other possibility is a demand of zero at node N3. Consider the failure of pipe P13-1 in Figure 3-5. To repair this pipe, valves V1 and V3 need to be closed. However, due to zero demand at N3, pipe P13-2 can convey only zero flow. Therefore, it becomes clear that the only possible locations for valves are next to the positive demand nodes. In reality, for long pipe lines intermediate valves are needed. They should be provided based on apportioning the demands between the adjacent nodes of the pipe in question.

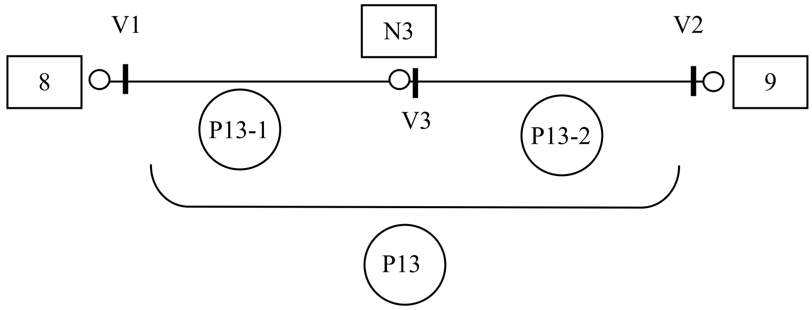


Figure 3-5 Artificial node and pipes corresponding to the artificial node

From the above discussion the following two observations emerge: (1) if N3 has zero demand, valves V1 and V2 associated with nodes 8 and 9 can be closed (in effect, valve V3 does not serve a purpose); and (2) if N3 has a positive demand, i.e., by accounting for the distributed demand along pipe P13, valve V3 becomes crucial and either V1-V3 or V3-V2 should be closed based on P13-1 or P13-2 failures.

Similar to the node-arc matrix, the valve location matrix also has two properties indicating how many valves are installed around nodes and how many valves are on a pipe. The first property is obtained by counting the “1”s in a row, with a maximum number of incident pipes (row sum of the node-arc matrix) and a minimum of 0. The second property is obtained by counting the “1”s in a column, with a maximum of 2 and a minimum of 0. The number of valves placed on a pipe should be less than or equal to 2 because each pipe has only two placeholders for valves. These properties can be expressed as:

- The row sum = the number of valves placed around node i

$$\textit{The number of valves around node } i = \sum_{j=1}^{m} C_{ij} \qquad (3\text{-}3)$$

Where C_{ij} = cell value of row i and column j, with 1 = valve present, 0 = no valve, m = total number of pipes in the network.

- The column summation: the number of valves placed on pipe j

$$Summation\ of\ \ column\ \ j = \sum_{i=1}^{n} C_{ij} \ \leq \ 2 \qquad (3\text{-}4)$$

Where n= total number of rows or nodes.

3.4.3 Valve Deficiency Representation

Using the node-arc matrix (A matrix) and the valve location matrix (B matrix), the valve deficiency matrix (C matrix) is obtained as the difference of the matrices **A** and **B**. The matrix **C** = **A** – **B** is given in Table 3-3.

Placing “1” in the C matrix means no valve is placed at that position. Because no valve is placed at the position, pipe failure cannot be confined at that position and it propagates to the adjacent pipes or nodes. With the C matrix, pipes and nodes within a segment can be identified.

Table 3-3
Valve Deficiency matrix (C matrix) for the sample network in Figure 3-4

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P 10	P 11	P 12	P 13	P 14	P 15	P 16	P 17	P 18	P 19	P 20
N1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N4	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N5	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N6	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
N7	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
N8	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0
N9	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
N10	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0
N11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
N12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
N13	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0
N14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
N15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1

3.5 Proposed algorithms

3.5.1 Segment finding algorithm

Consider Figure 3-4 with the failure of pipe P6. The algorithm employs the C matrix, using row search and column search as explained in this paragraph. The process starts with a pipe and follows the pipe along its column. If it has just "0s" (zero vector) without any "1" s, it has two valves on it and by itself can be isolated. If there is a "1", it indicates that one of the pipe's terminal nodes is without a valve. The valve tracing now follows the row corresponding to that node. There may be several "1" s in that row corresponding to the incident pipes that lack valves. Corresponding to each "1", each column must be traced separately, resulting in multiple branching paths. A row search ends when there are no additional "1"s along the row. The absence of "1"s along the row indicates that the node is valved in all other directions corresponding to other incident pipes. The column search corresponding to a pipe terminates when there are no additional "1"s in that column corresponding to the presence of a valve at the end node, i.e., there is a confining valve for that segment on that pipe.

Row search is to trace "1"s in a row, which is to find valve deficiency locations around nodes. Similarly, column search is to trace "1"s in a column corresponding to the pipe without a valve. Row search is performed when a node is found from column search. From the row search, the pipes that are within a segment can be found. Column search is needed to find which nodes are within a segment. In short, the algorithm combines row searches and column searches, alternatively looking for pipes and nodes within a segment. The lists containing pipes and nodes within a segment are called Pipe List and Node List, respectively. The following stepwise procedure explains the algorithm.

Step 1: Prepare two lists, Pipe List and Node List. Initially, both lists are empty

$$PipeList = \{\},\ NodeList = \{\}$$

Step 2: Add the broken pipe to Pipe List.

Step 3: Column search is performed for that pipe to find a "1" at an end node without a valve. If a "1" is found in that column, search that row of "1", and add that node to the Node List and go to step 4. If no "1" is in that column, the pipe is valved and the procedure is stopped. Note that there are at most two opportunities to find "1"s corresponding to the two end nodes.

Step 4: Row search is performed in the row of the node found in step 3. If a "1" is found in the row, add the pipe corresponding to the column to the Pipe List and go back to step 3. If no "1" is found in the row, all the incident pipes have valves at that node and the procedure is stopped.

Step 5: Pipes and nodes in the two lists define the segment associated with the pipes in the Pipe List.

Considering pipe P6 failure as an example, the algorithm is illustrated in the following paragraph. In Table 3-4, the procedure to find the segment corresponding to pipe P6 failure is shown. The procedure is explained in the following steps.

Table 3-4
Valve Deficiency matrix (C matrix) and path tracing for pipe 6 failure

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P 10	P 11	P 12	P 13	P 14	P 15	P 16	P 17	P 18	P 19	P 20
N1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N4	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N5	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N6	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
N7	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
N8	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
N9	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
N10	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0
N11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
N12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
N13	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0
N14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
N15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1

Step 1: $PipeList = \{\}$, $NodeList = \{\}$

Step 2: In Figure 3-4, pipe P6 is broken, thus, add P6 to the Pipe List, $PipeList = \{P6\}$

Step 3: Column search is performed in column P6. A "1" is found at the row of node N7. Thus, add N7 to the Node List, $NodeList = \{N7\}$, and go to step 4 for row search.

Step 4: Row search is performed in row N7. A "1" is found at column P12. Add P12 to the Pipe List, $PipeList = \{P6, P12\}$. Go back to step 3 for column search.

Step 3: From column search, a “1” is found at row N9. Thus, $NodeList = \{N7,\ N9\}$. Then go to step 4 because N9 is found.

Step 4: In row N9, a “1” is found at column P11. Add P11 to the Pipe List, $PipeList = \{P6,\ P12,\ P11\}$. Go back to Step 3 for column search in column P11.

Step 3: In column P11, a “1” is found at row N6. Update the Node List, $NodeList = \{N7,\ N9,\ N6\}$ and go to step 4.

Step 4: In row N6, a “1” is found at column P7. Add P7 to the Pipe List, $PipeList = \{P6,\ P12,\ P11,\ P7\}$. Go back to step 3 for column search in column P7.

Step 3: In column P7, no “1” is found; therefore, stop the procedure.

After the segment is identified, the next step is to find the valves to be closed. The valves that are to be closed in Figure 3-4 are identified as the valves that are located closest to the nodes that have the incident segment arcs. These are easily identified in matrix **A** (Table 3-1) as the nodes with “1”s corresponding to segment arcs (pipes) as the columns. These nodes are {N5, N7, N9, N6, N3}. This set will be called ***adjacent node set*** associated with segment S5. This set contains all the adjacent nodes defining segment S5. This set includes the node list of the segment but also contains nodes such as N3 and N5 that are not part of the segment. The corresponding valves are shown as “**1**”s (in bold) in Table 3.2. Recalling the notation V(i,j) as the valve located next to node i on pipe Pj, these valves are {V(5,6), V(7,20), V(7,14), V(9,13), V(6,5), V(6,8), V(6,10), V(3,7)}. This set will be called ***valve list*** associated with segment S5. Note that because there is no valve on pipe P11 all the valves at node N6 need to be closed, namely, {V(6,5), V(6,8), V(6,10)}. For node N7, V(7,14) and V(7,20) need to be closed, because pipes P6 and P12 in the pipe list do not have valves that are incident to node N7; however, for node N3 only V(3,7) needs to be closed because pipe P7 incident to node N3 is on the segment. The valves V(3,4) and V(3,9) are open. From a computer programming point of view it involves the following: (1) identify the segments; and (2) for each pipe in the segment check whether there is a valve on the pipe at its terminal node. If yes, include that valve as a part of the valve list that needs to be closed. If there is no valve on the pipe itself but there are valves next to the terminal node, include all the valves around that node to the list; if there are no valves next to the node, move to the next pipe in the segment list. This step is easily performed within matrix **B** (Table 3.2) by choosing the row node and the associated incident pipe column that has a bold "**1**". Based on the ***adjacent node set*** and ***pipe list*** the row corresponding to an element of the ***adjacent node set*** is examined**.** If a "**1**" is found on the incident pipe column from the *pipe list* that valve alone gets added to the *valve list,* which is called ***column pick.*** If there is only a "0" in the pipe column of the *pipe list* corresponding to that node, all the "**1**"s in that node row are selected as valves to be added to the *valve list,* which we call ***row pick.***

Digression: Consider pipe P12 being broken. As P12 column is entered in Table 3.4, two "1"s in rows N7 and N9 are encountered. These respective rows need to be tracked separately. Following N7, go to P6 and terminate with {P12, N7, P6}. Following N9, {P12, N9, P11, N6, P7} are obtained. To obtain the segment containing both the pipe list and node list, the N7 and N9 tracks are merged, yielding the segment S5 = {(P12, P11, P7, P6); (N7, N9, N6)}.

3.5.2 Node Segment Finding Algorithm

Thus far the discussion has focused on failure of pipes only as opposed to nodes. A node may be a pump station or some other appurtenance. Another point is that aggregate demands at nodes are assigned. However, in real networks there are no well-defined demand nodes. The demand is distributed along pipelines. Therefore, failure of a node is more realistic for an appurtenance failure. A node failure implies failure of all pipes connected to that node. If a node is a pump station, its failure will clearly result in not providing flow in all incident pipes to that node.

Consider a node surrounded by valves, i.e., there is a valve next to the node on each incident pipe. Such a node is connected to all the adjacent valves and by closing these valves the node alone can be isolated. This type of node forms a node segment that does not include any pipe. The implication is that the node failure is completely contained to the affected node alone.

From the node-arc incidence matrix, for any given node the incident pipes are identified by the presence of "1"s in the respective cells. If "1"s are observed in the same cells in the valve location matrix, it is known that all the incident pipes to that node contain a valve next to that node, making it a node segment.

In the following matrices, node N3 is a node segment and node N2 is not a node segment.

The node-arc matrix

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P 10	P 11	P 12	P 13	P 14	P 15	P 16	P 17	P 18	P 19	P 20
N2	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N3	0	0	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0

The valve location matrix

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P 10	P 11	P 12	P 13	P 14	P 15	P 16	P 17	P 18	P 19	P 20
N2	1	***0***	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N3	0	0	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0

In the valve location matrix, there is no valve installed on (N2, P2), and therefore, N2 is not a node segment. Figure 3-6 shows a schematic diagram of this search program.

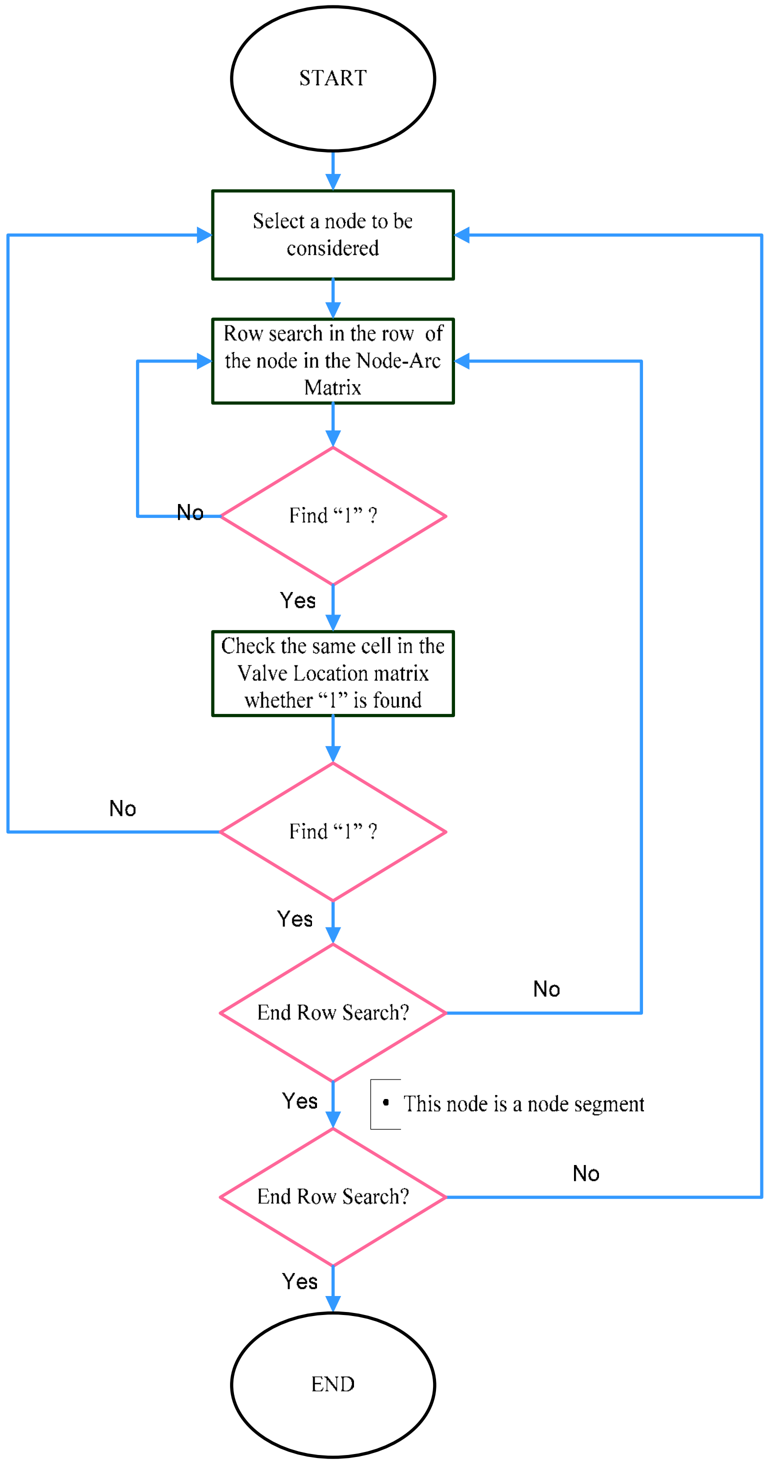


Figure 3-6 Flow chart describing the node segment algorithm

From the segment and node segment algorithms, all segments in the sample network are identified as shown in Figure 3-7 and Table 3-5.

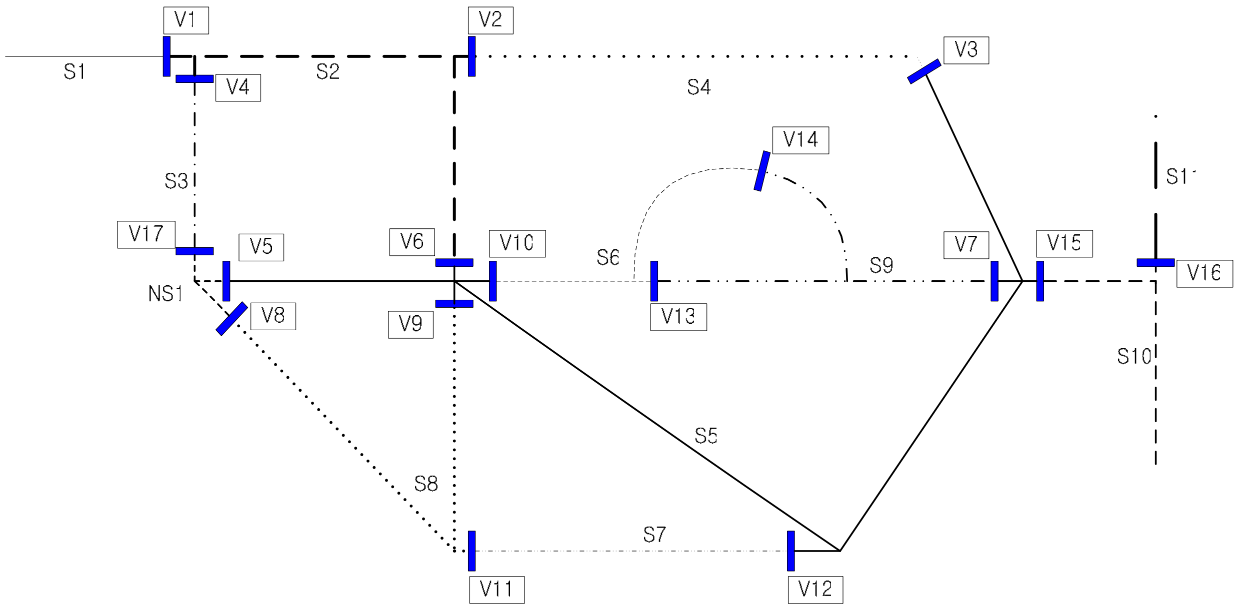


Figure 3-7 Segments corresponding to pipe failures in Figure 3-4

Table 3-5
Segments corresponding to pipe failures in Figure 3-4

Failure pipe	Corresponding segment	Valve list	Node list
P1	S1 = {P1}	V1	N1
P2	S2 = {P2, P5}	V1, V2, V4, V6	N2, N4
P3	S4 = {P3}	V2, V3	N5
P4	S3 = {P4}	V4, V17	-
P5	S2 = {P2, P5}	V1, V2, V4, V6	N2, N4
P6	S5 = {P6, P12, P11, P7}	V3, V5, V6, V7,V9, V10, V12, V15	N6, N7, N9
P7	S5 = {P6, P12, P11, P7}	V3, V5, V6, V7,V9, V10, V12, V15	N6, N7, N9
P8	S6 = {P8, P18}	V10, V13, V14	N13
P9	S8 = {P9, P10}	V8, V9, V11	N8
P10	S8 = {P9, P10}	V8, V9, V11	N8
P11	S5 = {P6, P12, P11, P7}	V3, V5, V6, V7,V9, V10, V12, V15	N6, N7, N9
P12	S5 = {P6, P12, P11, P7}	V3, V5, V6, V7,V9, V10, V12, V15	N6, N7, N9
P13	S7 = {P13}	V11, V12	-
P14	S10 = {P14, P16}	V15, V16	N10
P15	S11 = {P15}	V16	-
P16	S10 = {P14, P16}	V15, V16	N10
P17	S9 = {P17, P19, P20}	V7, V13, V14	N15
P18	S6 = {P8, P18}	V10, V13, V14	N13
P19	S9 = {P17, P19, P20}	V7, V13, V14	N15
P20	S9 = {P17, P19, P20}	V7, V13, V14	N15
Node 3	NS1= {N3}*	V5, V8, V17	N3

* NS1 is a node-segment containing N3

3.5.3 Segment-Valve matrix

It is observed that each segment has a certain set of pipes and nodes in the interior and ends of a segment are the valves. Therefore, we can easily visualize a segment as the entity with nodes and pipes in the interior and valves as the links to it. In Figure 3-7, the network structure is shown in segments and valves without nodes or links. The segments are connected to each other by valves. Instead of using a "diagram," we can also use a matrix of segments and valves. Similar to the previous matrices, rows represent segments and columns represent valves. Table 3-6 shows the segment-valve matrix corresponding to Figure 3-7. We create this matrix by listing segments as rows and valves as columns with entries of "0"s to begin with. From the valve list of each segment we replace the corresponding zeros by "1"s in the respective columns. For example, for segment S5, we have the valve list {V(5, 6), V(7, 20), V(7, 14), V(9, 13), V(6, 5), V(6, 8), V(6, 10), V(3, 7)}={V3, V7, V15, V12, V6, V10, V9, V5}. We put "1's" in columns V3, V7, V15, V12, V6, V10, V9, and V5 in row S5.

Because the segment-valve matrix is a node-arc incident matrix, the column count of "1"s equals 2. The row count of "1"s yields the number of valves that need to be closed to isolate the segment of that row. In calculating the performance indicators, this latter property is very useful.

Table 3-6
Segment-Valve matrix

	V1	V2	V3	V4	V5	V6	V7	V8	V9	V 10	V 11	V 12	V 13	V 14	V 15	V 16	V 17
S1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S2	1	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
S3	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
S4	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S5	0	0	1	0	1	1	1	0	1	1	0	1	0	0	1	0	0
S6	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0
S7	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
S8	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0
S9	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0	0	0
S10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
S11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
NS1	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	1

3.6 Unintended Isolation

3.6.1 Definition of Unintended Isolation

While the segment isolation is considered, in addition to the segment that we intend to isolate there may be other parts of the network that become disconnected from the sources. Depending on the network topology, other pipes and nodes may not be able to receive water. In general, there are two kinds of unintended isolation. First, there may be a section surrounded by a segment, i.e., the end nodes of an unintended section are within a segment or are connected to pipes within a segment. Second, usually it may happen in a branched distribution system that a segment may be the only path from the water source to the unintended section so that if the segment is isolated, there is no path to provide water to the section. With the following example, the two types of the unintended isolation are explained.

In Figure 3-8, Section A is considered. Two end nodes of Section A are node 6 and node 7. If segment S5 consisting of P6, P12, P11, and P7 is isolated, the two end nodes N13 and N15 fall within the node list of the segment. For this reason, P8, P17, P18, P19, and P20 (Section A) do not have a path from the water source node 1. It is an example of the first case of unintended isolation.

For the second case of unintended isolation, consider P14, P15, and P16 and nodes 10, 11, and 12 (Section B). The same segment, S5, is the only path providing water to Section B through pipe P14. Thus, with the isolation of the segment, Section B will lose its path to the water source, node 1. Moreover, there are more extreme cases. If P1, P2, or P5 fails, node 1, the only water source in the network, is isolated from the network. Thus, the entire network is out of service.

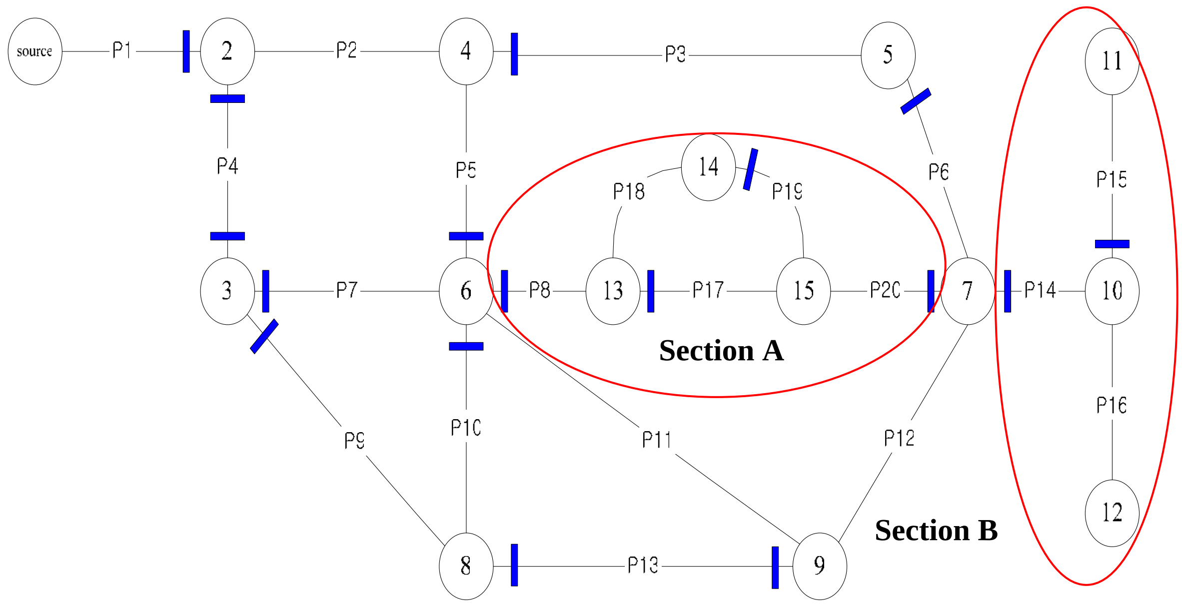


Figure 3-8 Unintended isolation example.

Section A and Section B are considered parts of segment S5. From the point of view of better maintenance practice, unintended isolation indicates an improper structure of a network. In general, the first case of the unintended isolation occurs when the distribution of valves is inadequate. For example, if a valve is added at node 6 on pipe 11 in the sample network, Section A maintains its connection to the water source even when segment 6 is isolated. Typically, the second case of unintended isolation results from less redundancy in the network. Because there is no alternate path for Section B, it loses the connection to the water source. If a pipe is added between node 5 and node 11, Section B has an alternate path to the source when segment 6 is isolated.

The identification of the unintended isolation due to a pipe failure is important not only for providing customers with reliable service but also for establishing a better management plan. Using the information from the unintended isolation, improper distribution of valves can be identified and modified. By adding additional pipes suitable alternative paths can be created or new water sources can be placed.

3.6.2 Algorithm to determine unintended isolation section

In the previous subsection, two explanations were presented namely, (1) a subset of pipes and nodes defined as a section surrounded by a segment, and (2) an intervening segment between a section and sources, both leading to an unintended isolation section. In either case, it is clear that the section lacks connectivity with sources. In this section, a "breadth first search" is used to determine the source-section connectivity. As given in Dossey et al. (1998) in the breadth first search a posse searches a cave and whenever a tunnel branches off into several others, the posse is split into subgroups to explore each branch simultaneously; i.e., at a given node, all adjacent nodes are explored and the process is repeated at each node.

The algorithm is stated in terms of a node-node adjacency matrix. An adjacency matrix, S, has rows and columns labeled by the respective nodes. For cell (i,j) representing node i and node j, a cell value S(i,j) of "1" is assigned if i and j are connected by a single pipe (i and j are end nodes); otherwise, a cell value S(i,j) of "0" is assigned. For a network with N nodes there is an $N \times N$ adjacency matrix. To explore the connectivity with sources for the various nodes as the result of a segment deletion, all cell entries S(i,j) are made zero for all the nodes that are on the node list of the segment under consideration. The algorithm is stated in steps as follows:

Step 1: Define NL of nodes in the node list of the segment under consideration. Let $NL = \{v_1, v_2, \ldots, v_n\}$.

Step 2: Define WS water source nodes in the network, as a set of $WS = \{v_{s1}, v_{s2}, \cdots, v_{sn}\}$.

Step 3: Define the set LIST nodes having a path to the source node set WS. Initially, the set $LIST = \{\ \}$ is empty but updated.

Step 4: Replace every "1" by 0 for cell s_{ij} in rows and columns in S corresponding to all nodes in the node set NL of a segment.

Step 5: Beginning with v_{s1} in WS, check for a "1" of s_{ij} in the row of v_{s1}. If a "1" is found in a column, the node corresponding to the column has a path from v_{s1}. If this node is not in LIST, it is sequentially added to LIST, i.e., we explore the predecessor level first before exploring the successor level. For example, if a "1" is found in the column of node 2, node 2 has a path and $LIST = \{v_{node\,2}\}$. If node 2 is already in LIST, then skip it and move to the next column. This search is continued to the last column of the row. The next row for searching is the row of the earliest and unexplored node in LIST. The unexplored node is a node whose row has not been searched. This process will continue until every row corresponding to nodes in LIST is searched.

Step 6: Once every node in LIST is explored, move to next water source, v_{s2} in WS, and go to step 5. When every water source is checked, the nodes in LIST have a path from some water source. The nodes that are not in the LIST form the unintended isolation. Of course, nodes in the node list are not checked; however, it is already known that these are disconnected from all water sources.

The following example illustrates the algorithm in detail. The adjacency matrix S of the sample network in Figure 3-4 is shown in Table 3-7.

Table 3-7

The adjacent matrix S of the sample network

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0
3	0	1	0	0	0	1	0	1	0	0	0	0	0	0	0
4	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0
5	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
6	0	0	1	1	0	0	0	1	1	0	0	0	1	0	0
7	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1
8	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0
9	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0
10	0	0	0	0	0	0	1	0	0	0	1	1	0	0	0
11	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
13	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1
14	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
15	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0

A cell valve of "1" indicates that there is a pipe between two nodes. For instance, "1"s in s(1,2) and s(2,1) represent pipe P1 and node 1 and 2 are connected. Consider the example of P6 failure. When P6 fails, the segment finding algorithm results in the following three lists:

- Node List : 6, 7, 9
- Pipe List : P6, P7, P 11, P12
- Valve List : V(3, P7), V(5, P6), V(7, P20), V(7, P14), V(9, P13), V(6, P5), V(6, P8), V(6, P10).

Step 1: Following the unintended isolation algorithm, set $NL = \{6, 7, 9\}$

Step 2: Node 1 is the only water source of the network and set $WS = \{1\}$

Step 3: Initialize $LIST = \{\ \}$

Step 4: Replace every 1 in the rows and columns corresponding to nodes 6, 7, and 9 by 0 as shown in Table 3-8.

Step 5: For the following discussion, refer to Table 3-8. Begin with the first row because the water source is node 1. Node 1 is added to LIST and now $LIST = \{1\}$. A cell value of "1" is found at S (1,2). Check whether node 2 is in LIST. If not, add node 2 to LIST so now $LIST = \{1, 2\}$. Because no more "1"s are in row 1, search of the node 1 row is completed. From LIST, the sequentially appended successor node is selected, namely, node 2. For row 2, repeat step 5.

In node 2 row, "1"s are found at S (2,1), S (2,3), and S (2,4). Corresponding to the cell entry of S (2,1), node 1 is already included in LIST. For cell entries of "1" in S (2,3) and S (2,4), nodes {3, 4} are appended to LIST and the updated $LIST = \{1, 2, 3, 4\}$. Because exploring the rows corresponding to nodes 1 and 2 is finished, the next row corresponds to node 3. In node 3 row, S (3,2) and S (3,8) are found to have unit values corresponding to nodes 2 and 8. Node 2 is already in LIST, we append 8 to $LIST = \{1, 2, 3, 4, 8\}$

After completing the node 3 row, move to row 4 and two "1"s are found at S (4,2) and S (4,5). Node 5 is not in LIST so $LIST = \{1, 2, 3, 4, 8, 5\}$ is updated.

The next row corresponds to node 8 row. In node 8 row, a "1" is at S (8,3) and node 3 is in LIST so move to the next node 5 row. In the node 5 row, a "1" is found at S (5,4) but node 4 is already in LIST. All nodes in LIST have been explored terminating step 5.

Step 6: Check WS for the next unexplored source node. If none is available, terminate the process.

From LIST, the connected nodes are {2, 3, 4, 5, 8}. The disconnected nodes from the source set WS is {N} – {LIST} = {10, 11, 12, 13, 14, 15, (6, 7, 9)}. The nodes (6, 7, 9) are from the segment node list

Table 3-8

Example of finding the unintended isolation due to the isolation of the segment of P6 failure

Search Level	Node \ Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Level 1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Level 2	2	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0
Level 3	3	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0
Level 3	4	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0
Level 4	5	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Level 5	8	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0
	11	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
	12	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
	13	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
	14	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
	15	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0

3.7 Summary of the matrices

As mentioned earlier, four matrices are required for the suggested methodology. In addition, one more matrix, the segment valve matrix, is needed to show the relationship between valves and segments. Thus, five matrices are required to complete the analysis and show the results.

As a fundamental rule applied to all the five matrices, values in the matrices should be “1” or “0”. A “1” means two entities represented by the rows and columns have a relationship. Otherwise, a “0” indicates no relationship between the two entities.

Among the five matrices, the node-arc matrix (**A** matrix) and the valve location matrix are fundamental. Creating the node-arc matrix is carried out by reading an EPANET input file containing the network topology. The columns in the matrix represent pipes and the rows represent nodes. A “1” in a cell indicates that the node is one of the pipe’s two ending nodes.

Valve locations are stored in the valve location matrix (B matrix). Similar to the node-arc matrix, the columns represent pipes and the rows represent nodes. Every pipe has two placeholders for valves at its ends. If a valve is placed at a placeholder of a pipe, a “1”is assigned to a cell of the matrix representing the placeholder. By the same manner, a “0” is assigned to a cell when no valve is placed at a placeholder of a pipe represented by the cell. Creating the valve location matrix is done by two methods: manually and programmatically. The manual method can be used for a small network by using the built-in user interface. The programmatical method requires MapObject which is a GIS product of ESRI and proper data structure like Shapefile which is widely used in GIS.

Once the node-arc and valve location matrix are created, other matrices are generated by the software when it is necessary. The valve deficiency matrix (**C** matrix) stores no-valved placeholders. It has the same structure of two previous matrices and is obtained as the difference between the node-arc matrix (**A** matrix) and the valve location matrix (**B** matrix), which is **C** = **A** – **B**. A "1" in a cell of the matrix indicates there is no valve at the placeholder represented by the cell. The segment finding algorithm is carried out on the C matrix.

The adjacency matrix S stores the network topology like the node-arc matrix does. However, it uses a different structure of the node-arc matrix. In this matrix, the columns represent nodes and a pipe is represented by two nodes which are the ending nodes of the pipe. For this reason, the matrix is symmetric. A "1" is assigned to a cell if two nodes are the ending nodes of the same pipe. Otherwise, a "0" is assigned. This matrix is automatically generated based on the node-arc matrix.

The fifth matrix is the segment-valve matrix. The columns of the matrix indicate valves and the rows indicate segments. This matrix is created only after all segments in water distribution system are delineated. During the delineation process, valves corresponding to each segment are identified and the relationship between valves and segments are established. The segment-valve matrix contains the same information found in the Walski's segment diagram so it can be said the segment-valve matrix is a matrix form of the Walski's segment diagram.

Table 3-9

Summary of the five matrices

Name of matrix	Columns	Rows	Stored Data	Usage	Creation
Node-Arc	Pipes	Nodes	Network topology	To create the valve deficiency matrix	From EPANET input by the program
Valve Location	Pipes	Nodes	With valve locations	To create the valve deficiency matrix	Manually using the built-in user interface
Valve Deficiency	Pipes	Nodes	Without valve locations	Segment identification	By the program
Adjacent S	Nodes	Nodes	Network topology	Unintended isolation identification	By the program
Segment-Valve	Valves	Segments	Segments and valves corresponding to a segment	Relationship between segments and valves	By the program

4. HYDRAULIC SIMULATION

4.1 Modifications required for the hydraulic simulation with the subsystem isolation

The isolation of a segment and the unintended isolation are done by closing valves. On-off valves are used to isolate a specific section of the network from the other sections. As shown in the previous survey (KIWA, 2002), more than 90% of valves placed in water distribution system are for the on-off function. Surprisingly, EPANET does not have the on-off valve simulation function directly. Moreover, if any node does not have a flow path from a water source, the hydraulic simulation by EPANET cannot be carried out; that is, the network becomes disconnected. For disconnected components, EPANET gives an error message and stops the simulation. Although no on-off valve function is built into EPANET, we can simulate it using the Initial Status option. EPANET has three initial status options for pipes: Open, Closed and CV (Check Valve). The option of "Closed" sets a pipe closed to simulate the same hydraulic condition created by closing an on-off valve. However, if a demand node having positive demand is connected to pipes whose status is "Closed" and no alternate path from water sources to the demand nodes is established, EPANET generates an error. To avoid this problem, positive demand at the demand node should be set zero. This procedure is used to simulate hydraulic conditions when the on-off valve operation is simulated.

For segment isolation implementation, let us consider the problem with the sample network (Figure 4-1) and segment 5 (S5). Once we determine a segment and the unintended isolation, we have three lists: Node list, Pipe list and Valve list. To simulate the hydraulic condition with the isolation, all positive demands at demand nodes within the segment are set to zero and the status of the pipes in the pipe list are changed to “Closed”. S5 consists of nodes 6, 9, and 7 and pipes P6, P12, P11, and P7 (shown in bold lines). Also, the unintended isolation of S5 is pipe P8. If we change only the status of these pipes to “Closed” and the positive demands at the three nodes to zero, then in simulating this network condition, it is expected that there will be no flow in P6, P12, P11, P7 and P8. In addition, P5 and P10 should not have any flow since there are on-off valves placed next to N6 on P5 and on P10 and they are closed to isolate S5. However, EPANET gives us different hydraulic conditions. As shown below, flow passes from P5 to P10 through node 6 (N6) which is shown in Figure 4-2. It is because the status of P5 and P10 is OPEN as they are not a part of the segment S5. For this reason, we need to change the status of all pipes connected to nodes within the isolation to “Closed” regardless of whether the pipes are within the segment or not. That is all pipes connected to the nodes in the node list should be closed. In this case, for example, pipes P5, P10 and P13 are connected to nodes in the segment need to be set as “Closed”. As explained in Appendix 2, artificial node simulation, if a pipe is connected to a zero demand node, the zero demand node is a “Dead end”, then there is no flow in the pipe. Let’s take a look at the relationship between P13 and node N9. After S5 is isolated, N9 is a “Dead end” for P13 since water cannot flow through N9 to P12 or P11. In Table 4-1, it is observed that there is no flow in P13 even though its status is “OPEN” due to zero demand at N9. Table 4-1 and 4-2 show the difference of hydraulic simulation results with and without the modification.

As a summary on how to modify an EPANET input to reflect the isolation of segments, the following steps are required

Step 1: Set demand of all demand nodes in the node list of a segment to zero.

Step 2: Find all the pipes connected to the nodes in the node list of a segment and set the status of these pipes to “Closed”.

Step 3: Set demands of all demand nodes in the node list of an unintended isolation section to zero.

Step 4: Find all the pipes connected to nodes in the node list of an unintended isolation and set the status of these pipes to “Closed”.

Table 4-1 shows that 15.4 GPM flows from P5 to P10 through N6 if two pipes open. It is obvious that this simulation result is wrong due to two valves on P5 and P10 next to N6 are closed.

4.2 Extension of segment definition considering hydraulic pressure failure

The network configuration changes when segments are isolated. When the remaining nodes are supplied at their full demand rates, the pressure at these nodes may be violated by exceeding the high pressure threshold or being lower than the low pressure threshold.

Including the hydraulic pressure limitation, we have three criteria to estimate failure impact due to a pipe failure.

- Segment: pipes and demand nodes isolated by closing valves including the pipe which fails.
- Unintended Isolation: pipes and demand nodes which are out of the segment but cannot have water from water sources due to the isolation of the segment (disconnected from supply).
- Hydraulic pressure limitation: demand nodes which have water from water sources yet pressure is lower than the minimum requirement (or higher than the recommended high pressure).

The number of customers impacted according to three criteria, Segment, Unintended Isolation, and Hydraulic pressure limitation, are considered the total number of customers affected as (shown in Figure 4-4). Also, in Figure 4-5, accumulation of the actual failure impact range or isolation is shown in order of the failure sequence.

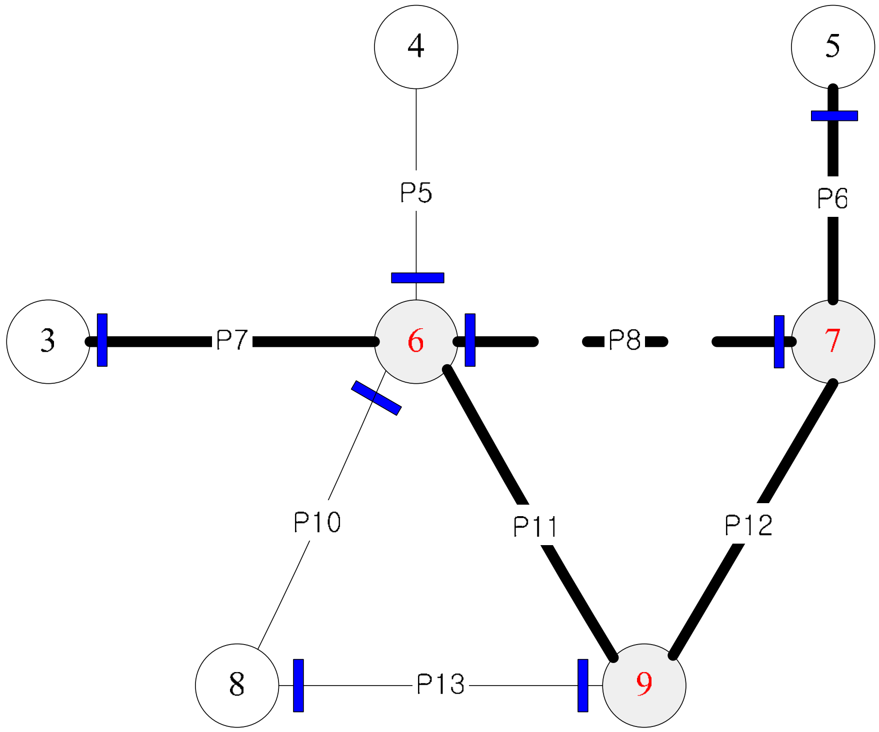


Figure 4-1 Segment 5 and unintended isolation of S5 (pipe P8)

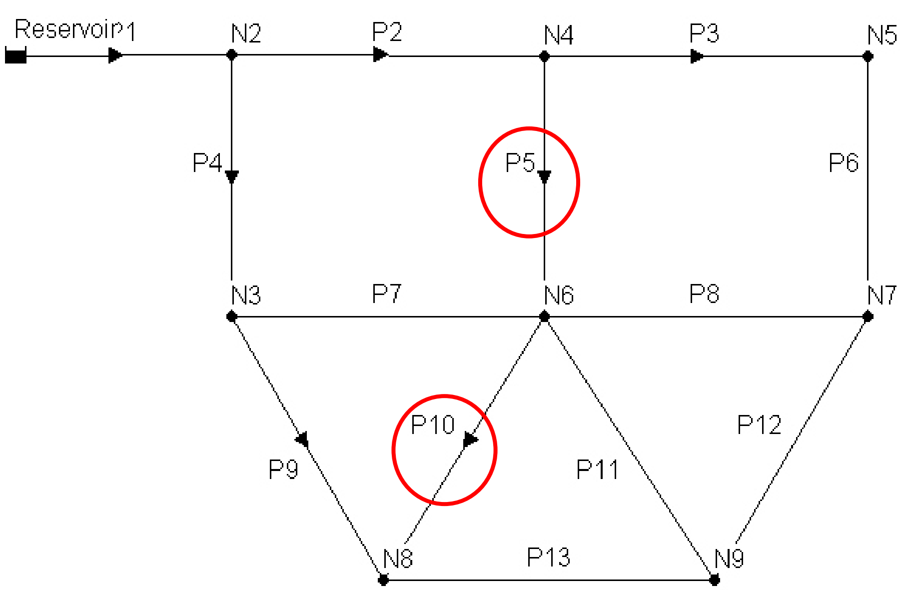


Figure 4-2 Flow condition no closing all pipes connected to nodes in the node list

Table 4-1
Hydraulic result of not closing all pipes connected to nodes in the node list

Pipe ID	Flow (GPM)	Velocity (fps)	Status
Pipe P1	140.0	0.40	Open
Pipe P2	65.4	0.19	Open
Pipe P3	30.0	0.09	Open
Pipe P4	64.6	0.18	Open
Pipe P5	***15.4***	***0.04***	***Open***
Pipe P6	0.0	0.00	Closed
Pipe P7	0.0	0.00	Closed
Pipe P8	0.0	0.00	Closed
Pipe P9	24.6	0.07	Open
Pipe P10	***15.4***	***0.04***	***Open***
Pipe P11	0.0	0.00	Closed
Pipe P12	0.0	0.00	Closed
Pipe P13	***0.0***	***0.00***	***Open***

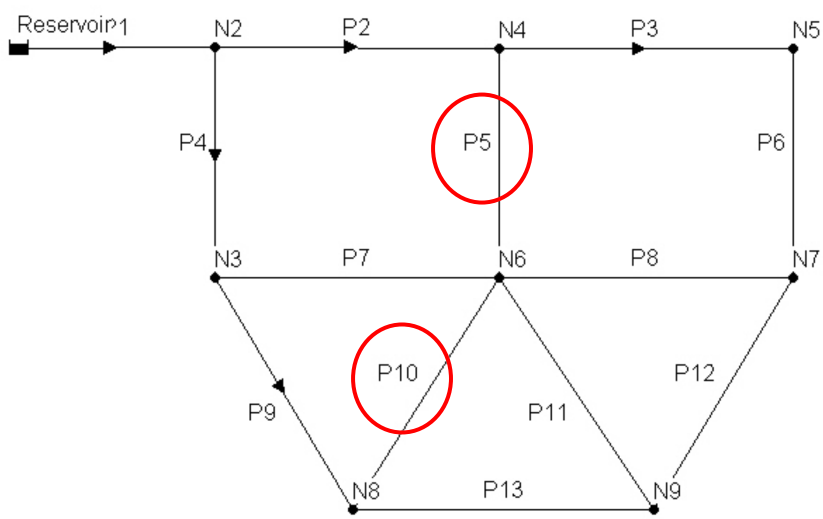


Figure 4-3 Flow condition provided by closing all pipes connected to nodes in the node list

Table 4-2

Hydraulic result of closing all pipes connected to nodes in the node list

Pipe ID	Flow (GPM)	Velocity (fps)	Status
Pipe P1	140.0	0.40	Open
Pipe P2	50.0	0.14	Open
Pipe P3	30.0	0.09	Open
Pipe P4	80.0	0.23	Open
Pipe P5	***0.0***	***0.0***	***Closed***
Pipe P6	0.0	0.0	Closed
Pipe P7	0.0	0.0	Closed
Pipe P8	0.0	0.0	Closed
Pipe P9	40.0	0.11	Open
Pipe P10	***0.0***	***0.0***	***Closed***
Pipe P11	0.0	0.0	Closed
Pipe P12	0.0	0.0	Closed
Pipe P13	***0.0***	***0.0***	***Closed***

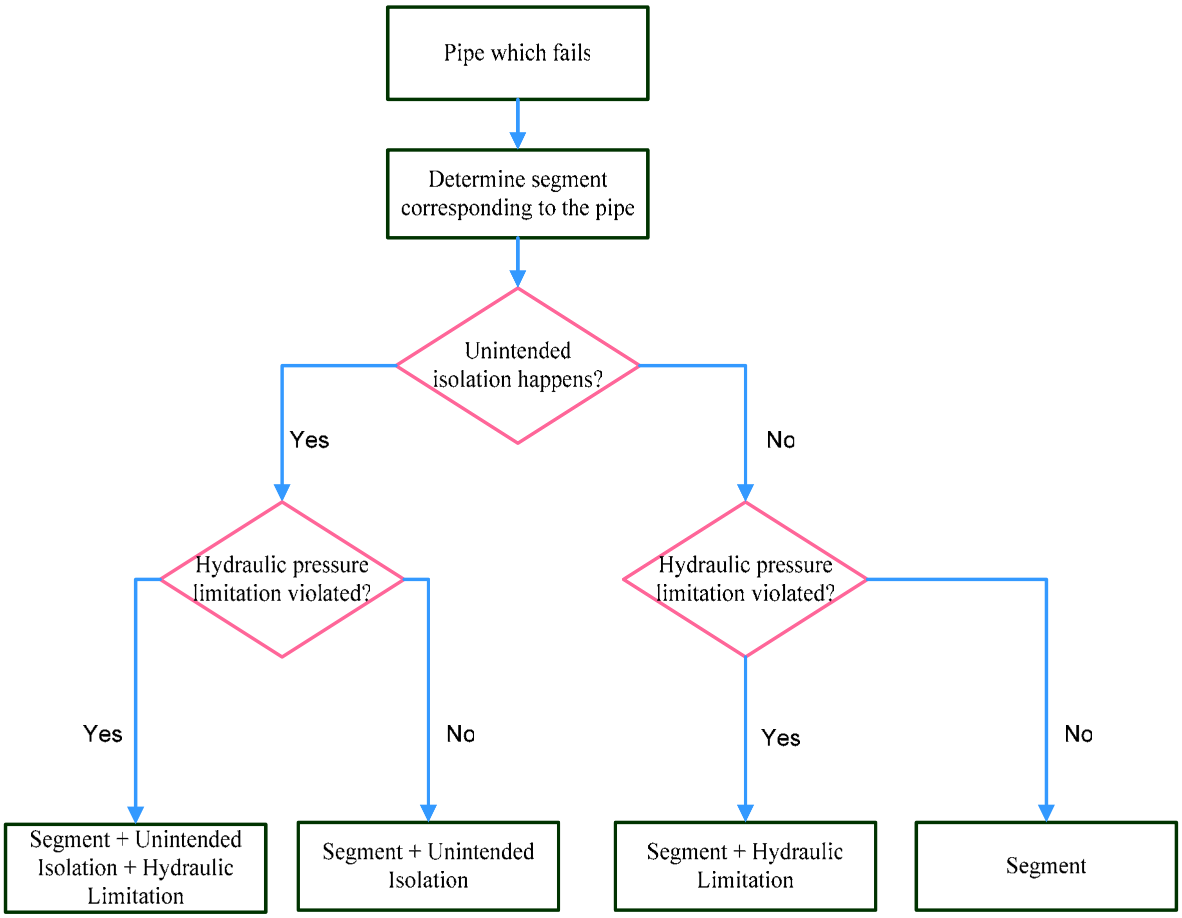


Figure 4-4 Four possibilities to count the number of customers out of service

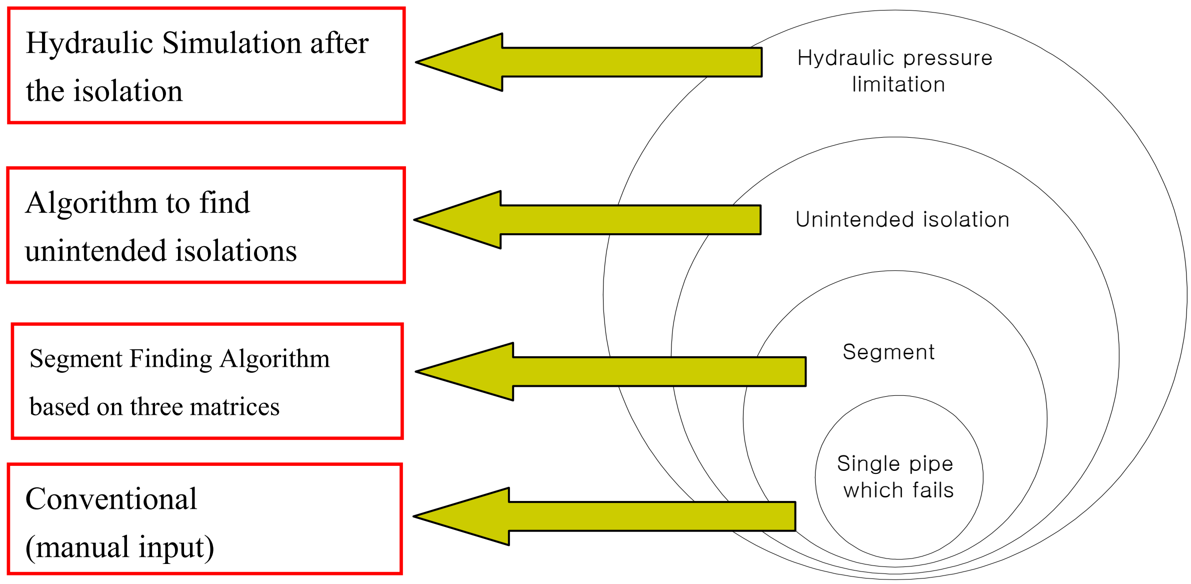


Figure 4-5 Accumulation of the actual failure impact range or isolation

5. VALVE FAILURE ANALYSIS

5.1 Introduction

Valves play a critical role in water distribution system to provide shutoff function when a subsystem is isolated. The subsystem isolation is necessary to repair broken components such as pipes and appurtenances or to perform maintenance tasks. In addition, confining contaminants within contaminated areas is another purpose to isolate a subsystem. Especially, the last situation has gained more attention due to the water security concerns.

In general, the subsystem isolation is completed by closing a series of valves. Reliability for the subsystem isolation is dependent on the number of valves closed and individual valves' reliability. The number of valves closed to isolate a subsystem is associated with valve distribution and network topology around the subsystem. Thus, it is governed by the existing network condition. However, the individual valve reliability is generally unknown until each valve is actually operated. Various aspects are involved in determining the valve reliability. AWWARF and KIWA (2002) define valve reliability by the following aspects:

- Can be found and identified in all weather conditions (maps, identification shields, etc.)
- Is accessible (no obstacles on cover, not paved over)
- Can be operated (no broken or bent stem or rounded nut, no obstructed or jammed valve)
- Works properly (watertight shutdown, no packing leaks)

As an example of valve reliability reported by a utility, the Boston Water and Sewer Commission (Shea, 1991) reported that 120 out 2,800 (= 4.3%) valves could not be operated which is 95.8% (2,680 operable valves) valve reliability. Also, they reported large number of valves with packing leaks so that valve reliability of their system may be less than estimated.

When any valve does not operate properly, a subsystem cannot be isolated and more pipes will have to be isolated by closing adjacent valves on those pipes. In this case, the impact of a valve failure can be measured by the following measures:

- Additional number of customers out of service.
- The additional length of pipes due to valve failure resulting in segment expansion.
- Additional water loss from circulation.

Among them, the number of customers out of service will be the most critical factor to the utility in that drawback in service for customers produces significant monetary loss and customer dissatisfaction. In the study, the valve failure impact is measured in terms of the number of customers out of service.

For evaluating the impact of individual valve failure and reliability of a particular valve configuration in a water distribution system, two analysis approaches are possible: a decision tree approach and a simulation approach. In the decision tree approach every possible combination of valve failures is considered. Then, the corresponding valve failure event probability and the valve failure impact measured by the number of customers out of service are estimated. The product of the two factors is the probability-weighted number customers out of service called the “expected number of customers out of service”. In the simulation approach a pipe failure is combined with the valve failure. Once a pipe fails, valves to be closed are identified. With the predetermined valve reliability, each valve is tested whether it operates or not by generating a random number. When all valves operate, the subsystem isolation is accomplished and the number of customers out of service within the isolated subsystem can be calculated. If not, additional valves in next segment are identified and each of them is tested whether it operates. This procedure continues until all valves, which are required to be closed, operate and the subsystem is isolated. After a certain number of simulations are completed, the average number of customers out of service is calculated.

The expected value of customers out of service from the decision tree approach and the average number of customers out of service from the simulation will be used to evaluate the reliability of a valve configuration in a water distribution system.

5.2 Valve failure impact

The following sample network which is the same as Figure 3-1 is used to explain a valve failure impact. The number of customers out of service is used to quantify a valve failure impact. In Table 5-1, the number of affected customers for each pipe and the number of customers for each segment obtained as the sum of the customers belonging to the respective pipes for that segment are shown.

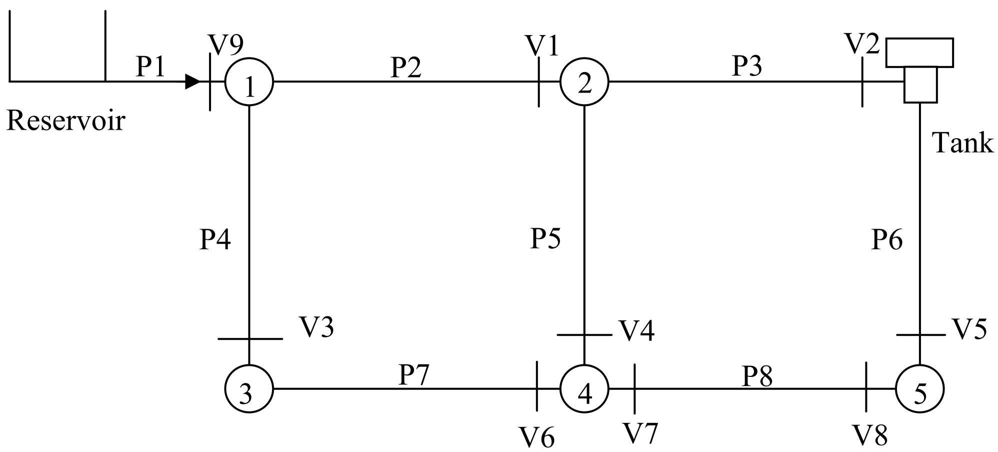


Figure 5-1 Sample network for the valve failure impact

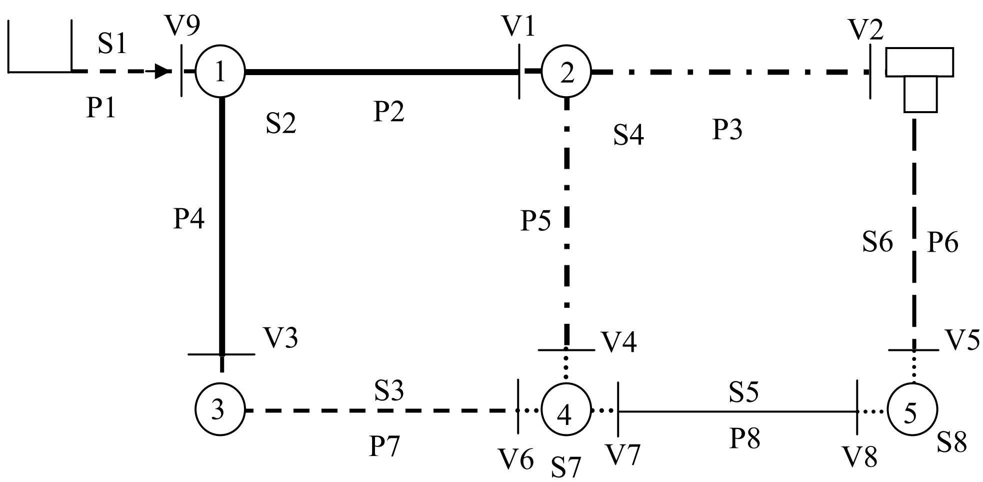


Figure 5-2 Segment delineation

Table 5-1
The number of customers for each segment

Segment	Link	Customers in link	Customers in segment	Valves needed to isolate segment
S1	P1	10	10	V9
S2	P2 P4	40 20	60	V9, V1,V3
S3	P7	70	70	V3, V6
S4	P3 P5	50 30	80	V1, V2, V4
S5	P8	80	80	V7, V8
S6	P6	60	60	V2, V5
S7*	-	-	-	V4, V6, V7
S8*	-	-	-	V5, V8
Total customers = 360				

*: Node Segment

As an example, we take segment S6 isolation. Segment S6 consists of a Tank node and pipe P6. Two valves, V2 and V5 have to be closed to isolate segment S6 (shown in Figure 5-3). If valve V5 operates but V2 does not, two more valves, V1, and V4, should be closed (shown in Figure 5-4). Because valves V1 and V4 belong to segment S4, segment S4 will be isolated with segment S6 by closing V1 and V4. In case that valve V2 operates properly, only segment S6 is isolated and S2 remains in service (shown in Figure 5-3). Due to the failure of valve V2, 80 customers in segment S4 are additionally out of service. Therefore, by failures of segment S6 and valve V2, 140 customers (= 60 + 80) are out of service and it is quantified as failure impact by valve V2 failure given that segment S6 is to be closed. This procedure can go further. If V4 operates but V1 does not, two valves of segment S2, V9 and V3, have to be closed as shown in Figure 5-5. In this case, because of S6, V2, V1 failures, 200 customers (= 60 + 80 + 60) are out of service. There is another issue involved which is to estimate the number of customers out of service when segments S3 and S5 lack water supply as the result of the unintended isolation due to the isolation of S2, S4 and S6. A reservoir is within segment S1 and a Tank is within S6 so that a path from the water sources to S3 and S5 is not available. For this reason, customers within S3 and S5 are out of service and will be added to the total number of customers out of service. They are 70 and 80 on S3 and S5, respectively. Thus, the total number of customer out of service by failures of segment S6, valve V2, and V1, is 350 customers (= 60 + 80 + 60 + 70 + 80).

With the three examples, the following aspects are reviewed.

- Valve failure results in next segment isolation and more customers will be out of service.
- Valve failure results in sequential isolations of segments as additional valves fail.
- When calculating the total number of customers out of service, an unintended isolation may occur and customers within the unintended isolation should be added to the total number of customers out of service.

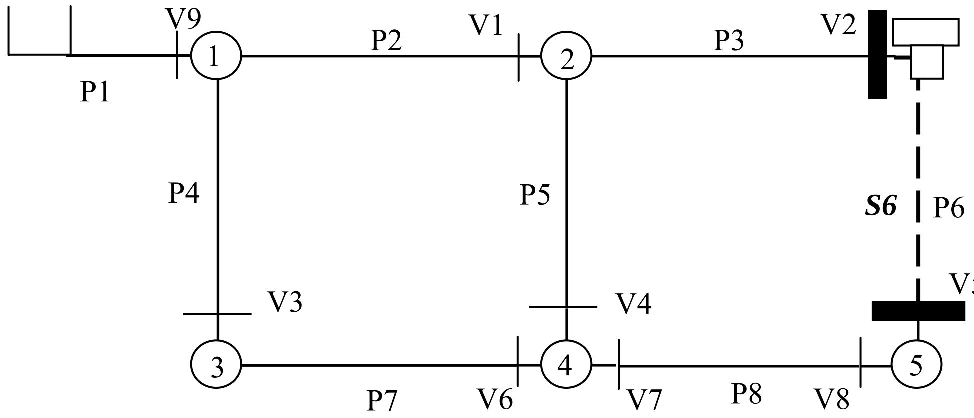


Figure 5-3 Case 1: V2 and V5 operate and segment S6 is isolated.

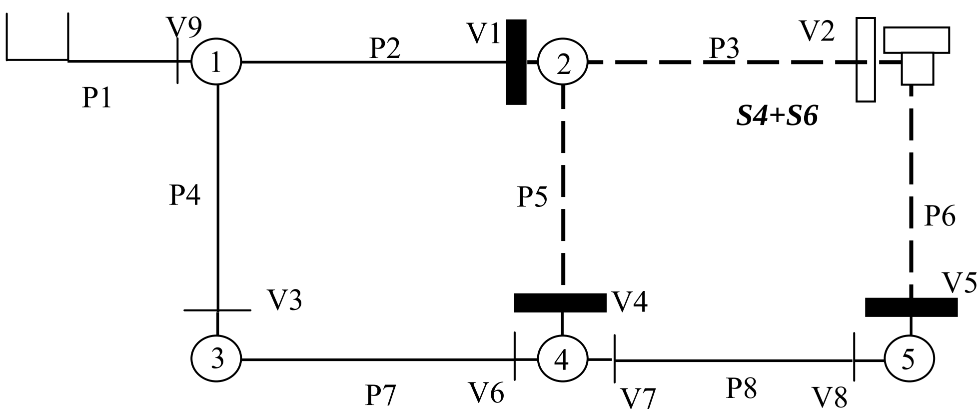


Figure 5-4 Case 2: V2 does not operate and segment S4 and S6 are isolated.

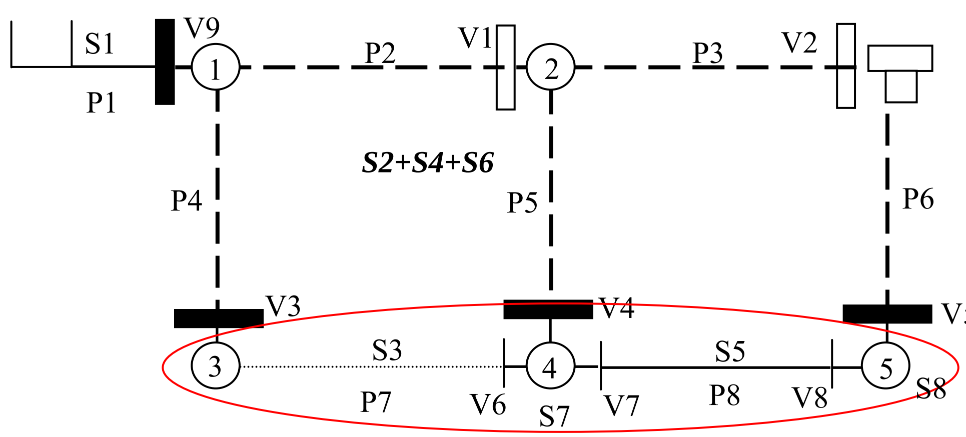


Figure 5-5 Case 3: V2 and V1 are malfunctioning and segment S2, S4 and S6 are isolate

5.3 Segment-Valve diagram based failure analysis

We find segment-valve diagram (Walski, 1993) to be valuable in performing the failure analysis. Figure 5-6 shows the segment-valve diagram for the sample network in Figures 5-1 through 5-5.

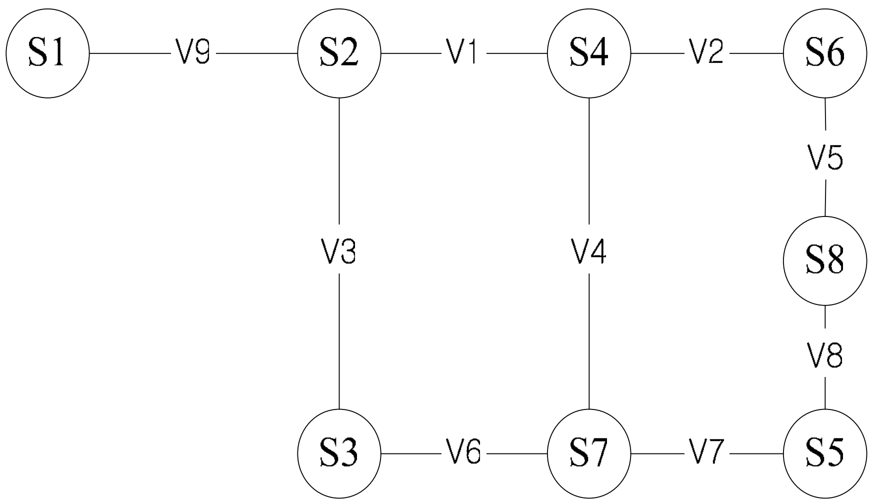


Figure 5-6 Segment-Valve diagram

First, we derive a formula for the number of combinations at any segment S_j starting failure analysis from segment S_i.

$$C_{s_i \to s_j} = 2^{n_i} \prod_{k \in (s_i \to s_j)} 2^{n_k - n_{P_k}} \tag{5-1}$$

in which: $C_{s_i \to s_j}$ number of combinations to be considered at segment S_j starting from segment S_i, n_i = number of valves at the beginning segment S_i, $S_i \to S_j$ =path followed from S_i to S_j without revisiting a node, n_k = number of valves in segment S_k, P_k = set of predecessor segments from S_i to S_k, n_{P_k} = number of valves of S_k connected to some member of P_k, and

$\prod_k$ = multiplication symbol over all k.

Let us calculate $C_{s_i \to s_3}$ through the path $S_1 \to S_2 \to S_3$ and we have

$P_1 = \{\Phi\}, P_2 = \{S_1\}, P_3 = \{S_1, S_2\}$. Therefore,

$$C_{s_i \to s_j} = \left(2^{n_1}\right)\left(2^{n_2 - n_{P_2}}\right)\left(2^{n_3 - n_{P_3}}\right) \tag{5-2}$$

n_1 = number of valves from segment S_1 = 1, $n_{P_2} = 1$ due to V9 to S_1, $n_{P_3} = 1$ due to V3 to S_2, n_2 = number of valves for S_2 = 3, n_3 = number of valves for S_3 = 2. Therefore,

$$C_{s_i \to s_j} = \left(2^1\right)\left(2^{3-1}\right)\left(2^{2-1}\right) = 16 \tag{5-3}$$

Let us also find $C_{s_1 \to s_3}$ through the path $S_1 \to S_2 \to S_4 \to S_6 \to S_8 \to S_5 \to S_7 \to S_3$.

Because we have traversed all the segments, we have traversed the entire network. The network has 9 valves. Therefore, the total number of combinations is 2^9 = 512. From Eq. (5-1) we obtain

$$C_{s_i \to s_j} = \underbrace{\left(2^1\right)}_{S1}\underbrace{\left(2^2\right)}_{S2}\underbrace{\left(2^2\right)}_{S4}\underbrace{\left(2^1\right)}_{S6}\underbrace{\left(2^1\right)}_{S8}\underbrace{\left(2^1\right)}_{S5}\underbrace{\left(2^1\right)}_{S7}\underbrace{\left(2^0\right)}_{S3} \tag{5-4}$$

$$C_{s_i \to s_j} = \left(2^9\right) = 512 \tag{5-5}$$

The advantage of Eq. (5-1) is that at any segment level following a particular path we can enumerate the available combinations. However, in Eq. (5-3), we permit V1 to fail without V9 failing. Our initial premise is that failure starts from S_1. Therefore, for V1 to fail, V9 must fail first. Hence, in Eq. (5-3) we are considering far too many combinations than needed.

It is clear that complete enumeration is not possible for large networks. Also, consider the path of $S_1 \rightarrow S_2 \rightarrow S_3$. The path ends at S_3 only when valves V1 and V6 can be closed. Assuming a reliability of 0.9, the event that V3 fails and V1 and V6 work has the probability of (0.1)(0.9)(0.9) = 0.081. Here we have assumed independence. Therefore, 3 or more valve failure analysis may not result in high probability values and many combinations can be ignored for practical purpose.

In Table 5-2, we consider failure of pipe P1 with 1- and 2-valve failures.

Table 5-2
Partial failure analysis for pipe P1 (segment S_1)

Valves failing	Controlling valves	Probability	Segments impacted	Customers	Prob. x Customers
None	9	0.90000	S1	10	9.0
9	1,3	0.08100	S1,S2	70	5.7
9,1	3,2,4	0.00729	S1,S2,S4	150	1.1
9,3	1,6,4	0.00729	S1,S2,S3	140	1.0
Total		0.99558	-	-	16.8

With 1- and 2- valve failures we have a total probability of 0.99558 with 0.00442 probability left. The approximate expected value is 17 customers. Table 5-7 considers only adjacent valve failures starting with a failure in a particular segment. In Table 5-7, we observe that there are 85 combinations possible when a failure is initiated in S_1. The expected value is 18 whereas Table 5-1 considering only 4 combinations yields 17. In Table 5-3, we consider a more complicated failure pattern starting from S_4. A pipe in $S_4 = \{P3, P5\}$ fails. Table 5-3 provides a partial failure analysis of S_4.

Table 5-3
Partial Failure analysis S4

Valves failing	Controlling valves	Event Probability	Segments impacted	Customers	Prob. x Customers	Associated Matrix	Associated Figure
None	1,4,2	$(0.9)^3$	S4	80	58.3	Table 5-4	Fig. 5-1
1	2,3,4,9	$(0.1)(0.9)^4$	S4,S2	140	9.2	Table 5-5	Fig. 5-7
2	1,4,5	$(0.1)(0.9)^3$	S4,S6	140	10.2	-	Fig. 5-8
4	1,2,3,6	$(0.1)(0.9)^4$	S4,S3	150	9.8	-	Fig. 5-9
1,2	3,4,5,9	$(0.1)^2(0.9)^4$	S4,S2,S6,	200	1.3	Table 5-6	Fig. 5-10
Total		0.93968			88.8		

For the five events in Table 5-3, the total probability is 0.93968. The approximate expected value is 89 customers whereas Table 5-8 provides an expected value of 95 customers considering 169 possible combinations. Figure 5-7 shows that when valve V1 fails, segments S4 and S2 are merged into one and the corresponding connectivity between valves and segments. The same information can also be obtained from the segment-valve matrix shown in Table 5-4. For no valve failure case column S4 shows that valves V1, V2, and V4 must be closed. When valve V1 fails, the dotted box in row V1 of Table 5-4 shows the merging of segments S4 and S2. The merged column shown in Table 5-5 has entries given by

$$(S4 \cup S2)_i = \max_i [S4_i, S2_i] \tag{5-6}$$

in which: i denotes the i^{th} row.

Figures 5-8 and 5-9 show the connectivity when valves V2 and V4 fail. Figure 5-10 shows the connectivity when valves V1 and V2 fail. Table 5-5 shows the matrix results when V1 fails. We delete the V1 row in Table 5-4 after calculating the $(S4 \cup S2)$ column entries by Eq. (5-6). After valve V1 fails, as shown in the $(S4 \cup S2)$ column of Table 5-5, valves V2, V3, V4, and V9 must be closed to contain further propagation. Table 5-6 shows the results for two valve failure of V1 and V2 case (see Figure 5-10). When valves V1 and V2 fail we merge the segments $(S4 \cup S2)$ with S6 to obtain $(S4 \cup S2 \cup S6)$ and row V2 is deleted in Table 5-5 after calculating the cell values for the column $(S4 \cup S2 \cup S6)$ in Table 5-10. The "1"s present in the merged segments column $(S4 \cup S2 \cup S6)$ show that valves V3, V4, V5 and V9 must be closed to contain the spread of failure. Therefore, we can effectively exploit the segment-valve matrix to obtain the adjacent valve failure results.

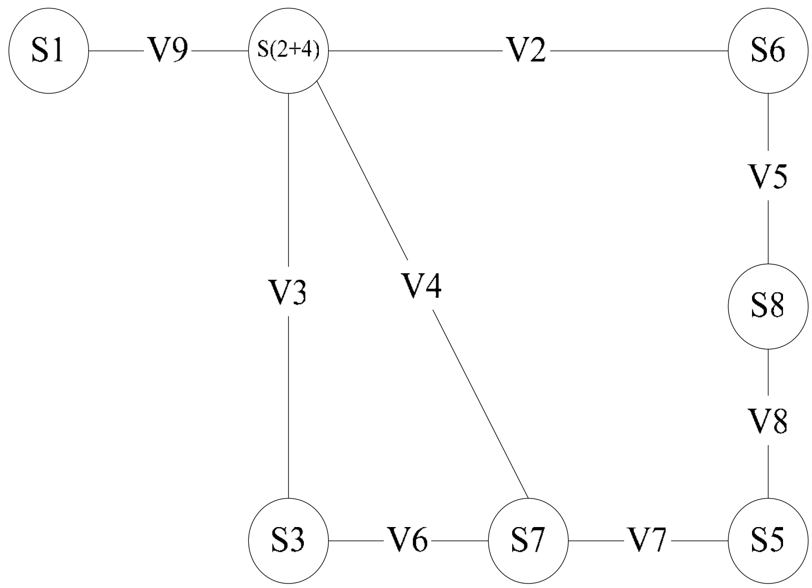


Figure 5-7 Failure of V1 $(S2 \cup S4)$

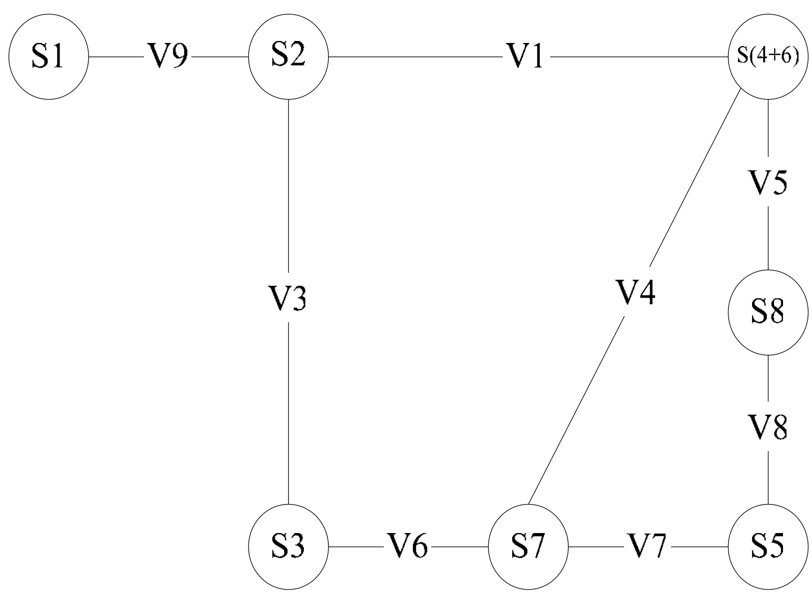


Figure 5-8 Failure of V2 $(S4 \cup S6)$

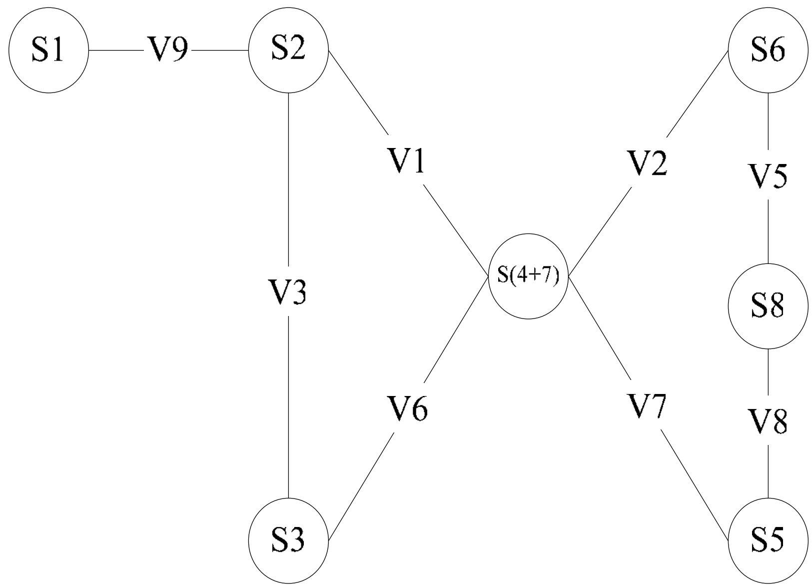


Figure 5-9 Failure of V4 $(S4 \cup S7)$

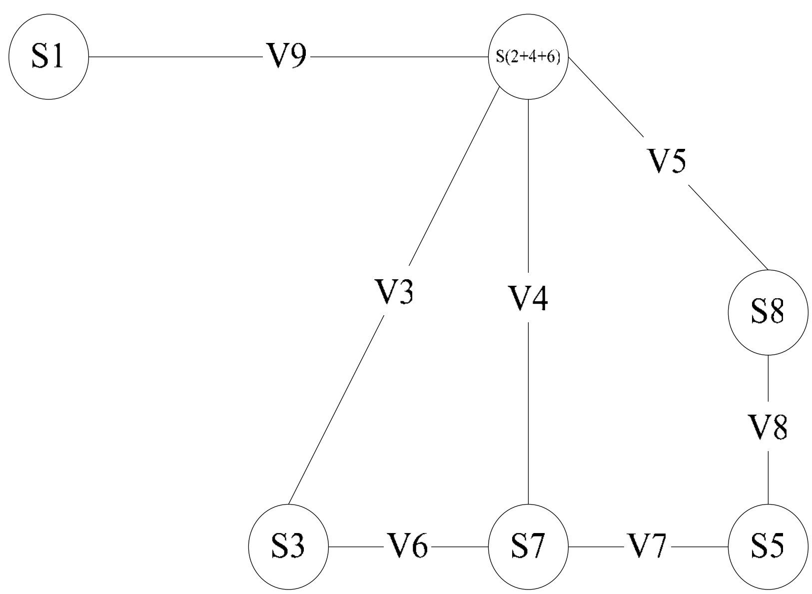


Figure 5-10 Failure of V1 and V2 $(S2 \cup S4 \cup S6)$

Table 5-4

Segment S4 – no valve fails

	S1	S2	S3	S4	S5	S6	S7	S8
V1	0	1	0	1	0	0	0	0
V2	0	0	0	1	0	1	0	0
V3	0	1	1	0	0	0	0	0
V4	0	0	0	1	0	0	1	0
V5	0	0	0	0	0	1	0	1
V6	0	0	1	0	0	0	1	0
V7	0	0	0	0	1	0	1	0
V8	0	0	0	0	1	0	0	1
V9	1	1	0	0	0	0	0	0
Total	3 valves to close (V1, V2, V4)							

Table 5-5

Segment S4 – valve V1 fails

	S1	S3	S4+S2*	S5	S6	S7	S8
V2	0	0	1	0	1	0	0
V3	0	1	1	0	0	0	0
V4	0	0	1	0	0	1	0
V5	0	0	0	0	1	0	1
V6	0	1	0	0	0	1	0
V7	0	0	0	1	0	1	0
V8	0	0	0	1	0	0	1
V9	1	0	1	0	0	0	0
Total	4 valves to close (V2, V3, V4, V9)						

* entries are maximum of columns S2 and S4 valves with V1 deleted for failure

Table 5-6

Segment S4 – valves V1 and V2 fail

	S1	S3	S4+S2+S6	S5	S7	S8
V3	0	1	1	0	0	0
V4	0	0	1	0	1	0
V5	0	0	1	0	0	1
V6	0	1	0	0	1	0
V7	0	0	0	1	1	0
V8	0	0	0	1	0	1
V9	1	0	1	0	0	0
Total	4 valves to close (V3, V4, V5, V9)					

5.4 Decision Tree approach with the expected number of customers out of service

5.4.1 Structure of a decision tree

The Decision Tree approach considers all possible adjacent valve failure combinations as shown in Figure 5-11. A decision tree is needed to consider valve failure combinations starting from one segment failure. It means that valve failure events arise when crews attempt to close valves to isolate a segment. If they cannot close any of them, the event explained in Figure 5-3s to 5-5 occurs and more valves are to be closed. Other combinations initiated by the same segment failure are possible so that one decision tree represents all such possible valve failure combinations initiated by the same segment failure. The number of decision trees for a water distribution network is same as the number of segments in the network. Since the node segment has no pipe, it is not considered. A branch of a decision tree represents one progressive adjacent valve failure combination. Thus the number of the branches in a decision tree is the number of possible valve failure combinations initiated by a segment failure. The consequence in a decision tree is the weighted customers for a valve failure combination.

5.4.2 Decision tree example

With the sample network in Figure 5-1, possible valve failure combinations from each segment are obtained. For each valve combination, the valve failure event probability and the number of customers out of service are calculated. As mentioned before, customers in the unintended isolation are added to total number of customers out of service for a valve failure combination. Figure 5-11 shows an example decision tree for segment S1 failure. As mentioned before, for the sample network, there are 6 segments so that 6 decision trees are required.

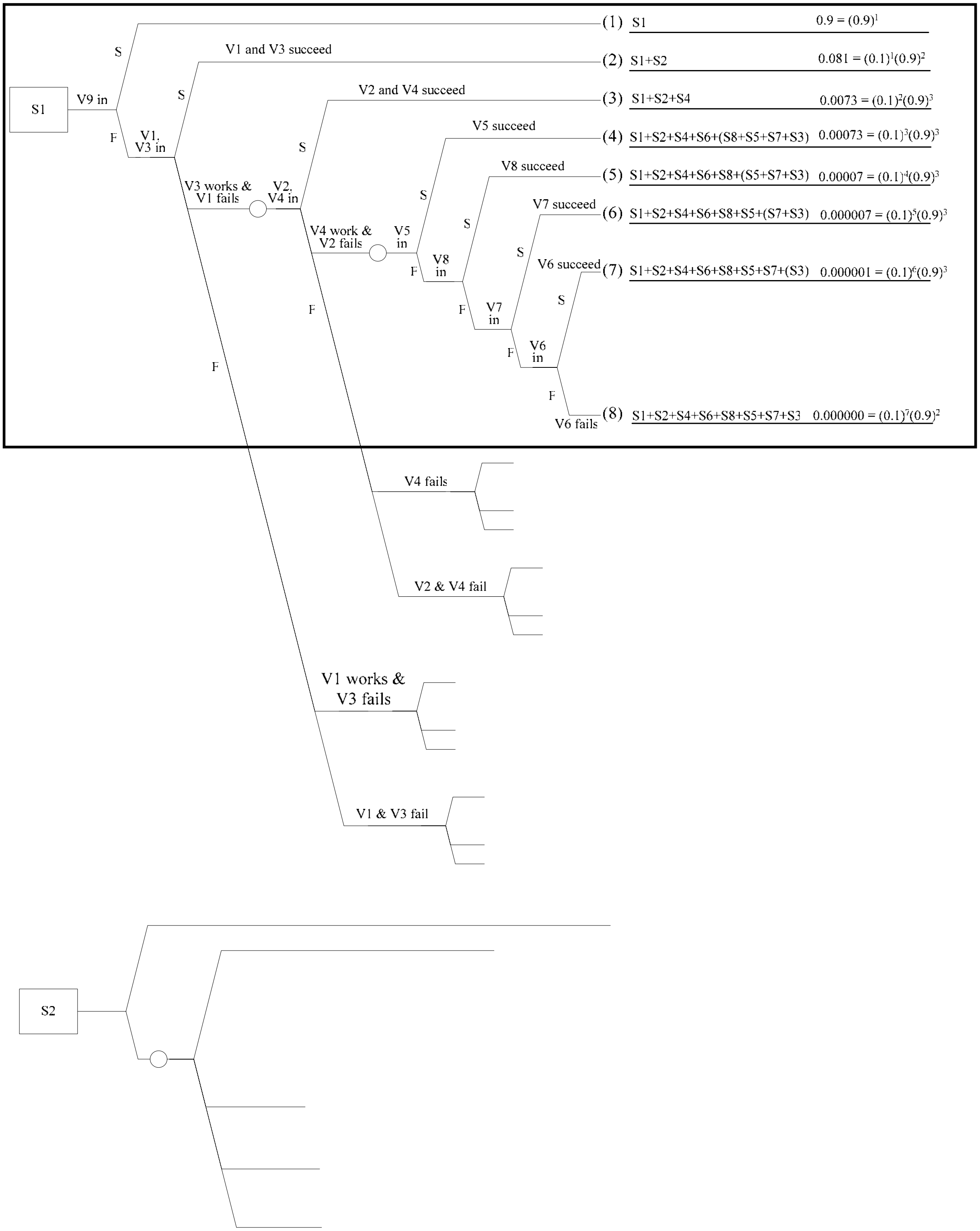


Figure 5-11 Example decision tree for segment S1

To show how each branch is established, first eight branches are taken as an example.

Branch (1): Segment S1 fails so valve V9 must be closed. If V9 is closed successfully, only S1 is isolated and the valve failure event probability is 0.9 with 90% valve reliability. In this case, only one segment, S1 and one valve V9 are involved.

Branch (2): If V9 fails as shown by the downward branch from S1 at "V9 in" with "F", adjacent valves have to be closed. In this case, V1 and V3 are the adjacent valves of V9. Consider V1 and V3 together for 4 combinations namely, "V1 and V3 succeed", "V3 works and V1 fails", "V1 works and V3 fails", and "V1 and V3 fail". Among them, "V1 and V3 succeed" is the combination represented by Branch (2).

Branch (3): Because we consider "V1 and V3 succeed", next combination to be considered is "V3 works and V1 fails". In this case, two adjacent valves, V2 and V4, have to be closed. Now, we have four new combinations resulting from the failure of V3, namely, "V2 and V4 succeed", "V4 works and V2 fails", "V2 works and V4 fails", and "V4 and V2 fail". Among them, "V2 and V4 succeed" is represented by Branch (3).

Branch (4): Next, we consider the "V4 works and V2 fails" combination. Before we explain the "V4 works and V2 fails" combination, it should be mentioned that *we know* Valves V9, V1, and V2 fail and Valves V3 and V4 work. Due to the failure of V2, V5 has to be closed. If V5 works, this adjacent valve failure combination is represented by Branch (4).

Branch (5): If V5 fails, V8 which is the adjacent valve of V5 has to be closed. If V8 works, it is represented by Branch (5).

Branch (6): If V8 fails, V7 has to be closed and it is represented by Branch (6).

Branch (7): If V7 fails, V6 has to be closed and it is represented by Branch (7).

Branch (8): When V6 fails, the adjacent valve is valve V3. However, we know that V3 is functioning. Therefore, we have considered all valves in the network and the process is terminated at Branch (8).

Next branches are initiated from the “V2 works and V4 fails”. The same procedure is applied to other adjacent valve failure combinations until all possible adjacent valve failure combinations are considered (see Table 5-7). It is clear that when closing of valves succeeds in a decision tree branch, that branch is pruned immediately; however, if a valve fails further exploration is needed.

Table 5-7

All possible adjacent valve failure combination initiated by S1 failure

Valves failing	Controlling valves	Prob	Segments impacted	Unintended Segment	Customers	Prob. x Cust.
None	9	0.90000	S1	-	10	9.00000
9	1,3	0.08100	S1,S2	-	70	5.67000
9,1	3,2,4	0.00729	S1,S2,S4		150	1.09350
9,1,2	3,4,5	0.00073	S1,S2,S4,S6	S3,S5,S7,S8	360	0.26244
9,1,2,5	3,4,8	0.00007	S1,S2,S4,S6, S8	S3,S5,S7	360	0.02624
9,1,2,5,8	3,4,7	0.00001	S1,S2,S4,S6, S8,S5	S3,S7	360	0.00262
9,1,2,5,8,7	3,4,6	0.00000	S1,S2,S4,S6, S8,S5,S7	S3	360	0.00026
9,1,2,5,8,7,6	3,4	0.00000	S1,S2,S4,S6, S8,S5,S7,S3	-	360	0.00003
9,1,4	3,6,7	0.00066	S1,S2,S4,S7	S3	220	0.14434
9,1,4,6	3,7	0.00007	S1,S2,S4,S7, S3	-	220	0.01604
9,1,4,7	3,6,8	0.00007	S1,S2,S4,S7, S5	S3	300	0.01968
9,1,4,7,8	3,6,5	0.00001	S1,S2,S4,S7, S5,S8	S3	300	0.00197
9,1,4,7,8,5	3,6	0.00000	S1,S2,S4,S7, S5,S8,S6	S3	360	0.00026
9,1,4,6,7	3,8	0.00001	S1,S2,S4,S7, S5	S3	300	0.00219
9,1,4,6,7,8	3,5	0.00000	S1,S2,S4,S7, S5,S8	S3	300	0.00022
9,1,4,6,7,8,5	3	0.00000	S1,S2,S4,S7, S5,S8,S6	S3	360	0.00003
9,1,2,4	3,5,6,7	0.00007	S1,S2,S4,S6,S7	S3,S8,S5	360	0.02362
9,1,2,4,5	3,6,7,8	0.00001	S1,S2,S4,S6,S7,S8	S3,S5	360	0.00236
9,1,2,4,5,8	3,6,7	0.00000	S1,S2,S4,S6,S7,S8, S5	S3	360	0.00026
9,1,2,4,6	3,5,7	0.00001	S1,S2,S4,S6,S7,S3	S8,S5	360	0.00262
9,1,2,4,7	3,5,6,8	0.00001	S1,S2,S4,S6,S7,S5	S8,S3	360	0.00236
9,1,2,4,7,8	3,5,6	0.00000	S1,S2,S4,S6,S7,S5, S8	S3	360	0.00026
9,1,2,4,5,6	3,7,8	0.00000	S1,S2,S4,S6,S7,S3, S8	S5	360	0.00026
9,1,2,4,5,6,8	3,7	0.00000	S1,S2,S4,S6,S7,S3, S8,S5	-	360	0.00003
9,1,2,4,6,7	3,5,8	0.00000	S1,S2,S4,S6,S7,S3, S5	S8	360	0.00026

Table 5-7 continued

Valves failing	Controlling valves	Prob	Segments impacted	Unintended Segment	Customers	Prob. x Cust.
9,1,2,4,6,7,8	3,5	0.00000	S1,S2,S4,S6,S7,S3, S8,S5	-	360	0.00003
9,1,2,4,5,7	3,6,8	0.00000	S1,S2,S4,S6,S7,S5, S8	S3	360	0.00026
9,1,2,4,5,7,8	3,6	0.00000	S1,S2,S4,S6,S7,S3, S8,S5	-	360	0.00003
9,1,2,4,5,6,7	3,8	0.00000	S1,S2,S4,S6,S7,S3, S8,S5	-	360	0.00003
9,1,2,4,5,6,7,8	3	0.00000	S1,S2,S4,S6,S7,S3, S8,S5	-	360	0.00000
9,3	1,6	0.00810	S1,S2,S3	-	140	1.13400
9,3,6	1,4,7	0.00073	S1,S2,S3,S7	-	140	0.10206
9,3,6,4	1,7,2	0.00007	S1,S2,S3,S7,S4	-	220	0.01604
9,3,6,4,2	1,7,5	0.00001	S1,S2,S3,S7,S4,S6	S8,S5	360	0.00262
9,3,6,4,2,5	1,7,8	0.00000	S1,S2,S3,S7,S4,S6, S8	S5	360	0.00026
9,3,6,4,2,5,8	1,7	0.00000	S1,S2,S3,S7,S4,S6, S8,S5	-	360	0.00003
9,3,6,7	1,4,8	0.00007	S1,S2,S3,S7,S5	-	220	0.01604
9,3,6,7,8	1,4,5	0.00001	S1,S2,S3,S7,S5,S8	-	220	0.00160
9,3,6,7,8,5	1,4,2	0.00000	S1,S2,S3,S7,S6,S8, S5	S4	360	0.00026
9,3,6,7,8,5,2	1,4	0.00000	S1,S2,S3,S7,S6,S8, S5,S4	-	360	0.00003
9,3,6,4,7	1,2,8	0.00001	S1,S2,S3,S7,S4,S5	-	300	0.00219
9,3,6,4,7,2	1,8,5	0.00000	S1,S2,S3,S7,S4,S5, S6	S8	360	0.00026
9,3,6,4,7,2,5	1,8	0.00000	S1,S2,S3,S7,S4,S5, S6,S8	-	360	0.00003
9,3,6,4,7,8	1,2,5	0.00000	S1,S2,S3,S7,S4,S5, S8	-	300	0.00022
9,3,6,4,7,8,5	1,2	0.00000	S1,S2,S3,S7,S4,S5, S8,S6	-	360	0.00003
9,3,6,4,7,2,8	1,5	0.00000	S1,S2,S3,S7,S4,S5, S8,S6	-	360	0.00003
9,3,6,4,7,2,8,5	1	0.00000	S1,S2,S3,S7,S4,S5, S8,S6	-	360	0.00000
9,1,3	2,4,6	0.00073	S1,S2,S3,S4	-	220	0.16038
9,1,3,2	4,6,5	0.00007	S1,S2,S3,S4,S6	S7,S8,S5	280	0.02624
9,1,3,2,5	4,6,8	0.00001	S1,S2,S3,S4,S6,S8	S7,S5	360	0.00204

Table 5-7 continued

Valves failing	Controlling valves	Prob	Segments impacted	Unintended Segment	Customers	Prob. x Cust.
9,1,3,2,5,8	4,6,7	0.00000	S1,S2,S3,S4,S6,S8, S5	S7	360	0.00026
9,1,3,2,5,8,7	4,6	0.00000	S1,S2,S3,S4,S6,S8, S5,S7	-	360	0.00003
9,1,3,4	2,6,7	0.00007	S1,S2,S3,S4,S7	-	220	0.01604
9,1,3,4,7	2,6,8	0.00001	S1,S2,S3,S4,S7,S5	-	300	0.00219
9,1,3,4,7,8	2,6,5	0.00000	S1,S2,S3,S4,S7,S5, S8	-	300	0.00022
9,1,3,4,7,8,5	2,6	0.00000	S1,S2,S3,S4,S7,S5, S8,S6	-	360	0.00003
9,1,3,6	2,4,7	0.00007	S1,S2,S3,S4,S7	-	220	0.01604
9,1,3,6,7	2,4,8	0.00001	S1,S2,S3,S4,S7,S5	-	300	0.00219
9,1,3,6,7,8	2,4,5	0.00000	S1,S2,S3,S4,S7,S5, S8	-	300	0.00022
9,1,3,6,7,8,5	2,4	0.00000	S1,S2,S3,S4,S7,S5, S8,S6	-	360	0.00003
9,1,3,2,4	6,5,7	0.00001	S1,S2,S3,S4,S6,S7	S8,S5	360	0.00262
9,1,3,2,4,5	6,7,8	0.00000	S1,S2,S3,S4,S6,S7, S8	S5	360	0.00026
9,1,3,2,4,5,8	6,7	0.00000	S1,S2,S3,S4,S6,S7, S8,S5	-	360	0.00003
9,1,3,2,4,7	6,5,8	0.00000	S1,S2,S3,S4,S6,S7, S5	S8	360	0.00026
9,1,3,2,4,7,8	6,5	0.00000	S1,S2,S3,S4,S6,S7, S5,S8	-	360	0.00003
9,1,3,2,4,5,7	6,8	0.00000	S1,S2,S3,S4,S6,S7, S5,S8	-	360	0.00003
9,1,3,2,4,5,7,8	6	0.00000	S1,S2,S3,S4,S6,S7, S5,S8	-	360	0.00000
9,1,3,2,6	4,5,7	0.00001	S1,S2,S3,S4,S6,S7	S8,S5	360	0.00262
9,1,3,2,6,5	4,7,8	0.00000	S1,S2,S3,S4,S6,S7, S8	S5	360	0.00026
9,1,3,2,6,5,8	4,7	0.00000	S1,S2,S3,S4,S6,S7, S8,S5	-	360	0.00003
9,1,3,2,6,7	4,5,8	0.00000	S1,S2,S3,S4,S6,S7, S5	S8	360	0.00026
9,1,3,2,6,7,8	4,5	0.00000	S1,S2,S3,S4,S6,S7, S5,S8	-	360	0.00003
9,1,3,2,6,5,7	4,8	0.00000	S1,S2,S3,S4,S6,S7, S5,S8	-	360	0.00003

Table 5-7 continued

Valves failing	Controlling valves	Prob	Segments impacted	Unintended Segment	Customers	Prob. x Cust.
9,1,3,2,6,5,7,8	4	0.00000	S1,S2,S3,S4,S6,S7, S5,S8	-	360	0.00000
9,1,3,4,6	2,7	0.00001	S1,S2,S3,S4,S7	-	220	0.00178
9,1,3,4,6,7	2,8	0.00000	S1,S2,S3,S4,S7,S5	-	300	0.00024
9,1,3,4,6,7,8	2,5	0.00000	S1,S2,S3,S4,S7,S5, S8	-	300	0.00002
9,1,3,4,6,7,8,5	2	0.00000	S1,S2,S3,S4,S7,S5, S8,S6	-	360	0.00000
9,1,3,2,4,6	5,7	0.00000	S1,S2,S3,S4,S6,S7	S8,S5	360	0.00029
9,1,3,2,4,6,5	7,8	0.00000	S1,S2,S3,S4,S6,S7, S8	S5	360	0.00003
9,1,3,2,4,6,5,8	7	0.00000	S1,S2,S3,S4,S6,S7, S8,S5	-	360	0.00000
9,1,3,2,4,6,7	5,8	0.00000	S1,S2,S3,S4,S6,S7, S5	S8	360	0.00003
9,1,3,2,4,6,7,8	5	0.00000	S1,S2,S3,S4,S6,S7, S5,S8	-	360	0.00000
9,1,3,2,4,6,5,7	8	0.00000	S1,S2,S3,S4,S6,S7, S5,S8	-	360	0.00000
9,1,3,2,4,6,5,7,8	-	0.00000	S1,S2,S3,S4,S6,S7, S5,S8	-	360	0.00000
TOTAL	-	1.00000	-	-	-	18

Table 5-8 shows the number of adjacent valve failure combinations for each segment and the expected number of customers out of service by three valve reliabilities.

Table 5-8

The expected value of customers out of service per segment

Segments	The number of combinations	Valve Reliability		
		90%	70%	50%
Segments 1	85	17.78	48.85	109.73
Segments 2	168	78.82	133.41	207.97
Segments 3	151	78.84	118.30	187.25
Segments 4	169	95.21	154.96	256.82
Segments 5	138	82.46	109.42	177.81
Segments 6	138	71.66	115.33	181.66
Total	849	-	-	-
Average	141	70.79	113.38	186.87

5.4.3 Problems in applying the decision tree approach to a real network

In the previous section, the decision tree approach has been explained to estimate the reliability of a valve distribution in terms of the expected number of customers out of service. Because all valve failure combinations are considered with corresponding probabilities, it produces an objective criterion to compare between different valve distributions on the same network. As shown in the sample network, 849 valve failure combinations (see Table 5-8) are found even though the size of the network is very small, consisting of only 8 pipes and 7 nodes. Also, evaluating all valve failure combinations is highly time-consuming and easily some of the combinations can be missed. One of our test networks is the network of Ottawa, Canada. It contains 1,816 pipes, 1,720 valves, and 1,414 nodes. A total of 1,166 segments have been delineated. Possible valve failure combinations from 1,166 segments are quite large. It is obvious that the number of the combinations increases exponentially as the network size is increased. For this reason, applying the decision tree approach to a real network may not be possible and at least, is not a cost and time efficient method to evaluate reliability of a valve distribution. To overcome the decision tree approach's defect in applying it to real networks, a simulation approach is followed.

5.5 Simulation analysis

5.5.1 Introduction

When there is a break in a pipe, the crew sets out to close the necessary valves. In a previous section, we established that these valves are the valves corresponding to the segment containing the failed pipe. By definition a segment is the region contained by adjacent valves. Therefore, it follows that when we visualize each segment as a node, the valves are the incident links to the node. If there are two or more segments, the valves serve as the links between the segments that are depicted as nodes within the context of segment-valve diagram representation. When the crew is unable to close a valve, the involved segment is merged with the adjacent segment connected by the failed valve. It is seen that theoretically, the progression in valve failure can be continued leading to various combinations of segments including the entire network as a merged segment. This kind of complete enumeration problem can be quite tedious for very large networks as explained earlier. In this chapter, we consider one deterministic and two probabilistic approaches for valve failure analysis. In the deterministic approach, we consider failure of each valve and the additional number of customers affected by the loss of service due to that valve alone. In the first probabilistic approach, every pipe is selected sequentially to fail one at a time. The valves associated with the segment are considered one at a time with a certain probability of failure. If a valve fails, adjacent segment’s valve list is appended to the current segment’s valve list to continue. This process of appending valves from the adjacent segment to the current list of valves whenever a new segment is merged is continued until all valves work to close the expanding segment. In the second probabilistic approach, as opposed to the first probabilistic approach, not all pipes are considered for failure but only pipes that are selected to fail at random are included in the analysis. The valve failure and consequent expanding segment analysis is identical to approach 2. Further details on the three approaches are given in the following.

5.5.2 Deterministic valve failure analysis (Tier1)

This deterministic simulation Tier 1 procedure accounts for the impact of a valve failure between adjacent segments. Each valve within a segment is assumed to fail. As a consequence the adjacent segment linked by the failed valve to the current segment is identified and the additional number of customers attached to the new segment is added to that of the current segment. This procedure continues until the failure impact of each of the valves defining the segment is estimated. The procedure continues from one segment to the next until all segments in the network are examined. The number of customers affected by each valve failure is divided by the total number of customers in the network to obtain the *Valve Importance Index* as

$$\text{Valve Impotance Index} = \frac{\text{Number of Customers relying on a valve}}{\text{Total Number of Customers in the network}} \qquad (5\text{-}7)$$

A flow chart of valve importance index simulation is shown on Figure 5-12.

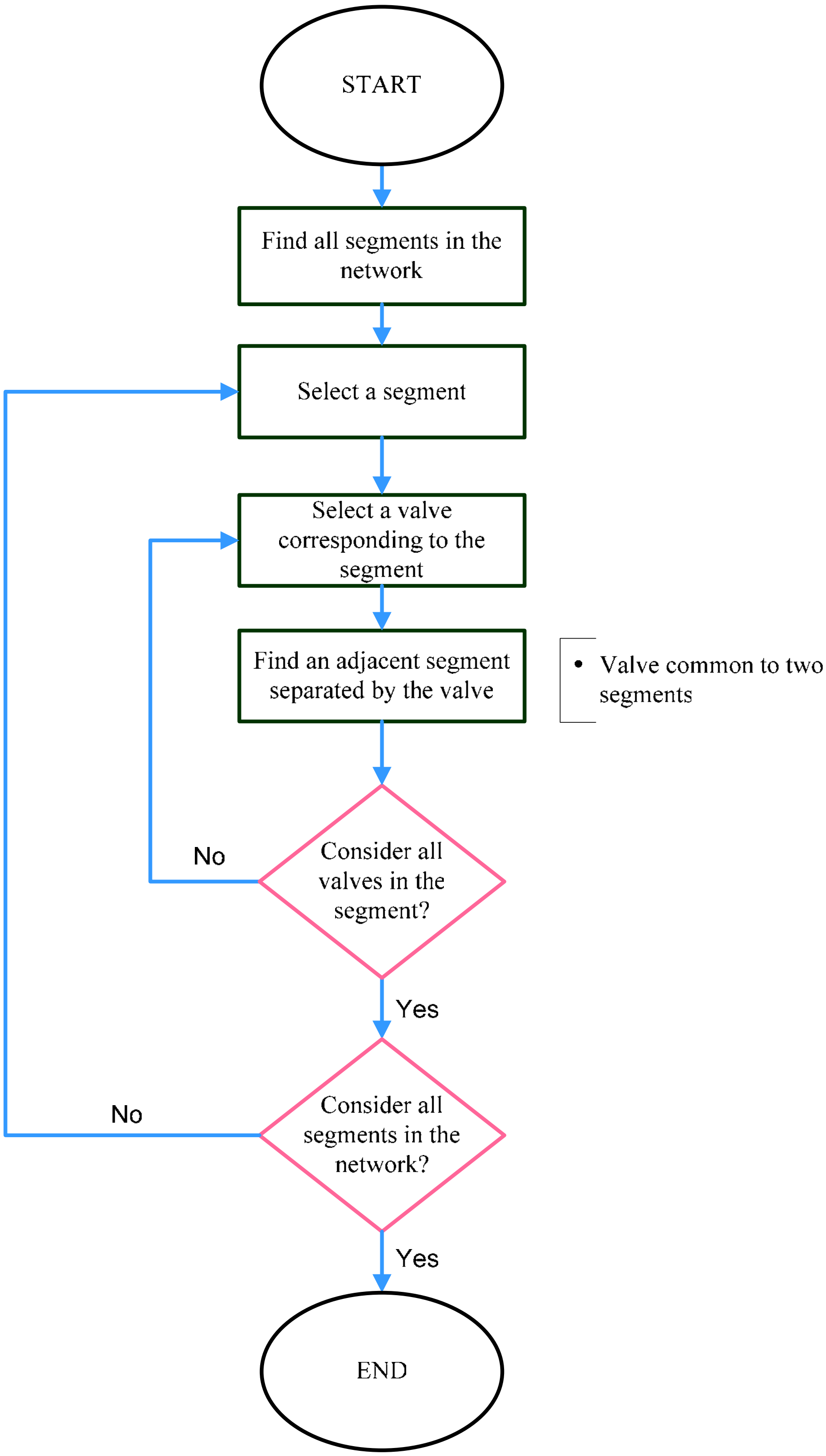


Figure 5-12 Valve importance index analysis

5.5.3 Sequential pipe failure analysis

We begin with the failure of the first pipe. From the associated valve list each valve is sequentially tested for failure. This step is performed as follows. A uniform random number U~U (0, 1) is generated. If the valve reliability is 90%, the valve is assumed to fail if U > 0.9. Otherwise, next valve in the list is considered for failure. If a valve fails, the valve deficient matrix is updated and the segment finding algorithm identifies the merged segment. The valve failure process is continued until all valves work. At this termination point, next pipe failure is initiated and the associated valve list is considered. In opposition to the deterministic Tier 1 approach in which only one valve is considered to fail, in Tier 2 analysis, several valves can fail and segments will merge accordingly. For each pipe at least 30 different valve failure scenarios are simulated and the descriptive statistics for the failure impacts from the different valve failure scenarios are obtained.

Using the segment-valve matrix, the efficiency of Tier 2 may be improved. Once we delineate all segments in a water distribution network and the corresponding unintended isolations, the segment merging procedure due to a valve failure can be identified on the segment-valve matrix without the merged segment finding procedure based on an updated valve deficiency matrix. It will be another capability of the segment-valve matrix and further research may be required to understand the potential capability of the segment-valve matrix.

5.5.4 System-Wide failure analysis (Tier 3)

For a system wide, Tier 3 failure analysis, a randomly selected pipe is assumed to fail. A uniform discrete distribution over the number of pipes is assumed. A random number U~ discrete U (1, N) with N = number of pipes is generated. The pipe corresponding to the generated random number is assumed to fail. From the valve list for the associated segment, valves are progressively screened for failure. If a valve fails, the adjacent segments valve list is appended and valve failure analysis is continued until all valves operate to contain an expanding segment. Another random pipe failure is initiated and the associated valve failure analysis is considered. The procedure mimics the actual failure process in a water distribution system. In reality, we will expect an arbitrary pipe and/or valve to fail. At least a thousand runs are made to obtain system-wide performance indicators. Additional sampling is carried out to verify whether the averages are stable. If not additional 100s of runs are performed.

5.5.5 Summary of Tier2 and Tier 3 probabilistic procedures

Step 1: Sequentially (Tier 2) or randomly (Tier 3) choose a failed pipe.

Step 2: Find the segment including the pipe and the valves.

Step 3: For each valve identified defining the segment, check whether it works properly or not. For example, suppose we assign 10% valve failure probability. We assume valve fails when a random number falls between 0.0 and 0.1. If all valves work properly, go to step 6 to finish the current simulation.

Step 4: If any valve fails, the C matrix is updated without the failed valves.

Step 5: Based on the updated C matrix, new segment is identified. Valves associated with the new segment are considered for step 3 of the simulation. Steps 3 through 5 are performed until all valves associated with the segment can be closed.

Step 6: Calculate the number of customers without service based on the segment in Step 5. Return to Step 1.

Step 7: After designated number of simulations are completed, estimate the mean and confidence interval of the number of customers.

These steps are shown in Figure 5-13.

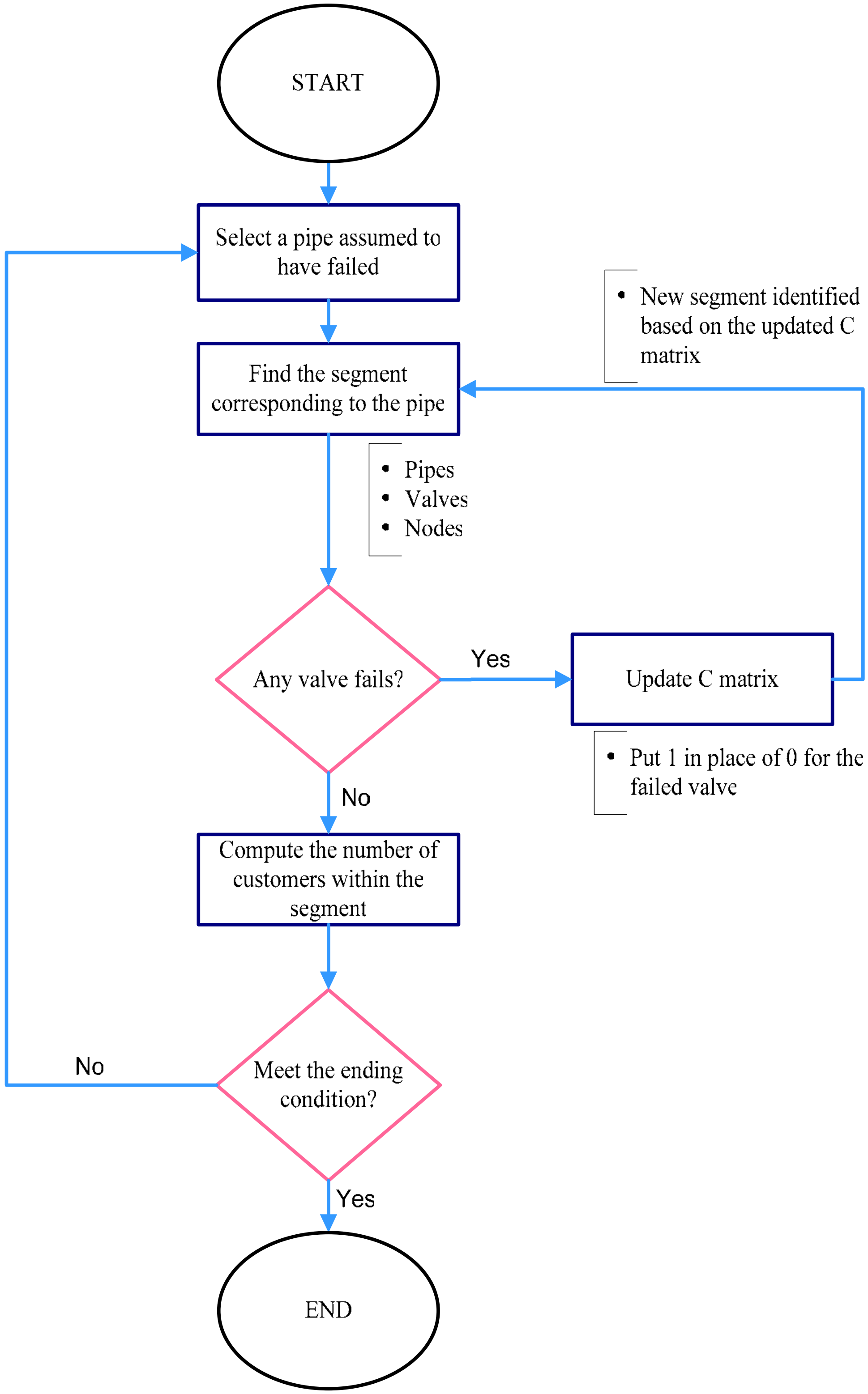


Figure 5-13 Probabilistic failure analysis

5.6 Comparison of the decision tree approach and the simulations

We have already assessed the difficulty in applying the decision tree approach to a real network. However, the decision tree approach is the most accurate to estimate the expected number of customers out of service caused by a pipe or segment failure. Thus, it is required to verify results obtained from the simulations when we apply it to evaluate reliability of the valve distribution on a large network. For this purpose, results from the simulation analysis and the decision tree approach are compared. Based on the sample network shown in Figure 5-1, the comparison is performed.

5.6.1 Tier 2 and the decision tree approach

In Tier 2 simulation, each pipe or segment is assumed to fail for certain times, say 30 times, and along with a pipe failure, valve failures are simulated as well. As a consequence of a Tier 2 simulation, the number of customers out of service caused by a pipe or segment failure is obtained. It is obvious that the number of customers out of service from each simulation will be different because of different valve failure combinations. If we simulate 30 failure events of Tier 2 for a certain pipe (or segment), 30 values of customers out of service are obtained. Also, the average number of customers out of service for the pipe (or segment) is calculated from those values and it represents the average failure impact by the pipe (or segment) failure. However, in Tier 2 simulation, all possible valve failure combinations are not considered. For example, there are 169 possible valve failure combinations in segment S4 of the sample network shown in Figure 5-1. In Tier 2, if 30 valve failure combinations are simulated for segment S4, it means at least 139 (= 169 - 30) valve failure combinations are not considered.

Moreover, some valve failure combinations, especially, high probability combinations, will be simulated more frequently. To make this point clear, Table 5-9 shows the four combinations with the highest probability values out of 169 valve failure combinations

.

Table 5-9

Four highest probability valve failure combinations, segment S4.

Case	Involved valves	Fail	Operate	Probability (90% Valve Reliability)
1	V1, V2, V4	-	V1, V2, V4	0.72900
2	V1, V2, V4, V9, V3	V1	V2, V4, V9, V3	0.06561
3	V1, V2, V4, V5	V2	V1, V4, V5	0.07290
4	V1, V2, V4, V6, V7	V4	V1, V2, V6, V7	0.06561
Total				0.93312

In Table 5-9, the four valve failure combinations account for a probability of 0.933. It means that one of the four valve failure combinations will occur with 93.3 % chance when S4 fails. Thus, among 30 valve failure simulations in Tier 2, more than 25 simulations may be one of the four valve failure simulations. This feature in Tier 2 makes the simulation result closer to the statistical expected number of customers from the decision tree approach since a valve failure combination with higher probability happens frequently. Thus, the number (frequency) of corresponding customers out of service in the total number of Tier 2 simulations, say, 30 times, is lager than others. As an example, Table 5-10 shows a typical frequency distribution of valve failure combinations from Tier 2.

Table 5-10

A typical frequency distribution of valve failure combination by S4 failure

Case	The number of customers out of service	Observed	Frequency (%)
1	80	27	0.900
2	140	1	0.033
3	140	1	0.033
4	80	0	0.000
Otherwise	Various	2	0.067
Total		**30**	1.000

In this case, “80” which is the number of customers out of service for Case 1 accounts for 27 out of 30 data when the average number of customers out of service is calculated. In other words, Case 1 is weighted by 0.90 for the average number of customers out of service. Thus, higher probability valve failure combinations may be properly weighted in the calculation of the average number of customers out of service and it can be thought that it may be a substitute for the expected number of customers out of service from the decision tree approach. If so, Tier 2 can be used to estimate the reliability of a valve configuration in a real network that is extremely difficult by the decision tree approach.

However, to verify this conclusion, the result from Tier 2 simulation should be compared with that of the decision tree approach. For the sample network, 40 Tier 2 simulations for each segment with three different valve reliabilities are performed. The results are compared with the decision tree approach as shown in Table 5-11.

Table 5-11

Comparison of expected number of affected customers between the Decision Tree (DT) approach and Tier 2 simulation

Seg.	# of valve failure comb.	90%			70%			50%		
		DT	Tier 2	Diff (%)	DT	Tier 2	Diff (%)	DT	Tier 2	Diff (%)
S1	82	17.78	19.00	6.9%	48.85	44.80	8.3%	109.73	115.20	5.0%
S2	168	78.82	83.50	5.9%	133.41	130.60	2.1%	207.97	229.80	10.5%
S3	151	78.84	73.00	7.4%	118.30	120.20	1.6%	187.25	207.40	10.8%
S4	169	95.21	99.80	4.8%	154.96	146.80	5.3%	256.82	244.60	4.8%
S5	138	82.46	91.20	10.6%	109.42	98.00	10.4%	177.81	153.80	13.5%
S6	138	71.66	79.60	11.1%	115.33	104.40	9.5%	181.66	174.20	4.1%
Average		70.79	74.35	***5.0%****	113.38	107.47	***5.2%****	186.87	187.50	***0.3%****

*: difference in the average. For example, ($|74.35 - 70.79| / 70.79 = 0.05 = 5\%$)

The difference between the expected and the average number of customers out of service from the decision tree approach and Tier 2, respectively, is around 5%. Among the differences for the individual segments, the largest is 13.5% and it is usually less than 10%. As we consider the applicability and effectiveness of Tier 2 simulation, especially, for a large network, the difference is affordable and it can be said that Tier 2 simulation properly evaluates reliability of a valve configuration.

5.6.2 Tier 3 and the decision tree approach

In Tier 3, a pipe assumed to fail is randomly chosen from the entire network and each pipe has the same probability to be chosen. For this reason, each segment has a different probability to be selected for the failure simulation since the number of pipes within a segment is different. For example, in the sample network, segment S2 has two pipes, P2 and P4 and segment S1 has one pipe, P1. Because each pipe has the same probability to be chosen in Tier 3, S2 has twice the chance to be chosen than S1. Thus, the failure results by S2 contribute twice to the expected number of customers out of service by a pipe failure than ones by S1 in Tier 3. It means the results shown in Table 5-8 and 5-11 cannot be compared to Tier 3's results. To compare results from the decision tree approach and Tier 3, results from the decision tree approach should be converted by multiplying the weight factor of the number of pipes within a segment. The weight factor for a segment is calculated by the following equation

$$Weight\ Factor\ segment\ i = \frac{the\ number\ of\ \ pipes\ within\ segment\ i}{total\ number\ of\ \ pipes\ in\ the\ network} \tag{5-8}$$

Then, the expected value of customers out of service by a segment failure is multiplied by the corresponding weight factor. Finally, the summation of the modified expected value of customers out of service by a segment failure has the same implication of Tier 3's results and can be compared. In Table 5-12, a comparison between two methods is shown. The number of Tier 3 simulations is 600.

Table 5-12

Comparison expected number of affected customers between the Decision Tree (DT) approach and Tier 3 simulation

Segment	# of pipes	Weighted factor	90%		70%		50%	
			DT	Converted	DT	Converted	DT	Converted
S1	1	0.125	17.78	2.22	48.85	6.11	109.73	13.72
S2	2	0.250	78.82	19.70	133.41	33.35	207.97	51.99
S3	1	0.125	78.84	9.85	118.30	14.79	187.25	23.41
S4	2	0.250	95.21	23.80	154.96	38.74	256.82	64.20
S5	1	0.125	82.46	10.31	109.42	13.68	177.81	22.23
S6	1	0.125	71.66	8.96	115.33	14.42	181.66	22.71
Total	8	1.000	-	74.85	-	121.08	-	198.25
Tier 3	-	-	-	75.49	-	124.52	-	195.57

As shown in Table 5-12, Tier 3 simulation and the decision tree approach produce almost the same results in evaluation of the expected number of customers out of service by a pipe failure under the current valve distribution and the network condition. Thus, Tier 3 simulation is verified to evaluate reliability of a valve distribution quantified by the expected number of customers out of service by a pipe failure and can be used for the analysis of a large network.

6. STRATEGIC VALVING RULES

In this chapter, we suggest two strategic valving rules to improve the network reliability and to reduce pipe failure impact on the network. In general, valve locations need to be decided when a new water distribution network is built or when a utility wants to add more valves in the existing system to improve the reliability. The first case is the planning stage and the second is the operating stage. At the planning stage, most utilities follow their own regulations to control the location and the number of valves. Two general rules, namely the N and N-1 valve rules, are widely accepted and used. In the following, we evaluate these rules and provide general recommendations.

6.1 Valving rules

Most utilities have regulations to specify placement of valves within water distribution systems. Rolla Municipal Utilities, MN, states valves shall be placed at all hydrants and to any fittings. Howard County, MD, suggests valves be installed sufficiently in number to minimize disruption of water service during maintenance and emergency condition. The general preference is that at every intersection, a valve should be placed on every incident pipe. Along with the number of valves at intersections and other key valve locations, the spacing between two valves is also to be specified. Willington Town, CT specifies the spacing between two valves should be less than 800 feet. At a tee, two valves are placed and one of the valves is placed at a pipe of the main pipeline. Village of Lemont, IL, specifies the valve spacing by land use. In commercial districts, 500 feet is maximum valve spacing and never more than one block. For other districts, it is 800 feet. They also specify the maximum number of valves to isolate a segment to be three. With the approval of the Public Works Director four may be allowed in unique cases. It is a very useful regulation for valve placement since this rule points out exactly why we need to place valves. Not only utilities, AWWA also suggests guidelines for placing of valves. Adding to these examples of utilities, the AWWARF and KIWA report (2001) suggests

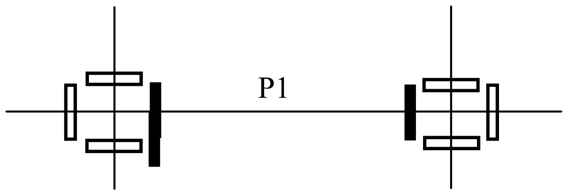
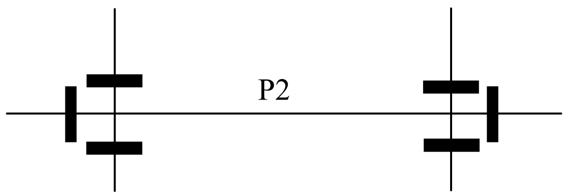
- AWWA Water Distribution Manual: less than 500 ft in business area, less than 800 ft in other areas.
- Usual practice: at least two valves at a tea and three at cross section.
- As a rule-of-thumb: no more than four valves for segment isolation

6.1.1 N and N-1 valve rules

Besides the spacing between two valves on a single pipe section, a way to place valves at the intersection is important to improve the reliability for the isolation of a segment. In general, the valving rules at an intersection can be categorized into two: placing valves on all pipes or placing valves on all but one pipe. We call the first rule as the N-valve rule since N valves are placed on all N pipes when N pipes are incident at an intersection. For the second rule, it is called the (N-1)-valve rule since only N-1 valves are placed on N pipes incident at an intersection. Thus, there is a pipe on which no valve is placed in the (N-1)-valve rule. Among the examples mentioned above, Howard County, MD adopts the N-valve rule and Willington Town, CT uses the (N-1)-valve rule for placing valves at the intersection. If the valve reliability is 100%, both methods produce the same isolation reliability; however, at two crossing junctions as shown in Table 6-1, the (N-1)-valve rule may need a maximum of 6-valves whereas the N-valve rule always requires two valves to close a pipe. In Table 6-1, the reliabilities of both methods are calculated.

Table 6-1

Reliabilities of two valving rules with 100% valve reliability

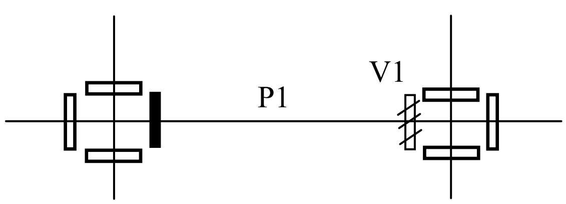
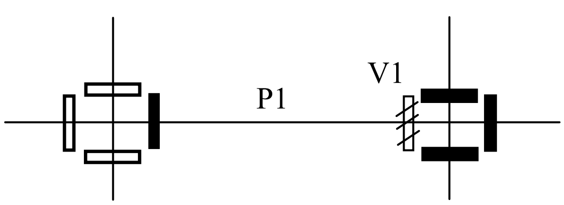
Rules	Diagram	Reliability
N rule		$(VR^*)^2 = (1.0)^2 = 1$
N-1 rule		(VR)6 = (1.0)6 = 1

***: VR: Valve Reliability**

In the example shown in Table 6-1, if the valve reliability is 90%, the reliability of the N-valve rule is $0.9^2 = 0.81$. For the (N-1)-valve rule, it is $0.9^6 = 0.53$. With more valves on a pipe, the N-valve rule has much higher redundancy than the (N-1)-valve rule. When a valve does not work, a pipe still can be isolated by closing the other adjacent valves in the N-valve rule but it is impossible in the (N-1)-valve rule. In Table 6-2, this situation is shown.

Table 6-2

Valve redundancy in the N-valve rule

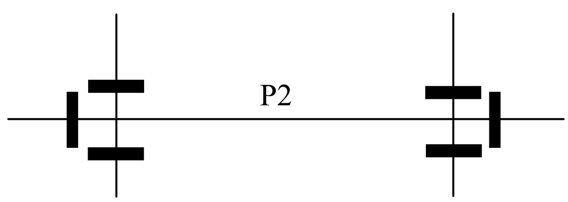
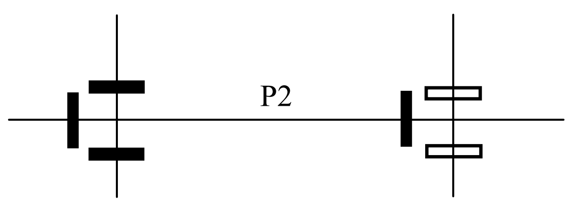
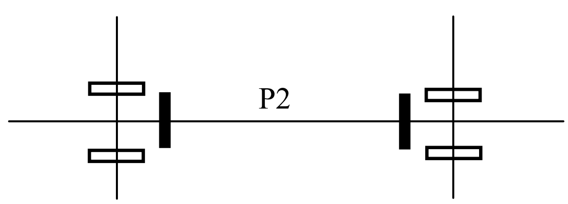
	Valve V1 does not work
	By closing three valves, pipe P1 is isolated.

6.2 Pipe isolation reliability and node reliability

6.2.1 Pipe isolation reliability and node reliability by (N-1)-valve rule

Although the reliability estimation of the N-valve rule is simple as shown in the previous example, it is much more complicated for the (N-1)-valve rule since we have many configurations to consider. Table 6-3 shows the possible valve configurations by the (N-1)-valve rule for a pipe.

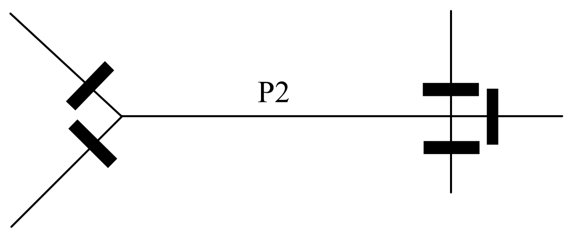
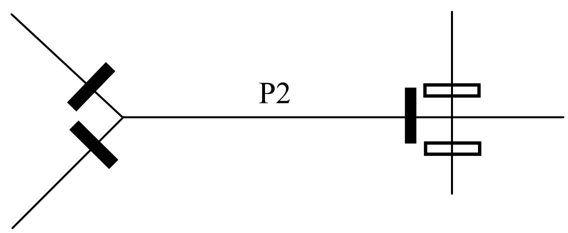
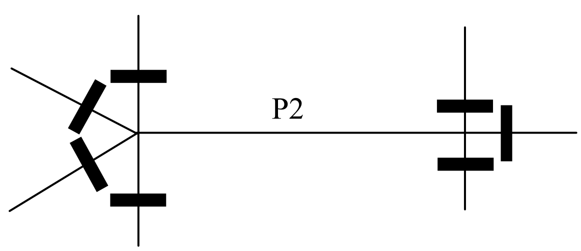
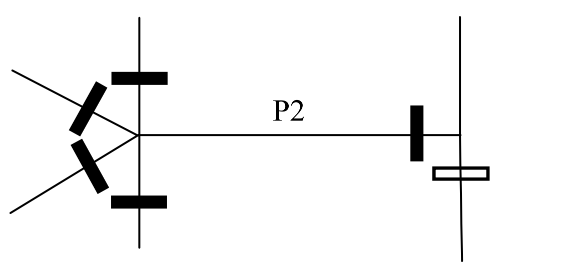
Table 6-3
Different reliability of the isolation depending on the valve configuration

# valves closed to isolate a pipe	Diagram	Reliability
6		$(VR)^6$
4		$(VR)^4$
2		$(VR)^2$

VR: valve reliability

In Table 6-3, we assume four pipes meet at an intersection, which means the degree of the node is 4. However, if we consider different degrees for a node, many valve and pipe configurations result and the reliability of the pipe isolation for each configuration will be different. A few possible valve and pipe configurations by the (N-1)-valve rule are shown in Table 6-4.

Table 6-4
More valve and pipe configurations in the (N-1)-valve rule

# valves closed to isolate a pipe	Diagram	Reliability
5		$(VR)^5$
3		$(VR)^3$
8		$(VR)^8$
5		$(VR)^5$

Because it is not easy to compare the pipe isolation reliability by both the rules, ***the node reliability*** is suggested. The node reliability is defined as the ability to confine a pipe failure at that node. With the aid of Figure 6-1, the node reliability is explained.

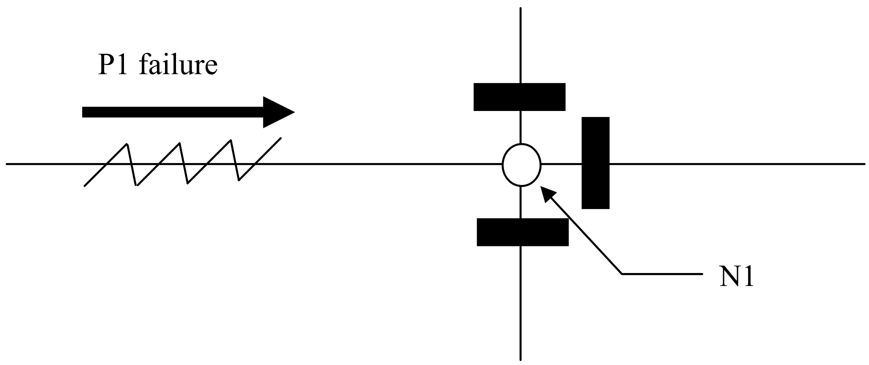


Figure 6-1 Node reliability

At node N1 in Figure 6-1, pipe P1 failure can be confined by closing three valves and no additional pipe is isolated due to P1 failure. The node reliability at node N1 with three valves is $(VR)^3 = (0.9)^3 = 0.729$ if VR is 0.9. Possible valve and pipe configurations for the node reliability by the (N-1)-valve rule are two: a valve is placed on the pipe which fails and all but one of the other pipes does not have a valve; or a valve is placed on every pipe that joins that node and the failure pipe does not have a valve. Table 6-5 shows all the valve and pipe configurations to compute the nodal reliabilities by the (N-1)-valve rule assuming the degree of the node ranges from 2 to 5. In general, we derive the following rule.

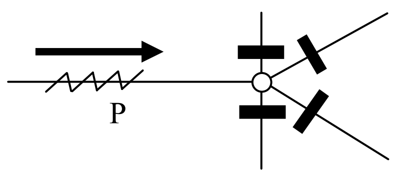
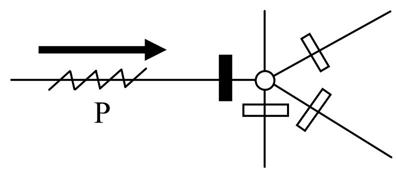
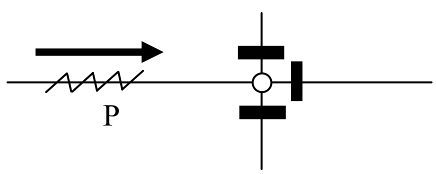
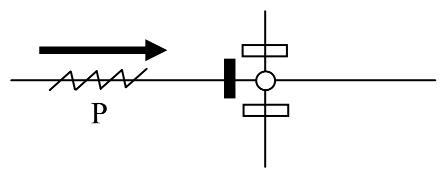
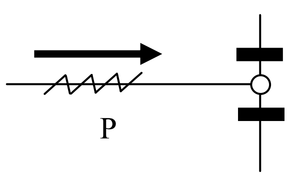
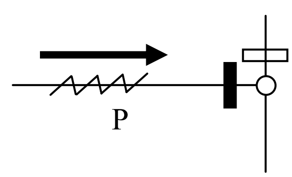
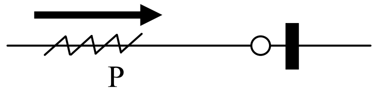
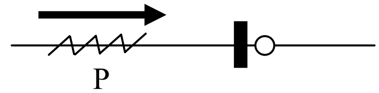
$$Node\ reliability = P\left[failure\ of\ a\ pipe\ at\ that\ node\ is\ NOT\ propagated\right]$$

$$= \begin{cases} VR_P & \text{if } VR_P > 0 \\ \prod_{j \neq P} VR_j & j \in all\ incident\ pipes\ and\ VR_P = 0 \end{cases} \qquad (6\text{-}1)$$

in which: VR_P = valve reliability of the failure pipe, P, and $VR_P = 0$ if there is no valve on failure pipe; VR_j = Valve reliability of incident pipe j at the node having the failure pipe and $j \neq P$.

Table 6-5

All possible valve and pipe configurations in the (N-1)-valve rule for node reliability

The Degree of node (N)	Case 1: $VR_P = 0$ (N – 1) valves closed	Case 2: $VR_P > 0$, $k \neq p$ closing the valve on the pipe which fails
5		
	NR = $(VR)^4$	NR = VR
4		
	NR = $(VR)^3$	NR = VR
3		
	NR = $(VR)^2$	NR = VR
2		
	NR = VR	NR = VR

6.2.2 Node reliability for N-valve rule

The node reliability for the N-valve rule is calculated as

$$\begin{aligned} Node\ reliability(N\ rule) &= 1 - P(pipe\ \ failure\ \ propagates\ to\ next\ \ pipe) \\ &= P(pipe\ \ failure\ is\ not\ \ propagated) \end{aligned} \tag{6-2}$$

P(pipe failure propagates to next pipe) is the product of two probabilities: the probability that the valve placed on the failure pipe fails ***and*** the probability that at least one of valves doesn't work, placed around the node. With the following example shown in Figure 6-2, the node reliability for the N rule is explained. At node N1 with valves placed by the N rule, valve V1 and at least one of the valves V2, V3, and V4 must fail for the failure to be propagated.

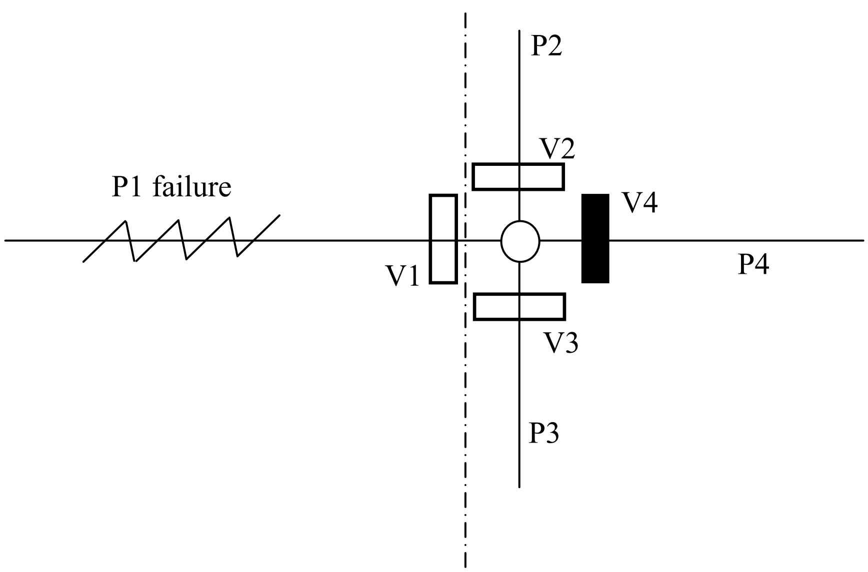


Figure 6-2 Failure of node N1 by the N valving rule

A general formula for node reliability for the N-valve case can be derived as follow. In the (N-1)-valve case, the valve on the failure pipe plays a critical role. If this valve with reliability VR_P operates, failure is not propagated. We call this event A. Regardless of the failure pipe valve, if all other valves work, the failure is not propagated. We call this event B. Therefore, the node reliability is defined as

$$\begin{aligned} P[\textit{pipe failure is not propagated}] &= P[\textit{Either event } A \textit{ occurs or event } B \textit{ occurs}] \\ &= P(A \cup B) \\ &= P(A) + P(B) - P(A \cap B) \\ &= VR_P + \prod_{j \neq P} VR_j - VR_P \prod_{j \neq P} VR_j \end{aligned} \tag{6-3}$$

We can also derive Equation (6-3) by

$$\begin{aligned} P[\textit{pipe failure is propagated}] &= P[\textit{the valve on the failure pipe fails and} \\ &\quad \textit{at least one of the other valves does not work}] \\ &= (1 - VR_P)(1 - \prod_{j \neq P} VR_j) \end{aligned} \tag{6-4}$$

and

$$\begin{aligned} P[\textit{pipe failure is not propagated}] &= 1 - P[\textit{failure is propagated}] \\ &= 1 - (1 - VR_P)(1 - \prod_{j \neq P} VR_j) \\ &= VR_P + \prod_{j \neq P} VR_j - VR_P \prod_{j \neq P} VR_j \end{aligned} \tag{6-5}$$

Equations (6-3) and (6-5) are exactly the same. Also, we can derive the (N-1)-valve case from Equation (6-3). For the (N-1)-valve case we must have either VR_P=0 corresponding to no valve on the failure pipe or one of the incident pipes does not have a valve, that is, $VR_k=0$ for some $k \neq p$ among the incident pipes at the node. Therefore, the node reliability for the (N-1)-valve case from Equation (6-3) is

$$P\left[failure\ not\ propagated\right]_{(N-1)=Valve} \tag{6-6}$$

$$= \begin{cases} VR_P & \text{for } VR_k = 0 \text{ for } k \neq p \\ \prod_{j \neq P} VR_j & for\ VR_P = 0 \end{cases}$$

Equation (6-6) is exactly the same as Equation (6-1).

6.2.3 Comparison of node reliability between N-valve and (N-1)-valve rule

In the previous section, we have explained the concept of node reliability and how it can be estimated for the N and the N-1 valving rule. In this section, we show the difference in the node reliability by the N- and the (N-1)-valve rules using different values of valve reliability and different numbers of pipes at a node. The valve reliabilities range from 0.5 to 0.95 and the number of pipes at a node range from 2 to 5. Table 6-6 shows the results.

The difference in nodal reliability values for fully valved case (N-valve) and (N-1)-valves is calculated as follows. Here, we must specially consider whether the failed pipe has a valve or not.

Failed pipe without a valve: using Equation (6-3) and (6-6) we calculate Rdiff1 which is the node reliability difference between the N and the (N-1) valve rules when the failed pipe has no valve by

$$Rdiff1 = VR_P(1 - \prod_{j \neq P} VR_j) \tag{6-7}$$

in which: $j \neq P$ denotes incident pipe "j" not including the failed pipe P, VR_j = valve reliability for the valve on pipe "j". Using identical valve reliability values of 0.95 we have for the case of 5-incident pipes

$$Rdiff1 = 0.95 \times [1 - 0.95^4] = 0.176 \tag{6-8}$$

Failed pipe with a valve: using Equation (6-3) and (6-6), we calculate Rdiff2 which is the node reliability difference between the N and (N-1) valve rules when the failed pipe has a valve by

$$Rdiff2 = \prod_{j \neq P} VR_j(1 - VR_P) \tag{6-9}$$

Using an equal valve reliability of 0.95 we obtain

$$Rdiff2 = 0.95^4 \times [1 - 0.95] = 0.041 \tag{6-10}$$

The comparison between the reliability differences in Equations (6-8) and (6-10) shows that having a valve on the failed pipe is at least 4 times better than closing the other surrounding valves. Also, increased cost and crew time are involved.

The cost, crew time, maintenance, intermittent nature of water demand for most users, provision of temporary above ground pipeline connections, infrequent failures, and purchased water including trucked-in and bottled water demand a critical analysis of N and (N-1) valve rules. Therefore, there is a desire to consider the trade-offs between reliability and cost. Consider Figure 6-3 in which we are following the strategy of installing one valve per pipe. It is clear by considering nodes N3 and N4 that some pipes will have to have 2-valves on them to satisfy (N-1) valve requirement at the junctions. Clearly we like to choose pipes with critical connectivity such as providing unique paths to demand locations, and carrying significant flow magnitude. Therefore, it is a problem of which pipes get two valves such that all nodes are covered by at least (N-1) valves each.

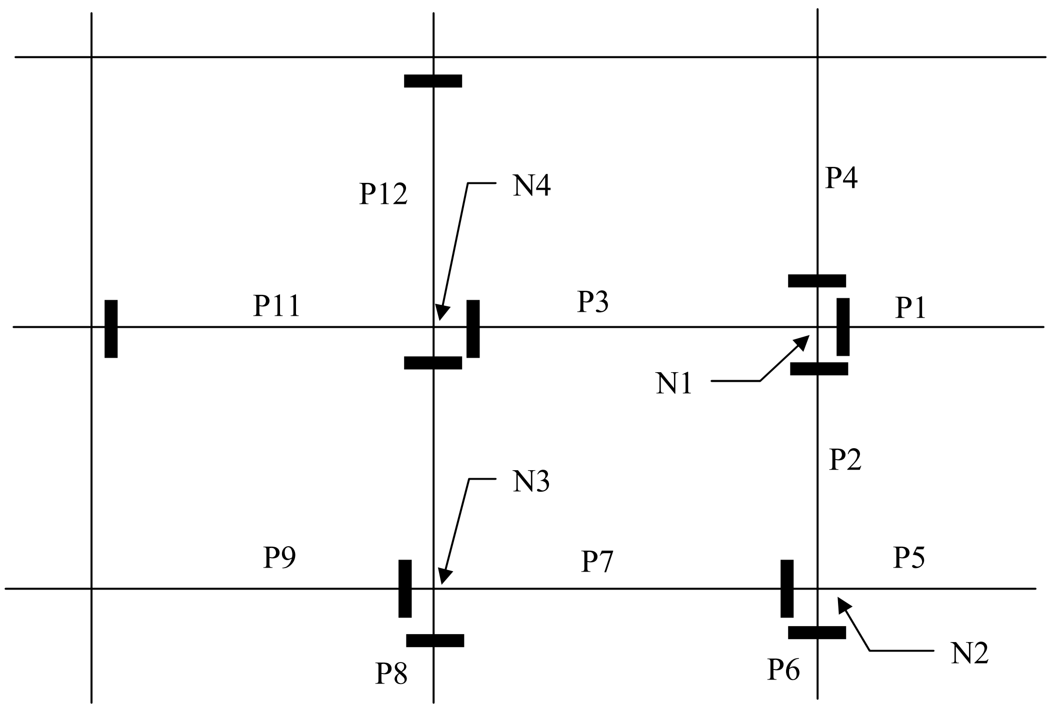


Figure 6-3 Valve positioning

Table 6-6

The node reliability estimation by the degree of node and the valve reliability

The degree of node	Case	# of pipes applied	95%			90%			80%		
			N-1	N	Diff.	N-1	N	Diff.	N-1	N	Diff.
5	case 1	1	0.815	0.991	0.176	0.656	0.966	0.310	0.410	0.882	0.472
	case 2	4	0.950	0.991	0.041	0.900	0.966	0.066	0.800	0.882	0.082
4	case 1	1	0.857	0.993	0.135	0.729	0.973	0.244	0.512	0.902	0.390
	case 2	3	0.950	0.993	0.043	0.900	0.973	0.073	0.800	0.902	0.102
3	case 1	1	0.903	0.995	0.093	0.810	0.981	0.171	0.640	0.928	0.288
	case 2	2	0.950	0.995	0.045	0.900	0.981	0.081	0.800	0.928	0.128
2	case 1	1	0.950	0.998	0.047	0.900	0.990	0.090	0.800	0.960	0.160
	case 2	1	0.950	0.998	0.048	0.900	0.990	0.090	0.800	0.960	0.160

Table 6-6 continued

The degree of node	Case	# of pipes applied	70%			60%			50%		
			N-1	N	Diff.	N-1	N	Diff.	N-1	N	Diff.
5	case 1	1	0.240	0.772	0.532	0.130	0.652	0.522	0.063	0.531	0.469
	case 2	4	0.700	0.772	0.072	0.600	0.652	0.052	0.500	0.531	0.031
4	case 1	1	0.343	0.803	0.460	0.216	0.686	0.470	0.125	0.563	0.438
	case 2	3	0.700	0.803	0.103	0.600	0.686	0.086	0.500	0.563	0.063
3	case 1	1	0.490	0.847	0.357	0.360	0.744	0.384	0.250	0.625	0.375
	case 2	2	0.700	0.847	0.147	0.600	0.744	0.144	0.500	0.625	0.125
2	case 1	1	0.700	0.910	0.210	0.600	0.840	0.240	0.500	0.750	0.250
	case 2	1	0.700	0.910	0.210	0.600	0.840	0.240	0.500	0.750	0.250

6.3 Suggested strategic valving rules

6.3.1 Mixed N and N-1 valve rule

Placing more valves result in high cost for installation and maintenance. The N-valve rule provides redundant reliability to isolate a segment. In contrast, the (N-1)-valve rule may lead to insufficient reliability to isolate a segment but it has the cost efficiency if all valves are maintained well and have high reliability. For this reason, the mixed N and N-1 valve rule is suggested to obtain the best cost and benefit tradeoff. However, the problem is to determine which intersection is valved under the N rule or N-1 rule. Thus, based on the results given above, the following suggestions can be made for strategic valving rules between the N and N-1 valving rules.

- Applying the N valving rule to higher degree nodes first if the valve reliability is higher than 70%..
- When the valve reliability is higher than 90%, the N-1 valving rule may be better valving rule in terms of cost. Lower number of valves makes the valve maintenance easy and cost effective compared to the N valving rule.
- When the valve reliability is less than 60%, a valve must be placed on each pipe.
- To select nodes among the degree two nodes to add more valves and check the degree of adjacent nodes. Nodes whose adjacent nodes are of higher degree may yield better contribution in the system reliability improvement.

The mixed N and N-1 valve rule can be used for both planning and operating stages while the next rule we suggest can be used only for the operating stage.

6.3.2 Selecting new valve locations: reducing size of (large) segments

Walski [1993(b)] mentions that higher portions of pipes do not have two valves at each end which means many water distribution networks do not meet the (N-1)-valve rule. Although it is suggested that a combination of N-1 or N valving systems be followed, it is a good practice to place valves effectively to obtain the maximum benefit. Using Tier 3 procedure, the utility can examine several combinations of new valve locations and determine the most suitable option. The problem is how to select new valve locations since the number of possible combinations can be large. For example, for the Cherry Hill network, there are 208 possible valve locations available. Among them, only 94 valves are placed so that we have 114 possible new valve locations. Let us select 6 new valve locations out of 114. The combination is

$$ {}_{n}C_{r} = \frac{n!}{r! \times (n-r)!} = {}_{114}C_{6} = \frac{114!}{6! \times (114-6)!} = 2{,}666{,}926{,}108 $$

Although the Cherry Hill network is a relatively small network, the possible valve combinations for 6 new valves are considerable. For this reason, we suggest the following criteria to select a combination of new valve locations.

.

Step 1: Select “segments” instead of “possible valve locations” since we assume reducing the size of large segments, can reduce the number of customers out of service effectively.

Step 2: Do not select segments containing a “critical link” even though they are large segments. A critical link means a link that is the only path from water sources to the latter parts of a network. In Figure 6-4, a critical link is illustrated.

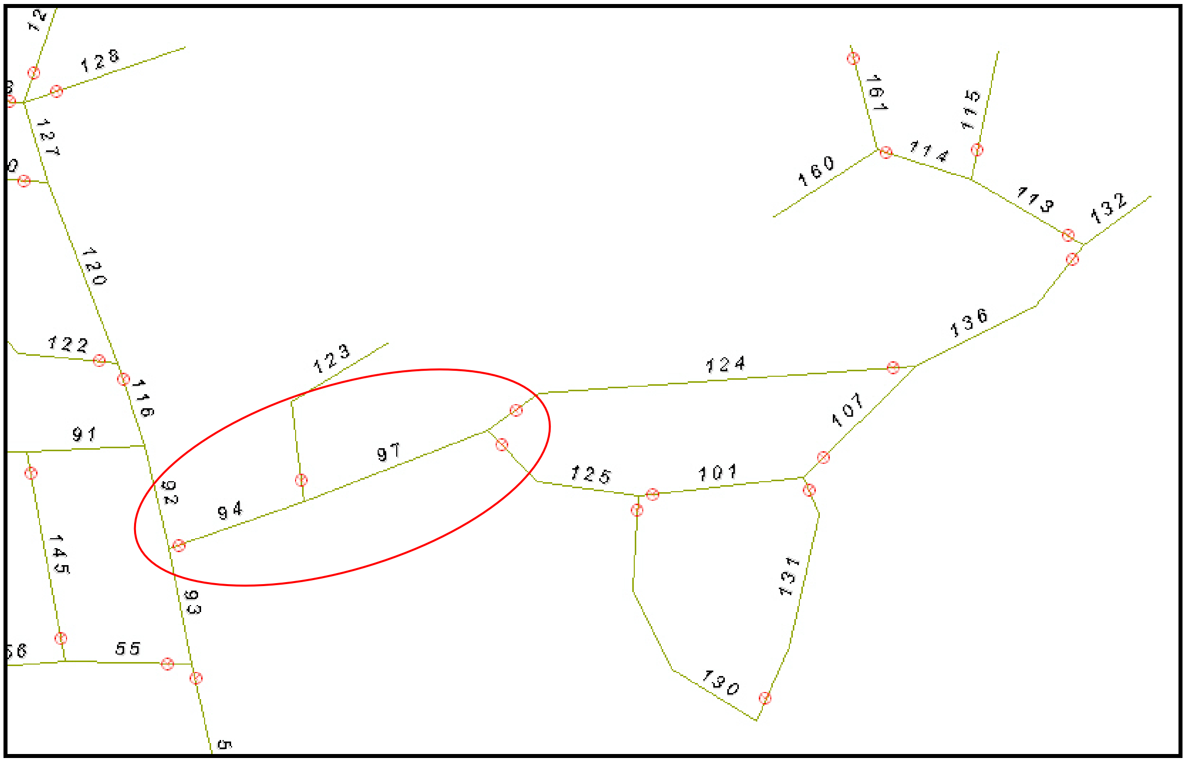


Figure 6-4 First example of a Critical Link

As shown in the Figure 6-4, the link within the circle is the only path from the water sources to the later part of the network consisting of pipes labeled 124, 125, and so on. Placing a valve on pipe 97 or 94 does not make any reliability improvement since the latter part will be disconnected from its water sources by failure of pipe 97 or 94 regardless of closing valves on those pipes. However, a temporary above ground connection may be used when such a link fails. These connections require valves to block off the failed part of a pipe.

In Figure 6-5, we have a different case of a critical link.

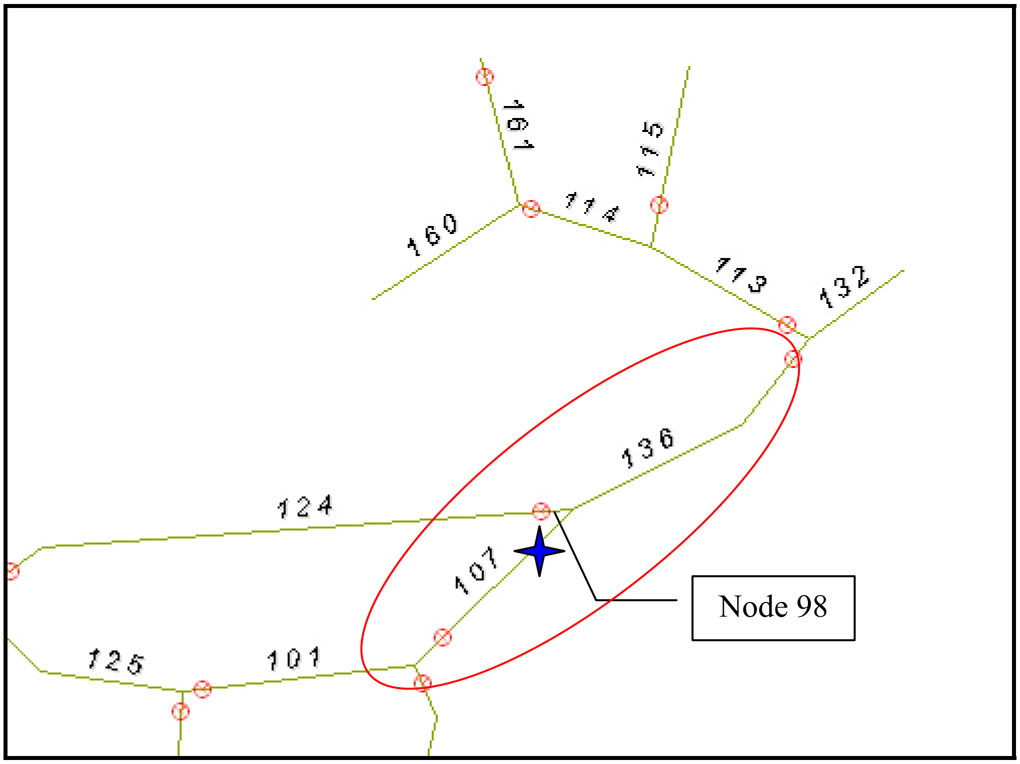


Figure 6-5 Second example of the Critical Link

Currently pipes 107 and 136 are within the same segment. Let us call the segment S20. S20 is also a critical link for pipes 113, 132, 114, 115, 161, and 160. However, if we put a valve at node 98 and pipe 107 shown in star symbol, we can reduce the size of S20 by half. If a valve is placed on pipe 107 near node 98, we can isolate pipe 107 by itself when it fails. In this case, pipes 113, 132, 114, 115, 161, and 160 have a path from the water source through pipe 136. Of course, if pipe 136 fails, these pipes will lose their path to the water source. It is shown that every possible valve location does not have the same importance for reliability improvement. Based on the above two criteria, better choice can be made in the selection of new valve locations.

7. PERFORMANCE INDICATORS

As mentioned earlier, the pipe isolation problem can be divided into planning and analysis categories. In the planning stage, the optimal locations for valves are determined to provide maximum control within budgetary restrictions. In the analysis stage, the system performance is evaluated based on the existing valves at their given locations. An existing system of valves may also be enhanced with a new set of valves to improve the performance of the system. In order to conduct these analyses a set of performance indicators is needed. These indicators are metrics by which the performance of the valving system is evaluated. In this chapter, the following performance indicators are defined and to measure the effectiveness of a valving program. For many of the indicators, an "ideal" value can also be defined. This ideal value is based on the "N-valve" rule design where a valve is placed at the upstream and downstream end of each pipe. The ideal value, however, is not the least cost or economically optimal design but is the one that provides maximum control.

(1) Average length of segment

$$l_a = \frac{\sum l_s}{n_s} \tag{7-1}$$

where l_s = length of segment

n_s = number of segments

The summation is over the number of segments. For the ideal case, only one pipe should form a segment. Therefore, the average length of a segment should be the same as the average length of a pipe. This indicator identifies the average length of pipe without water in case of a break.

(2) Average number of valves per pipe

$$\frac{number\ of\ valves}{number\ of\ pipes} \tag{7-2}$$

In an ideal system, this value would be “2” because all pipes should have two valves following the “n-valve” rule and all segments will consist of a single pipe only. In general, this value for a water system will be less than 2. The system will be considered better if the value is close to 2.

(3) Average number of valves to be closed to isolate a segment

$$V_a = \frac{\sum V}{n_s} \tag{7-3}$$

where V = number of valves to be closed to isolate a segment

n_s = number of segments in the network

For the ideal system it should be 2 because at least two valves are required to isolate a single pipe. The higher the value of this indicator, the lower will be the probability of isolation.

(4) Length–valve ratio

$$\frac{total\ length\ of\ distribution\ mains}{number\ of\ valves} \tag{7-4}$$

Using the ideal values, the length-valve ratio should be one-half the average pipe length.

(5) Average Impact of failure of a valve = Valve Importance Index = customers without service

Number of customers without service due to segment expansion and resulting unintended isolations (parts of network that lose connection with sources) as a consequence of the valve failure.

(6) Average reliability of isolating a segment

$$Average\ reliability = \frac{\sum Isolation\ reliability}{number\ of\ segments} \tag{7-5}$$

If four valves are required to isolate a segment and the reliability of each valve is 0.9, the reliability = 0.9^4 = 0.66. For the ideal fully valved system (n-rule) the average reliability is (reliability of each valve)^2.

(7) Average number of pipes in a segment

$$Average\ number\ of\ pipes = \frac{\sum The\ number\ of\ pipes\ in\ a\ segment}{number\ of\ segments} \tag{7-6}$$

For the ideal system, the average number of pipes in a segment is 1. Other interpretations or equations to compute the performance indicators are possible. By definition, ls is the length of a segment or total length of pipes in a segment, and $\sum l_a$ is the total length of pipes in segments. Because every pipe belongs to a segment and to only one specific segment, the $\sum l_a$ is, then, the total length of all pipes in a water distribution network. Thus, the average length of a segment can be rewritten as:

$$l_a = \frac{Total\ length\ of\ \ pipes}{n_s} \tag{7-7}$$

where l_a = average length of segment

n_s = number of segments

The lower the value of average length (l_a) of the segment will indicate higher reliability of the system. In addition, to compute the average number of pipes in a segment, the sum of the number of pipes in all segments is the same as the total number of pipes in a water distribution network, and we obtain:

$$Average\ number\ of\ \ pipes\ = \frac{total\ number\ of\ \ pipes\ in\ \ the\ system}{number\ of\ \ segments} \tag{7-8}$$

8. MODELING OF A TEST WATER DISTRIBUTION SYSTEM

8.1 Test network

The hypothetical test network used in this study is based on the Cherry Hill, Conn., water service area distribution system that is part of the South Central Connecticut Regional Water Authority. This service area is primarily residential and covers approximately 2 square miles (5 square kilometers [km^2]) with an average water use of approximately 0.5 mgd (1,700 cubic meters [m^3] per day). The network representation is based on maps, consumption data, calibration information, and operational data that reflect the system in approximately 1990. Therefore, it does not represent the current day situation. The original network representation available through the literature was a skeletonized version of the distribution system, which included 34 nodes and 37 links.

The original network model was modified for this study to include all pipes. It is composed of 90 nodes, 104 pipes, 94 valves, 1 storage tank, and a source reservoir that represents the pump station providing water to this system. The system serves an estimated 2,335 equivalent residential customers. Figure 8-1 shows the network representation. For clarity only node identification numbers (IDs) are shown. Figure 8-2 shows the same network with pipe IDs. Figure 8-3 shows the network with the location and identification of valves. The valve IDs used in this figure are composed of the ID of the node adjacent to the valve and the link on which the valve is located.

8.2 Analysis of hypothetical water distribution system based on the current valve distribution

The hypothetical water distribution system is analyzed using the methodology described in the previous chapters. It includes a Tier 1 deterministic analysis in which all valves are assumed to function properly and Tier 2 and 3 probabilistic analyses in which valve reliability is also considered.

8.2.1 Segment Analysis

The initial step in performing the Tier 1, 2, and 3 analyses is to divide the system into segments. The segment identification algorithm is employed to define the segments in the Cherry Hill (hypothetical) network. Based on this process, there are a total of eighty segments consisting of nine node segments, and seventy one regular (non-node) segments. Table 8-1 presents the characteristics of the seventy one regular segments. No low pressure nodes result from the segment isolation with unintended isolation but high pressure nodes result from eleven segments (shown in Table 8-2). Table 8-3 shows the nine node segments. The information in Table 8-1 can be used to identify the most crucial segments in terms of a valving program. Out of the seventy one regular segments, seventeen segments result in unintended isolations. Five of these segments, S(8), S(17), S(18), S(23), and S(25), are especially crucial in that each results in at least fourteen separate pipes being directly or unintentionally isolated by a break.

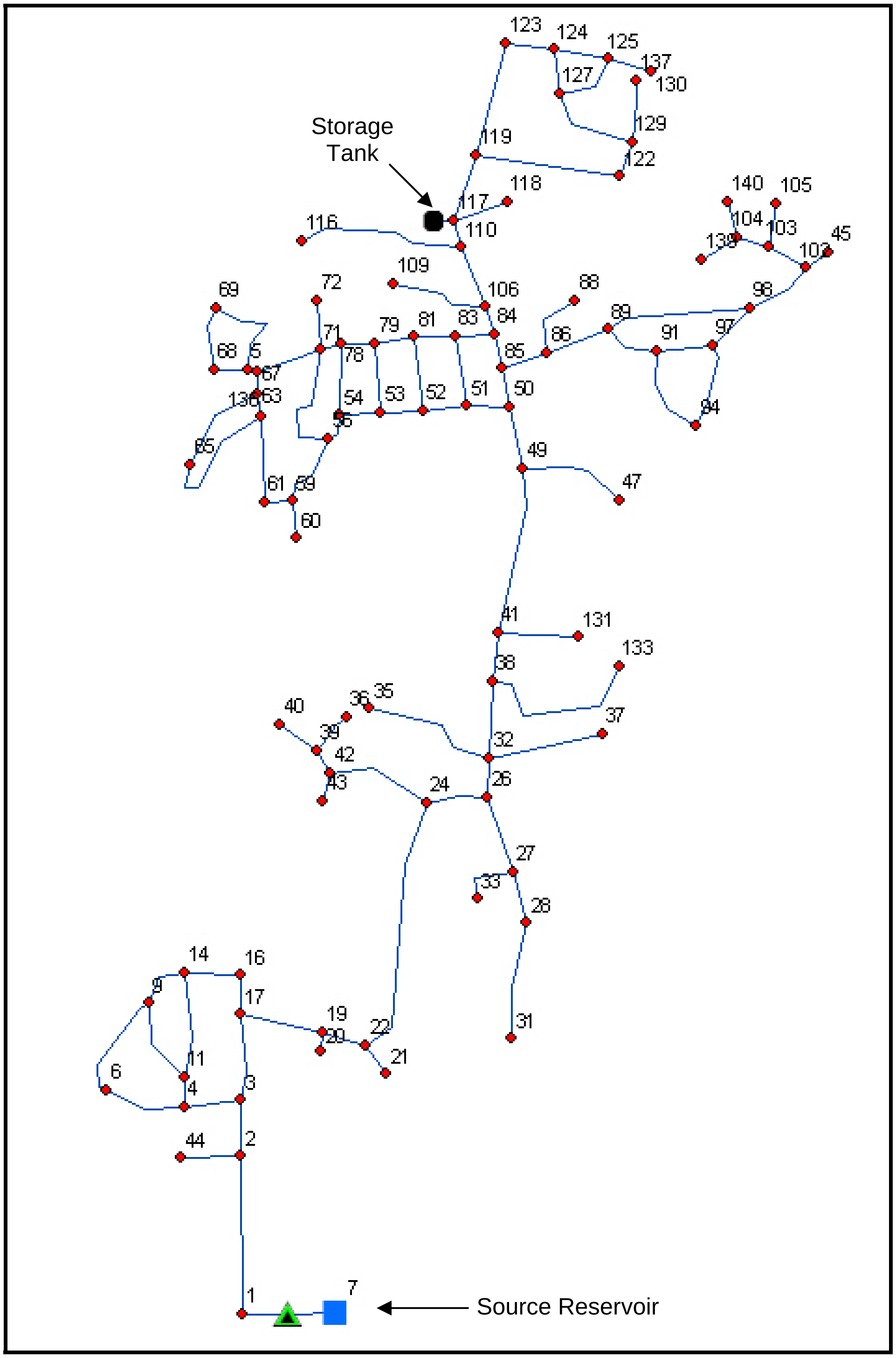


Figure 8-1 Hypothetical case network with node numbers

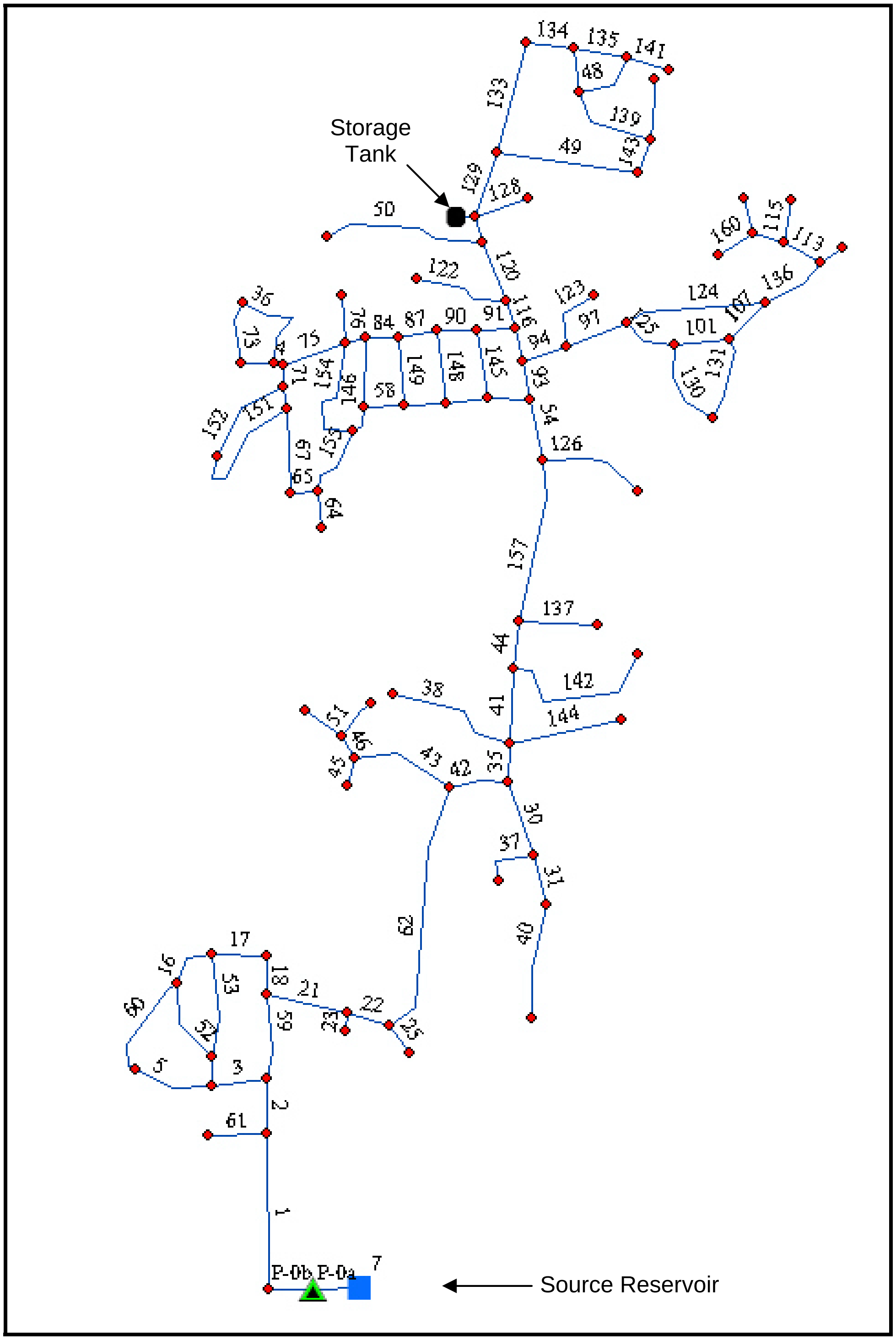


Figure 8-2 Hypothetical case network with link numbers

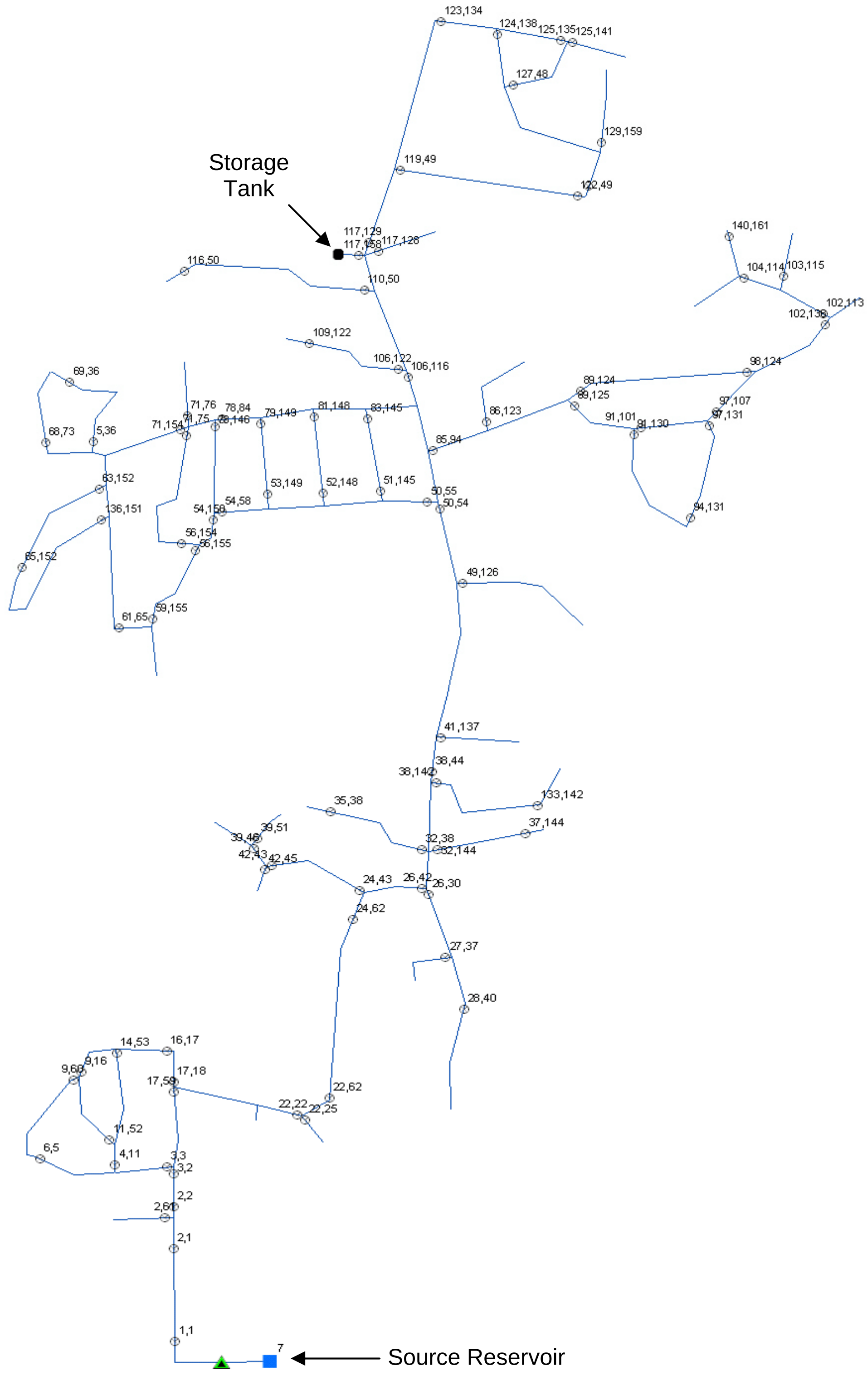


Figure 8-3 Hypothetical case network with valves [V(node, pipe)]

Table 8-1
Segments of the hypothetical test case network

	Segment		Unintended isolation	
Segment no.	Pipe no.	Node no.	Pipe no.	Node no.
S(0)	2,	No node in this segment	-	-
S(1)	3, 5,	4,	-	-
S(2)	11, 53,	11,	-	-
S(3)	16, 17,	14,	-	-
S(4)	18,	16,	-	-
S(5)	21, 22, 23,	17, 19, 20,	-	-
S(6)	25,	21,	-	-
S(7)	30, 31,	27, 28,	37, 40,	31, 33,
S(8)	35, 41,	26, 32, 38,	30, 31, 38, 142, 144, 37, 40,	27, 28, 31, 35, 37, 133, 33,
S(9)	38,	No node in this segment	-	-
S(10)	44, 157, 54,	41, 49,	126, 137,	47, 131,
S(11)	55, 56, 57, 58,	51, 52, 53,	-	-
S(12)	64, 65,	59, 60,	-	-
S(13)	67, 156, 71, 75, 4, 72,	61, 136, 63, 67, 5, 68,	73, 151, 152, 36,	65, 69,
S(14)	73,	69,	-	-
S(15)	76,	72,	-	-
S(16)	83,	71, 78,	76,	72,
S(17)	84, 87, 90, 91, 92, 93, 116,	79, 81, 83, 84, 85, 50,	55, 56, 57, 58, 64, 65, 67, 71, 72, 73, 75, 76, 83, 94, 97, 101, 107, 113, 114, 115, 145, 146, 156, 160, 161, 123, 124, 125, 130, 131, 132, 136, 148, 149, 150, 151, 152, 154, 155, 36, 4,	51, 52, 53, 54, 59, 60, 61, 63, 65, 67, 68, 69, 71, 72, 78, 86, 88, 89, 91, 94, 97, 98, 102, 103, 104, 105, 136, 56, 139, 140, 45, 5,
S(18)	94, 97,	86, 89,	101, 107, 113, 114, 115, 160, 161, 123, 124, 125, 130, 131, 132, 136,	88, 91, 94, 97, 98, 102, 103, 104, 105, 139, 140, 45,
S(19)	101,	97,	-	-
S(20)	107, 136,	98,	113, 114, 115, 160, 161, 132,	102, 103, 104, 105, 139, 140, 45,

Table 8-1 (Continued)

	Segment		Unintended isolation	
Segment no.	Pipe no.	Node no.	Pipe no.	Node no.
S(21)	113, 114,	103,	115, 160, 161,	104, 105, 139, 140,
S(22)	115,	105,	-	-
S(23)	120, 127,	106, 110, 117,	128, 129, 133, 134, 135, 138, 139, 141, 143, 159, 48, 49, 50, 122,	109, 116, 118, 119, 122, 123, 124, 125, 127, 129, 130, 137,
S(24)	128,	118,	-	-
S(25)	129, 133,	119, 123,	134, 135, 138, 139, 141, 143, 159, 48, 49,	122, 124, 125, 127, 129, 130, 137,
S(26)	134, 135,	124,	-	-
S(27)	138, 139, 143,	127, 129,	159,	137,
S(28)	141,	130,	-	-
S(29)	145,	No node in this segment	-	-
S(30)	146,	54,	-	-
S(31)	1,	No node in this segment	-	-
S(32)	158,	138,	-	-
S(33)	159,	137,	-	-
S(34)	160, 161,	104, 139,	,	140,
S(35)	48,	125,	141,	130,
S(36)	49,	No node in this segment	-	-
S(37)	50,	No node in this segment	-	-
S(38)	122,	No node in this segment	-	-
S(39)	123,	88,	-	-
S(40)	124,	No node in this segment	-	-
S(41)	125,	91,	-	-
S(42)	126,	47,	-	-
S(43)	130,	94,	-	-
S(44)	131,	No node in this segment	-	-
S(45)	132,	102, 45,	113, 114, 115, 160, 161,	103, 104, 105, 139, 140,
S(46)	137,	131,	-	-

Table 8-1 (Continued)

	Segment		Unintended isolation	
Segment no.	Pipe no.	Node no.	Pipe no.	Node no.
S(47)	142,	No node in this segment	-	-
S(48)	144,	No node in this segment	-	-
S(49)	148,	No node in this segment	-	-
S(50)	149,	No node in this segment	-	-
S(51)	150,	56,	-	-
S(52)	151,	65,	-	-
S(53)	152,	No node in this segment	-	-
S(54)	154,	No node in this segment	-	-
S(55)	155,	No node in this segment	-	-
S(56)	36,	No node in this segment	-	-
S(57)	37,	33,	-	-
S(58)	40,	31,	-	-
S(59)	42,	24,	43, 45, 46, 47, 51,	36, 39, 40, 42, 43,
S(60)	43,	No node in this segment	-	-
S(61)	45,	43,	-	-
S(62)	46,	42,	45, 47, 51,	36, 39, 40, 43,
S(63)	47,	39, 40,	51,	36,
S(64)	51,	36,	-	-
S(65)	52,	9,	-	-
S(66)	59,	3,	-	-
S(67)	60,	6,	-	-
S(68)	61,	44,	-	-
S(69)	62,	No node in this segment	-	-
S(70)	0,	1, 7,	-	-

Table 8-2
Node segments in the hypothetical test case network

Node segment IDs	Node
S(71)	2
S(72)	22
S(73)	35
S(74)	37
S(75)	109
S(76)	116
S(77)	122
S(78)	133
S(79)	140

8.2.2 Performance Indicators

The performance indicators are used to evaluate the overall general nature of the valving system and how it compares to an ideal valving (n-rule) system. A complete or ideal valving program is one where every segment is composed of one pipe, every pipe has a valve at each end, only two valves are needed to isolate any break, and no more than one pipe is affected by any break. Comparatively, for the hypothetical network, on the average, 2.45 valves are needed to isolate a segment, and on average there are 1.46 pipes per segment. The average length of a segment is 960 feet and the length of pipe and valve ratio is 725 feet. Table 8-3 presents the performance indicators for this network and compares several of these values to values associated with a complete valving program.

Table 8-3
Performance indicators of the hypothetical test case network

Performance indicators	Unit	Hypothetical network	Ideal network
Average length of segment (feet)	length (feet)/segment	960	-
Average number of valves per pipe	valve/pipe	0.90	2.00
Average number of valves to be closed to isolate a segment	number	2.45	2.00
Length – valve ratio (feet)	length (feet)/valve	725	-
Average impact of failure of a valve (equivalent residential customers out of service)	customers	838	-
Average reliability of isolating a segment with 90% (0.90) valve reliability for all valves	per segment	0.78	0.81
Average number of pipes in a segment	pipes/segment	1.46	1.00

8.2.3 Tier 1 Analysis

Tier 1 determines valve importance index (VII) for all valves which identify the importance of present valves and can be used to help prioritize a valve maintenance program.

In this Tier 1 analysis, it is assumed that all valves are 100% operational and that a crew will be able to locate them and close them when needed. In reality, crews may not be able to locate a valve when needed or may not be able to close it. In Tier 1, the system is analyzed by allowing each valve to fail, one at a time. When one valve fails, the current segment that is controlled by the failed valve is combined with the adjacent segment. This results in the addition of customers out of service to that portion of the present segment. The ratio of combined number of customers without service to the total number of customers in the system is called the valve importance index (VII). Table 8-4 shows the VII values for several valves. As illustrated, the valve with the greatest VII of 55.7% results in 1,300 customers being affected if it fails. The valve with the lowest VII value of 1.3% results in only 30 customers being impacted. Obliviously, this is an important index in establishing a priority for a maintenance and valve replacement program.

Table 8-4
Tier 1 valve importance index

Valve ID (node ID, pipe ID)	Customers	Valve Importance Index (VII)	Rank order
106,116	1,300	55.66%	1
50,54	1,049	44.93%	2
38,44	440	18.83%	9
1,1	63	2.71%	67
109,122	30	1.30%	89

8.2.4 Tier 2 and Tier 3 Pipe Failure Analysis

In Tier 2 and Tier 3, a probabilistic framework is used by removing the assumption that all valves will operate properly at all times. In Tier 2 analysis, the impacts of a single pipe break are examined by sequentially allowing each pipe to fail (i.e., experience a pipe break), one at a time. In the Tier 3 analysis, the entire system is examined as a whole in a probabilistic framework.

In the Tier 2 analysis, a pipe is selected for analysis and a valve from the valve list of the segment associated with that pipe is checked for failure. If it fails, the current segment is merged with the corresponding adjacent segment. Because, all valves in the current segments have been set to open or closed (failure / success), only the valves corresponding to the adjacent segments need to be checked. For example, a failed valve in the current segment cannot be checked again. Its status has been fixed. The process continues until every valve corresponding to the valves of the adjacent segments for the merged segment can be closed.

The following example is used to illustrate this process. Assume that the current segment has only four valves with each valve having a reliability of 90%. The probability of expansion to the adjacent segments is the same as the probability that at least one valve does not work. This probability for the four valves is: $1-(0.9)^4 = 0.3439$ which means that if a break occurs in that segment on average, 34.4% of the time, the impacts will extend beyond this segment. If it is assumed that exactly two valves fail, failure of two valves implies that the remaining two valves are working and have been closed. If the two adjacent segments having an additional six valves among them are merged (as a result of the nonworking valves) with the current segment, the risk of at least one valve out of the six additional valves not working is: $1-(0.9)^6 = 0.47$.

If all six valves corresponding to the two segments being merged work, the merged segment can be closed and one repetition in Tier 2 is finished. Otherwise, when a subset of the six valves does not work, the corresponding adjacent segments are to be merged with the current segment; also, only the valves corresponding to the newly merged adjacent segments should be checked for failures. When all valves work, the next pipe is selected and the process is continued. In Tier 2, each pipe break analysis is repeated at least 30 times (expanding segments) using the same input valve selection strategy and assigned reliability value; i.e., the input and initial conditions are kept the same. This repetition is conducted in order to have a statistically valid result.

An example of a Tier 2 analysis is shown by examining pipe 67. The segment containing pipe 67 is segment 13, which is composed of the following elements:

- Pipe list: 67, 4, 71, 72, 75, 156
- Valve list: (61,65), (63,152), (68, 73), (71,75), (136,151), (5,36)

The location of pipe 67 and segment 13 is shown in Figure 8-4. Using 50% and 90% valve reliabilities and 30 simulation runs, the resulting number of customers impacted is shown in

Table 8-5. For this example, on the average, the number of customers impacted more than doubles when the valve reliability drops from 90% to 50%. This effect is even more pronounced when the upper tail of the distribution is examined. For example, when examining the 75th percentile case (i.e., the top 25%), the number of customers increases almost five times.

Tier 3 differs from Tier 2 in that rather than sequentially looking at each pipe separately, pipe breaks are also treated probabilistically. In this example, the probability of a pipe break is the same in all pipes. Then pipe breaks and valve failures are simulated randomly. At least a thousand runs (iterations) are made starting with a randomly selected pipe to fail and continuing with valve closing. More than 1,000 pipe failure cases are used to calculate the mean, median, 90^{th}, and 95^{th} percentile for one sample. Then, 100 such samples of these parameters are collected for the estimation of the mean and confidence interval of the four parameters. We compare the average number of impacted customers taken across all pipes from Tier 2 called ensemble average with that of Tier 3 systemwide simulation. The Tier 2 averages for 90% and 50% valve reliability are 677 and 2007. These averages are calculated from the 30 simulations per pipe. They compare well with the Tier 3 simulation averages of 688 and 2021 (see Table 8-6).

Table 8-5
Tier 2 results (pipe 67 with 30 runs) – number of customers impacted

	Valve reliability		Difference (%)
	90%	50%	
	Number of customers impacted		
Mean	938	2425	1487
Median	867	1397	530
Percentile (25%)	867	915	48
Percentile (75%)	867	4196	3329

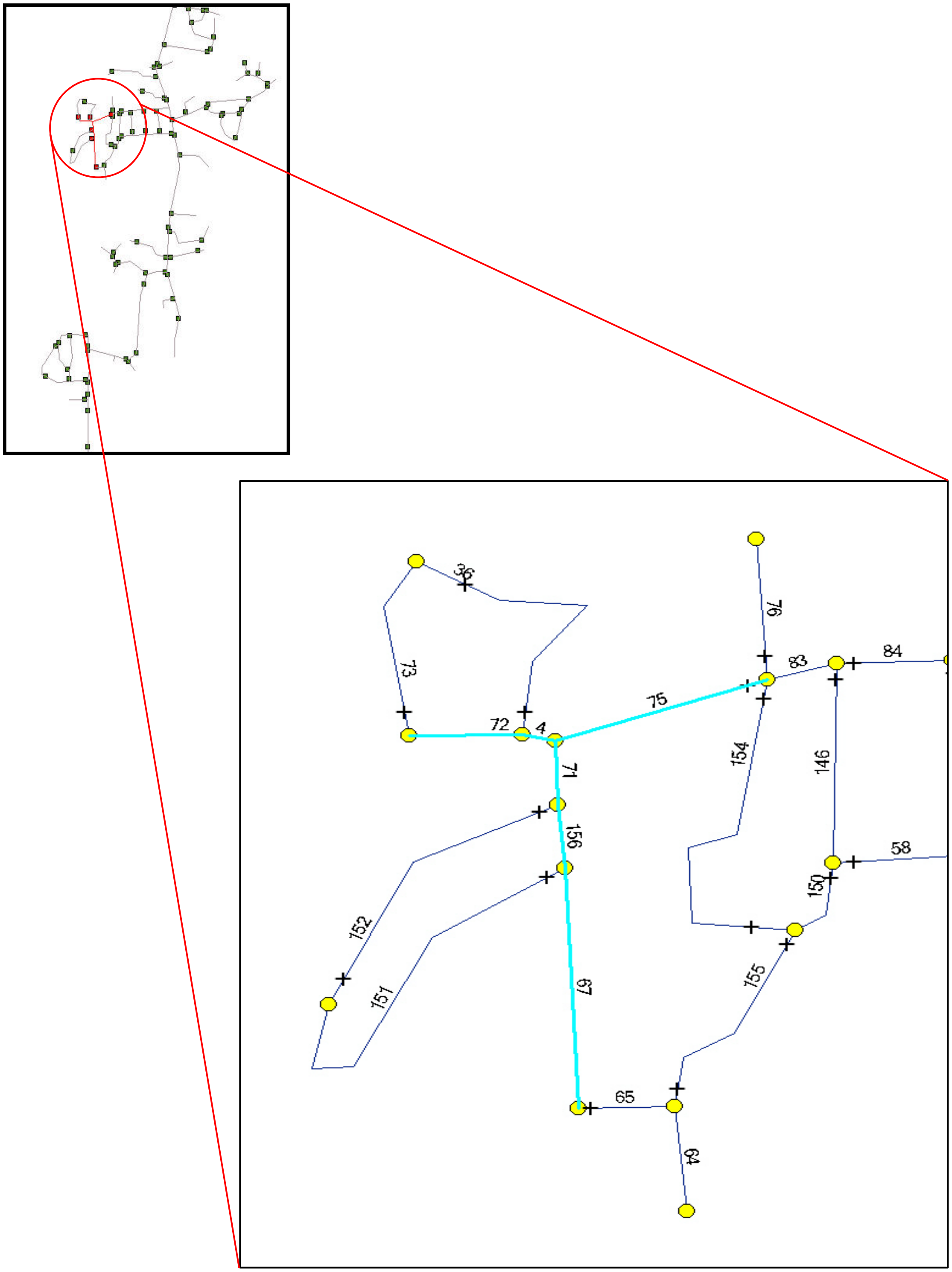


Figure 8-4 Location of pipe 67 and the corresponding segment

Table 8-6
Statistical parameters of Tier 3 simulation

		Valve reliability		Difference (%)
		90%	50%	
The number of samples		50	50	-
The confidence level		0.95	0.95	-
Mean customer out of service *	Sample mean	688	2012	192%
	L. confidence interval	676	1989	194%
	U. confidence interval	700	2036	191%
Median customer out of service*	Sample mean	220	1060	382%
	L. confidence interval	215	1045	386%
	U. confidence interval	224	1075	380%
90^{th} percentile customer out of service *	Sample mean	1906	5704	199%
	L. confidence interval	1717	5648	229%
	U. confidence interval	2095	5759	175%
95^{th} percentile customer out of service *	Sample mean	3558	6514	83%
	L. confidence interval	-	6377	-
	U. confidence interval	-	6651	-

* This represents total customer out of service (direct customers out of service and unintended customer out of service).

8.2.5 Findings

A full analysis using Tier 1, Tier 2, and Tier 3 is conducted. The following are the findings:

- Average length of pipe between valves (length–valve ratio) in the hypothetical network is 725 feet.
- Average length of a segment (length of pipe that will have water outage) is 960 feet.
- Average number of valves required to isolate a pipe break is 2.45.
- On an average 838 customers will be out of water if a valve fails.
- Segment 17 has the potential of water outage in largest number of pipes (direct isolation of 7 pipes and an unintended isolation of 41 pipes).
- Valve number 106,116 has the highest VII value of about 56%. If this valve does not operate, there is the potential for 56% of the customers to be out of service. This valve should get the highest priority for maintenance.
- Average number of customers impacted almost triples when the average valve reliability drops from 90% to 50%.

8.3 Comparison between different valve systems by the Strategic valving rules

In chapter 7, two strategic valve rules, the mixed N and N-1 rules and decreasing the size of the larger segments are suggested. Thus, four different valving rules can be tested on the hypothetical network. Making the current valve system to one of different valving system, additional valves are required. Six valves are placed additionally to decrease the five largest segments in the current valve system. The current valve system does not meet the N-1 valving rule so that 33 additional valves are placed. At an intersection, one of pipes entering the intersection should not have a valve. Thus, it is required to determine which one does not have a valve for every intersection. To do that, we place additional valves on downstream pipes and no valve is placed on the upstream pipe. It is suggested by Walski (2002) to prevent the upstream node (intersection) from the downstream pipe failure. For the mixed N and N-1 rule valving system 23 valves are added to the N-1 valving system. While determining the new locations, we follow the suggested rules in the previous chapter. Finally, we put 104 new valves to the current valve system for the N valving system. The number new valves needed to create each system are shown in Table 8-7. The 114 additional valves for the N rule system are not included since all pipes in the intersections have valves.

Table 8-7
Additional valves for different valving system

Valving systems	Total valves	Additional valves	Base system
Current	94	-	-
6 valves added	100	6	Current system
N-1 rule	127	33	Current system
Mixed N and N-1 rule	150	23 (56 valves added to the current system)	N-1 rule
N rule	208	114	Current system

Locations of the new valves for three valving systems are shown in Table 8-8.

Table 8-8
Locations of the new valves for three valving systems

Valving systems	Valve Locations [V(node, pipe)]	Total new valves
6 valves added	(67, 75), (26, 35), (136, 156), (84, 92), (98, 107), (117, 127)	6
N-1 rule	(4,5), (11,53), (14,17), (19,21), (19,22), (27,30), (32,35), (41,157), (49, 54), (51,56), (52,57), (53,58), (59,65), (63156), (67,71), (67,75), (79,84), (81,87), (83,90), (84,91), (84,116), (85,92), (86,94), (98,107), (103,113), (104,160), (110,120), (119,129), (124,135), (127,139),(129,139), (136,67), (5,72)	33
Mixed	(3,59), (11,11), (20,23), (32,41), (26,35), (38,41), (49,157), (50,93), (85,93), (52,56), (54,146), (63,71), (71,83), (78,83), (81,90), (89,97), (97,101), (103,114), (110,127), (117,127), (119,133), (127,138), (42,46)	23

To compare them, the seven performance indicators and Tier 3 simulation are used. Table 8-9 shows the performance indicators from the five valve systems.

As gradually adding more valves to the current valve configuration, we have improvements in the performance indicators. Among the performance indicators, “Average Impact of Failure of a Valve” is the most improved indicators by adding valves. The N valving system is the ideal system so that the four performance indicators, Average Number of Valves per Pipe, Average Number of Valves to isolate a segment, Average Reliability of Isolating a Segment, Average Number of Pipes in a Segment, are the same as the ones of the ideal system.

Table 8-9
Performance indicators from the five valve systems

Items	Unit	Current	6 valves added	N-1 rule	Mixed	N rule
Average Length of Segment	Length / segment	960.42	909.20	655.67	655.67	655.67
Average # of Valves per Pipe	Valve / pipe	0.90	0.96	1.22	1.44	2.00
Average # of Valves to isolate a segment	Valves / segment	2.45	2.39	2.31	2.08	2.00
Length Valve Ratio	Length / valve	725.43	681.90	536.93	454.60	327.84
Impact of Failure of a Valve	Customer / valve	838.45	520.87	413.61	292.09	223.15
Average Reliability of Isolating a Segment *	Reliability / segment	0.78	0.78	0.79	0.81	0.81
Average # of Pipes in a Segment	Pipes / segment	1.46	1.39	1.00	1.00	1.00

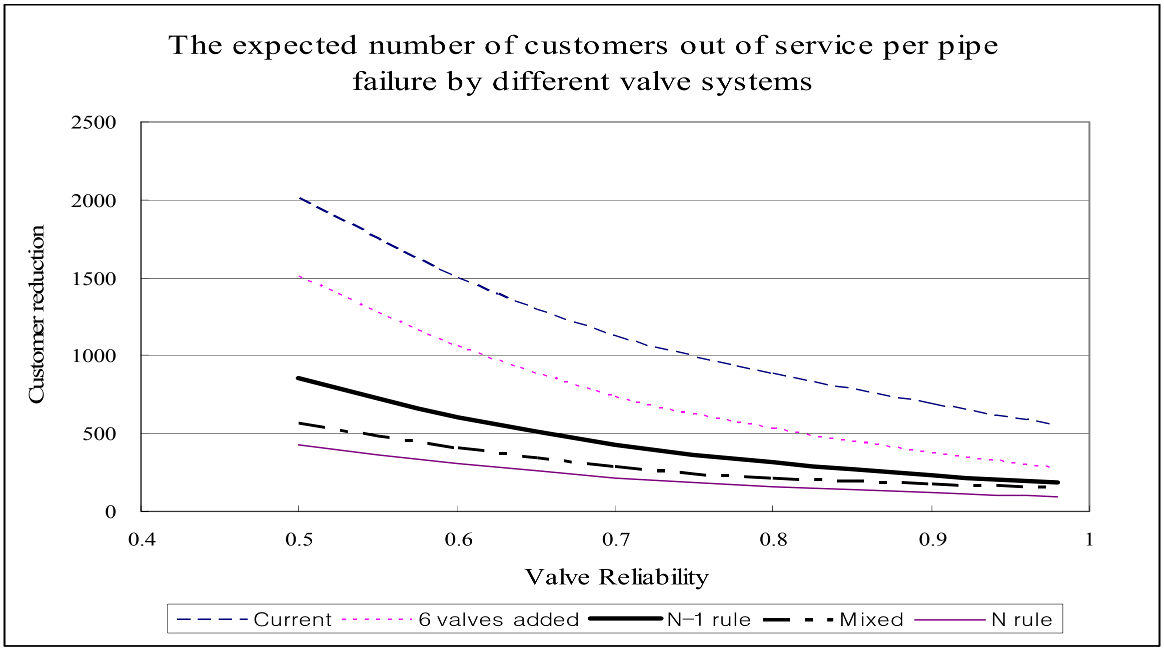
*: 90% valve reliability is used

Table 8-10 and Graph 8-1 show a summary of the average customers out of service per pipe failure by different valve systems from Tier 3. In the table, "Direct" means customers within a segment and "InDirect" means customers within an unintended isolation. In Graph 8-2, it is shown the reduction in the expected number of customer out of service per pipe failure for the four valve systems by adding a valve. As expected, the N rule system produces the highest customer reduction from the current system. However, if the customer reduction is estimated by an additional valve, the 6 valve added system produces the most efficient result. Also, it is observed that higher customer reduction is obtained as the valve reliability is lower. Thus, it can be said that maintaining high valve reliability with proper valve maintenance may generate desirable results with less number of valves added.

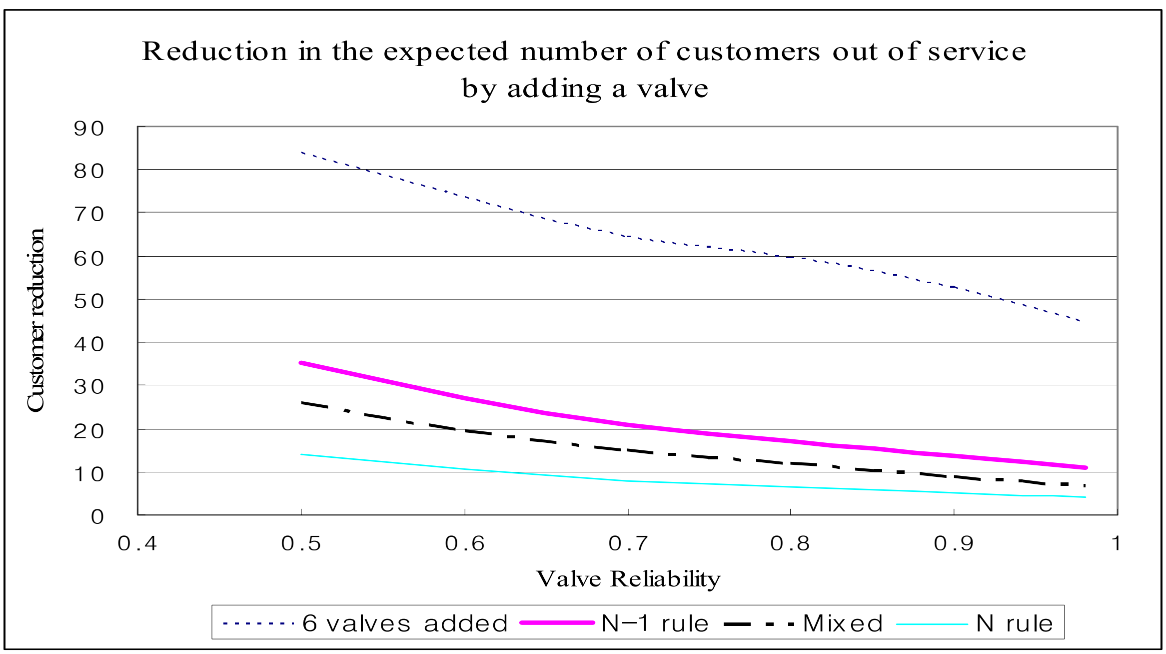
Table 8-10
Summary of the average number customers out of service per pipe failure by different valve systems from Tier 3

Valve Reliability	Current			6 valves added			N-1 Rule			Mixed N and N-1 rule			N Rule		
	Direct	InDirect	Total	Direct	InDirect	Total	Direct	InDirect	Total	Direct	InDirect	Total	Direct	InDirect	Total
0.5	1075	937	2012	823	684	1508	408	446	854	289	276	565	210	217	427
0.6	687	809	1496	526	529	1055	269	337	606	206	201	407	155	149	304
0.7	450	673	1123	351	387	738	195	236	430	154	133	287	122	96	218
0.8	313	574	887	251	279	530	148	172	320	120	95	215	104	57	161
0.9	225	463	688	185	187	372	114	122	236	105	76	181	92	27	119
0.98	175	371	546	150	129	279	95	87	182	94	61	155	91	5	96

Graph 8-1 Average customers out of service per pipe failure by different valve systems from Tier 3



Graph 8-2 Reduction in the expected number of customers out of service by adding a valve



9. ANALYSIS OF LARGE-SCALE WATER DISTRIBUTION SYSTEMS

9.1 Introduction

In Chapter 8 the application of the proposed methodology to the hypothetical water distribution system based on a real system was discussed. In this chapter, application of the proposed methodology to two real water distribution systems, namely, Chester Water Authority (CWA), Pa., and Ottawa Water System, Ottawa, Canada, are described. These two systems were selected based on the availability of valve location data in electronic form in addition to the hydraulic network data. Both systems have hydraulic data suitable for EPANET. The valve location information is provided in the form of a shape file as part of the GIS database. From this shape file the valve location matrix is created. These tasks emphasize the need for consistency in the database and the advantages of maintaining an electronic database. In the following subsections, system characteristics, a discussion of delineated segments, and performance indicators are presented.

9.2 Analysis of Chester Water Authority distribution system

The Chester Water Authority (CWA) network consists of five major sections and one of these five sections is modeled. The network has 566 pipes, 537 nodes, and 354 valves. Actually, there are more than 354 valves installed in the selected section, but valves installed on hydrants and laterals were removed since these valves could not be used to isolate a subsystem when a pipe fails. As discussed in Appendix 2, intermediate valves in a long pipeline affect segment delineation only if demands are distributed along the pipeline. Because it is assumed demands are always consumed at nodes, the intermediate valves are not needed in segment delineation and subsequent performance indicator calculations. Therefore, intermediate valves placed along the pipes (but not adjacent to nodes) remain in the valve shape file but are not used to create the valve location matrix (B matrix) for the network. A total of 335 out of 354 valves are used to create the valve location matrix and 19 (= 354-334) valves are intermediate valves.

In the network, four water sources are available: two reservoirs and two tanks. In Figure 9-1, the reservoirs are displayed as rectangles and tanks are indicated by pluses. Because of the unavailability of customer data per pipe, the number of customers in the network is estimated by the following equation:

$$The\ \#\ of\ customers\ for\ pipe\ i = \frac{length\ \ of\ \ pipe\ i}{total\ length\ of\ \ pipes} \times Total\ \#\ of\ customers \tag{9-1}$$

After the segment delineation, 314 segments are identified. Among them 84 node segments are found, which implies 84 out of 537 nodes are fully valved. Of 229 normal segments, 53 have unintended isolation. Regarding low pressure head, 41 out of 229 normal segments are affected if the low pressure limit is set at 25 pounds per square inch (psi).

From Table 9-1, among the segments, some consist of a large number of pipes such as segment S(28) and segment S(107) consisting of 16 pipes and 12 pipes, respectively. In Table 9-2, segment S(223) consists of only one pipe, 77151, but the unintended isolation of S(223) consists of 124 pipes. Figure 9-2 shows that pipe 77151 connects two components of the network. The downstream component of pipe 77151 shown in the top right corner of Figure 9-2 is disconnected from the water sources and consists of 124 pipes. In contrast, segment S(7) has the largest number of pipes (16) but no unintended isolation. Therefore, it is necessary to consider both sets of pipes, i.e., the pipes that are within the segment, and in the unintended isolation. Table 9.3 lists the five valves with the highest Valve Importance Index (VII). Valve (JT050AV16, 77149) is located the left side of segment S(223) containing 2,146 customers. The VII of this valve is 27.7% (ratio with respect to total number of customers), the largest share. Therefore, it is clear that in addition to valves, providing multiple paths to sources is essential. Figure 9-3 shows the location of segment S(7). Table 9-4 lists the characteristics of segment S(7). It is a summary of the output for that segment obtained from the software. It includes: (1) segment information in terms of pipes and nodes (output includes valves as well [see Table 9-6 for ranking of valves]); (2) unintended sections information; (3) hydraulic performance in terms of low pressure nodes after removing the segment; and (4) number of customers without service. The performance indicators are reported in Table 9-5. The average number of valves per pipe is only 0.59 compared to 2.0 of the ideal system. The average number of pipes in a segment is 2.46 compared to 1 for the ideal system. Therefore, it follows that the system lacks a sufficient number of valves. To improve performance, new valves can be added based on the segment characteristics reported in Tables 9-1 through 9-3.

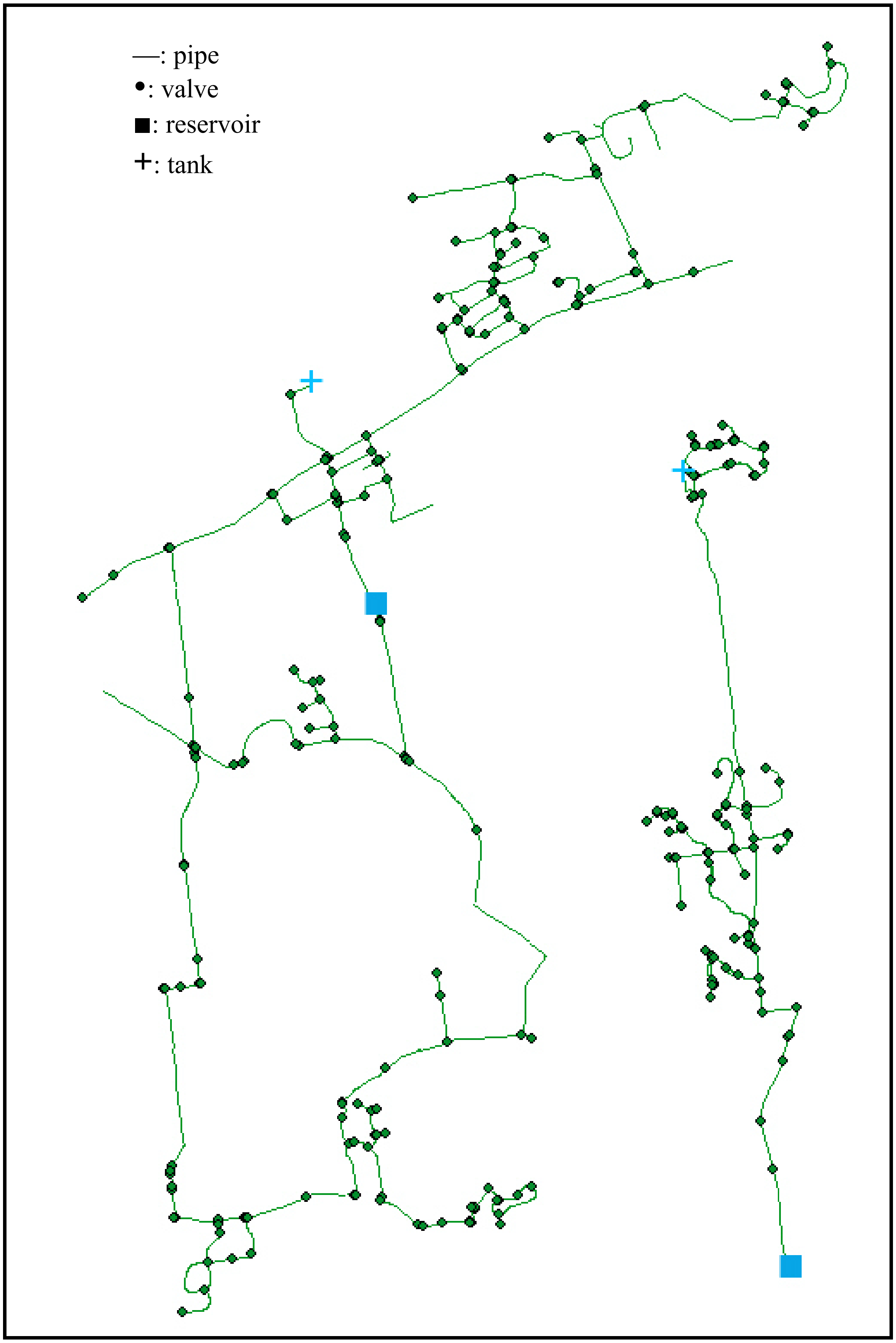


Figure 9-1 The Chester Water Authority Water Main Network

Table 9-1
Five segments having largest number of pipes in the CWA network

Segment	Pipes	No. of pipes
S(7)	83112, 112635, 83116, 112634, 95117, 83121, 83110, 83108, 83106, 83118, 76974, 76972, 76970, 77618, 77116, 95111	16
S(28)	77359, 77364, 77366, 77367, 77369, 77371, 77392, 77390, 77357, 77355, 77234	11
S(31)	88097, 88099, 88101, 88103, 88105, 88107, 88109, 88161	8
S(39)	79636, 79592, 79590, 79588, 79586, 79584, 79638, 79642, 79644, (P-555, P-557)	9 (11)
S(107)	81656, 81654, 81658, 81660, 81662, 81664, 120244, 120246, 120248, 120250, 120252, 120254	12

Table 9-2
Five segments having largest number of pipes in unintended isolations

Segment	Pipes	No. of pipes
S(49)	77359, 77392, 79888, 77357, 77389, 77355, 79894, 77390, 72785, 77364, 77371, 77387, 77234, 79892, 72783, 79898, 72792, 77369, 77377, 77375, 77373, 77236, 77385, 77379, 77366, 79896, 72790, 77367, 77381, P-562, P-563	31
S(53)	77359, 77392, 79888, 77228, 77357, 77238, 77389, 77355, 79894, 77390, 77240, 72785, 77364, 77230, 77371, 77387, 77234, 79892, 72783, 79898, 72792, 77369, 77377, 77222, 77375, 77373, 77236, 77385, 77232, 77379, 77224, 77366, 79896, 72790, 77367, 77381, P-562, P-563	38
S(115)	88155, 88097, 88164, 88121, 88139, 179101, 88145, 88101, 88126, 179105, 88141, 179103, 88105, 88107, 88156, 179095, 179108, 179090, 179099, 88124, 88095, 88109, 88128, 179083, 88143, 179092, 88103, 88131, 179087, 179107, 88099, 179097, 179085, 179094, 88133, 88137, 88161, 88135, 88113, 88167	40
S(119)	88155, 30322, 88097, 88164, 88121, 88139, 179101, 88145, 88101, 88126, 179105, 88141, 88081, 88078, 179103, 88105, 88107, 88156, 179095, 179108, 179090, 88085, 179099, 88124, 88095, 88109, 88128, 179083, 88143, 179092, 88103, 88131, 88083, 179087, 179107, 88099, 179097, 88152, 179085, 179094, 88133, 88137, 88161, 88135, 88113, 88167	46
S(223)	77302, 77300, 77359, 77326, 77392, 79888, 77286, 81738, 77228, 76955, 81740, 77357, 77298, 77328, 77306, 76939, 77238, 77389, 77355, 79894, 77390, 77345, 77240, 72785, 81736, 81730, 76930, 82660, 77261, 76953, 77296, 76950, 77364, 77214, 77230, 77333, 77371, 77320, 77387, 77314, 77319, 81723, 77234, 79892, 77317, 77308, 77175, 77349, 77257, 72783, 76945, 76928, 79898, 76967, 72792, 81728, 82648, 77369, 77247, 81717, 77377, 77241, 77222, 81741, 76957, 77329, 77343, 77538, 77350, 77211, 77375, 82662, 77346, 77331, 81715, 77335, 77294, 77310, 77288, 77373, 77236, 77385, 77312, 243815, 77318, 81721, 77232, 82655, 77171, 77379, 81726, 76942, 76963, 77315, 77339, 77337, 77224, 81719, 77253, 77209, 77366, 77249, 79896, 76965, 76926, 72790, 77173, 77367, 82646, 82658, 77381, 77341, 77255, 77243, 77290, 77245, 77251, P-550, P-551, P-552, P-553, P-562, P-563	124

9.2.1 Results of Tier 1 Valve-by-Valve simulation/Valve Importance Index

A Tier 1 valve-by-valve analysis is performed by assuming that only one of the valves associated with a segment fails. This failure leads to combining the two segments linked by the failed valve and identifying the unintended isolation resulting from the isolation of the combined segments. Table 9-6 lists five critical valves having the highest VII. As expected from previous discussions, rank 1 through 4 valves are found around pipe 77151. As pointed out earlier, for a secure supply of flow both valves and multiple paths to sources are important.

9.2.2 Tier 2 and Tier 3 probabilistic analyses

Tier 2 probabilistic analysis entails the following. A pipe is selected and the corresponding segment is identified. From the segment's valve list, valves are randomly checked for failure or operational status. If a subset of valves fails, the segment is enlarged by merging with the corresponding adjacent segments linked by the failed valves. The valve lists of these adjacent segments (without the failed common valves) are checked for failed valves by testing against random numbers. If valve reliability is 0.9, the valve is considered to have failed if the generated random number is less than 0.1. If the generated random number is between 0.1 and 1.0, the valve is considered operable and is shut. This process is continued until all valves of the segment at that stage can be closed. This attainment of having all valves operational constitutes one repetition replicating a situation where a repair crew has successfully shut off all valves to contain a failed pipe. For each pipe, 30 such repetitions are performed. The results for pipe 77162 are shown in Table 9-7. The pipe belongs to S(64) consisting of:

- Pipes: 77162, 77160
- No unintended isolation

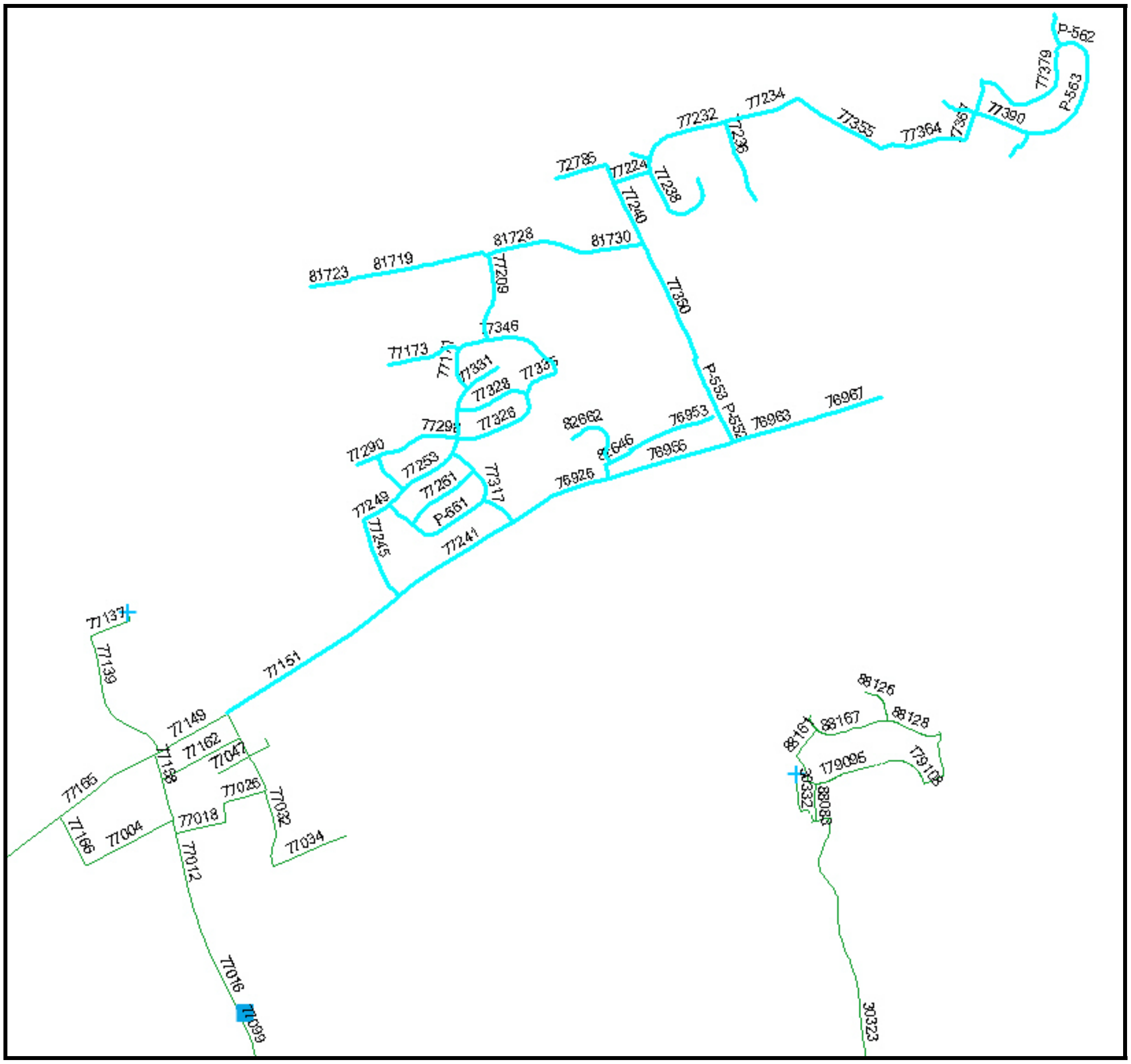


Figure 9-2 Location of segment S(223) and unintended isolation of pipes

Table 9-3
Five segments having maximum number of customers from segments and unintended isolations

Segment	Number of customers within segment	Percent	Rank
S(28)	219	5.1%	5
S(49)	661	8.4%	3
S(53)	766	9.7%	2
S(180)	449	5.7%	4
S(223)	2,146	27.2%	1

Total number of customers: 7,884

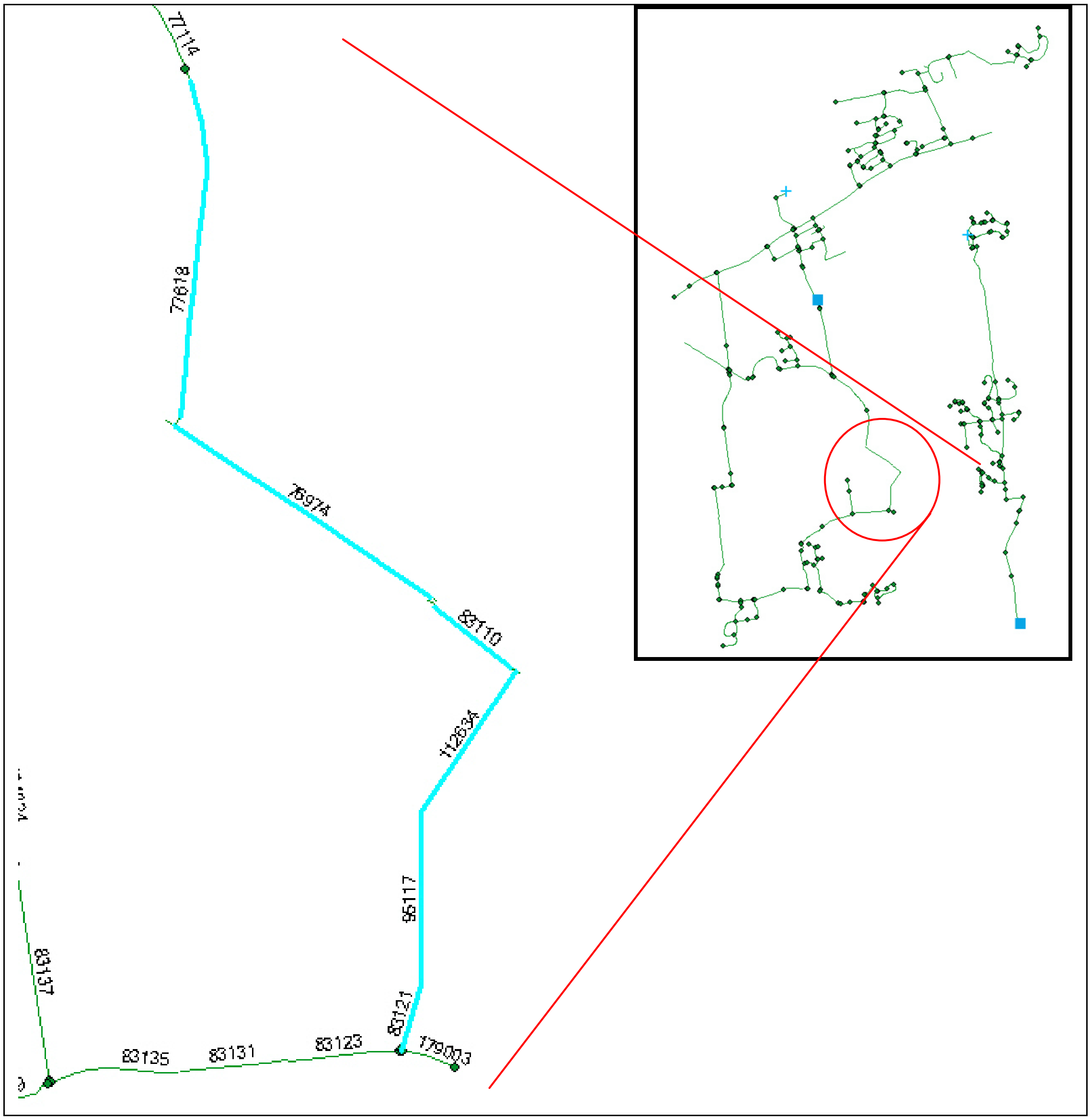


Figure 9-3 Location of segment S(7) and isolated pipes

Table 9-4
Segment S(7) components

Types	Pipe/node	Total no. of pipes/nodes	Pipe/node ID
Segment	Pipes	16	83112, 112635, 83116, 112634, 95117, 83121, 83110, 83108, 83106, 83118, 76974, 76972, 76970, 77618, 77116, 95111
	Nodes	15	JL015AT07, JT019AT07, JD022AT07, JL026AT07, JL030AT10, JL010AT07, JL005AT07, JL001AT07, JL025AT07, JT020AT07, JT005AT03, JD010AT03, JL001AT03, JL005AU15, JD015AT07
Unintended isolation	Pipes	0	-
	Nodes	0	-
Hydraulic pressure	Nodes	15	JL015AT07, JL030AT10, JL010AT07, JT005AT03, JD022AT07, JL001AT03, JD010AT03, JT020AT07, JT019AT07, JL026AT07, JL001AT07, JL005AU15, JL005AT07, JL025AT07, JD015AT07
No. of customers	245	3.10% (= 245 / 7,884), 10th largest	

Table 9-5
Performance indicators for the CWA network

Performance indicators	Unit	CWA network	Ideal network
Average Length of Segment	length/segment	744.54 ft	-
Average Number of Valves per Pipe	valve/pipe	0.59	2.00
Average Number of Valves to Be Closed to Isolate a Segment	valves/segment	2.28	2.00
Length – Valve Ratio	length/valve	511.18 ft	-
Average Impact of Failure of a Valve (additional customer equivalent out of service)	customers/valve	131.30	-
Average Reliability of Isolating a Segment with 90% (0.90) valve reliability for all valves	per segment	0.79	0.81
Average Number of Pipes in a Segment	pipes/segment	2.46	1.00

Table 9-6
Five most critical valves in CWA system in terms of affected customers

Valve ID	Node ID	Pipe ID	No. of customers	Valve importance index	Rank
JT050AV16,77149	JT050AV16	77149	2188	27.75%	1
JT050AV16,77575	JT050AV16	77575	2172	27.55%	2
JT001AP13,77241	JT001AP13	77241	2146	27.22%	3
JT001AP13,77243	JT001AP13	77243	2146	27.22%	4
JL170AP14,81740	JL170AP14	81740	848	10.76%	5

Table 9-7
Tier 2 results (pipe 77162 from 30 simulations)

	Valve reliability	
	90%	50%
Average number of customers out of service per pipe 77162 failure		
Mean	52	1,021
Median	46	76

- Nodes: JR070AV16
- Valves: (JT065AV16, 77160), (JR020AU04, 77162)
- Customers: 46

Pipe 77162 is located near pipe 77151, which is the most critical pipe mentioned before. Because segment S(64) has only two valves, with 90% reliability, there is an 81% probability that both valves will work. Therefore, out of 30 simulations it would be expected that about 24 replications will involve shutting both valves successfully. In the present simulation there were 29 replications with successful closure of both valves. In contrast, there is only a 25% probability that both valves can be closed successfully when the probability of successful closure is 50%. Therefore, out of 30 replications it is expected that about 23 replications will have at least one of the two valves failing. In the present simulation exactly 23 replications had at least one valve fail. The resulting averages of customer outages are 52 and 1,021, respectively, for 90% and 50% probabilities as shown in Table 9-7. It is the probability of success of a valve closure that affects these results drastically. It also implies that even in an ideal system, low reliability of valves can lead to frequent and significant failures. Therefore, maintenance of valves is critical. The average customer outages across pipes for Tier 3 simulation are 107 and 310 for 90% and 50% probabilities of success which reflect the role of the varying number of valves and demand distribution. These results emphasize that critical pipes should have a sufficient number of valves and multiple paths from sources. The systemwide simulation results are shown in Table 9-8.

Table 9-8
Tier 3 simulation results for CWA system

		Valve reliability		Difference (%)
		90%	50%	
The number of samples		50	50	-
The confidence level		0.95	0.95	-
Mean customer out of service *	Sample mean	107	310	190%
	L. confidence interval	106	307	190%
	U. confidence interval	109	313	187%
Median customer out of service*	Sample mean	54	138	156%
	L. confidence interval	53	137	158%
	U. confidence interval	55	140	155%
90^{th} percentile customer out of service *	Sample mean	247	696	182%
	L. confidence interval	246	685	178%
	U. confidence interval	249	708	184%
95^{th} percentile customer out of service *	Sample mean	384	1222	218%
	L. confidence interval	375	1175	213%
	U. confidence interval	393	1268	223%

* All population numbers are expressed in terms of total customers affected.

9.3 Analysis Results of the city of Ottawa distribution system

The Ottawa network is the largest of the three networks included in this study. Figure 9-4 shows the network layout. It has 1,816 pipes, 1,720 valves, and 1,414 nodes. One reservoir is located on the left side of the network and one tank is placed at the mid part of the network on the right. The network shown is about one-half of the entire Ottawa water distribution system. To create the valve location matrix, intermediate valves not on pipelines and valves on laterals and hydrants are removed from the valve data file. Out of 1,720 valves on the system, 1,554 valves are placed around nodes, and 166 (= 1720-1554) valves are placed in the middle of pipes. The total number of customers in the portion of Ottawa system studied is 30,332.

A total of 1,166 segments are delineated for the Ottawa network. Among them, there are 85 node segments, i.e., 6% of nodes are fully valved. Among the remaining pipe-failure-based segments, 82 (out of 1,081) have unintended isolation. This low unintended isolation of 8% implies that the network is well looped. There are only 36 (out of 1,081) segments that have more than 4 pipes, which is 3% of the total segments. However, there are 3 large segments that have more than 50 pipes, as shown in Table 9-9.

Segment S(717) is the most critical segment in terms of the number of customers out of service as shown in Tables 9-10 and 9-11. It is interesting to note that the pipe list of S(717) has only two pipes, 654 and 682, as shown in Figure 9-5. In Figure 9-5, pipe 682 is not recognizable because it is too small to be displayed; it is located between pipes 654 and 667, which are visible. However, these two pipes are on the only path to the downstream section shown (to the left of segment S717 in Figure 9-5). The isolation of S(717) makes this large left section isolated. From the performance indicator table (Table 9-12) it is observed that the average number of pipes in a segment is 1.69 pipes per segment, close to the ideal value of 1.

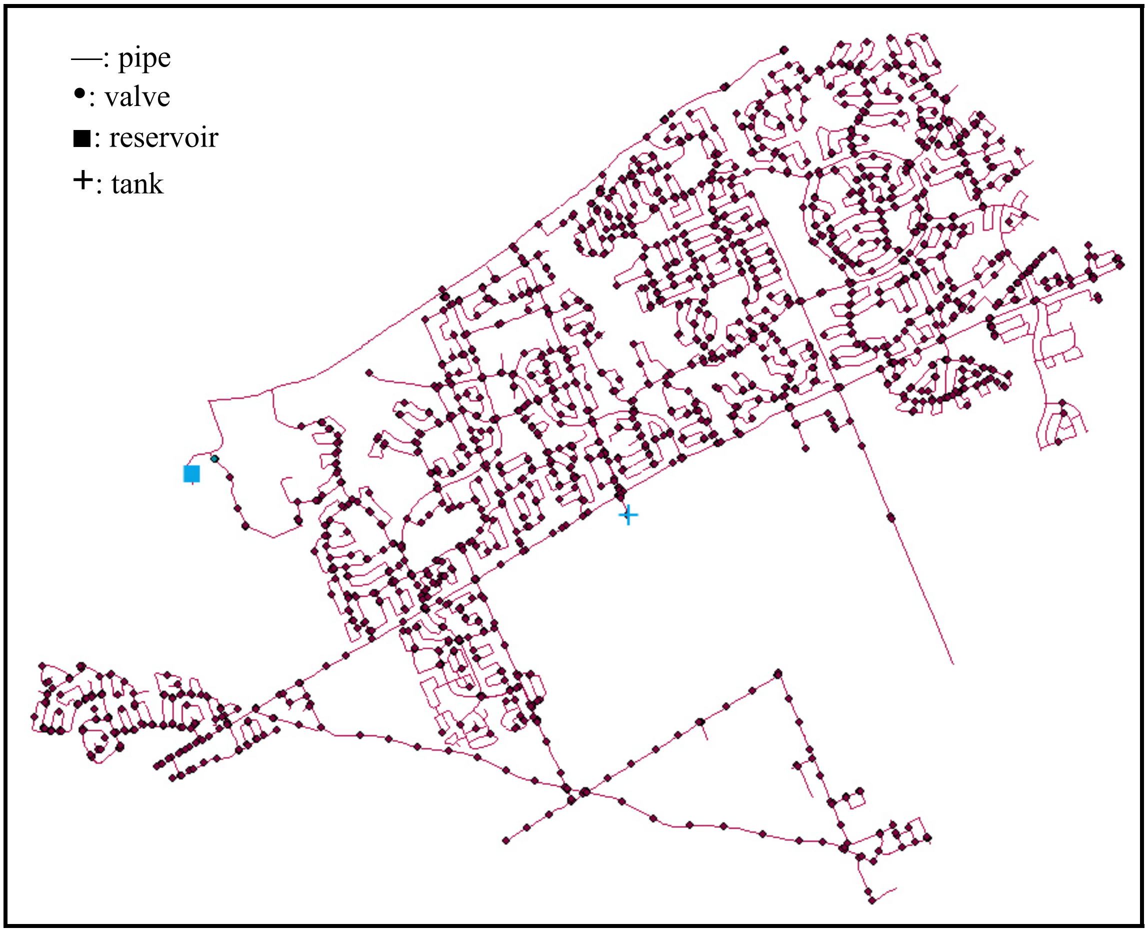


Figure 9-4 The City of Ottawa network

Table 9-9
Five segments having the largest number of pipes in the Ottawa network

Segment	Pipes	No. of pipes
S(23)	10486, 10705, 10491, 6604, 6605, 9635, 9616, 9653, 9654, 11685, 10706, 12158, 12149, 11217, 6634, 19806, 18109, 18116, 18110, 18111,	20
S(54)	11009, 11012, 11011, 11013, 11018, 17057, 14341, 14342, 14343, 17056, 14344, 14339, 14345, 14346, 11021, 14348, 14347, 17857, 17859, 15119, 17860, 17864, 17865, 17863, 17866, 17867, 17861, 17870, 17858, 17869, 15114, 17871, 17868, 17875, 17887, 17884, 17885, 17882, 17879, 17881, 17880, 17883, 17886, 17876, 17889, 17888, 17873, 17872, 17874, 17862, 15118, 15117, 14340	53
S(65)	11288, 4103, 4102, 4101, 4109, 4110, 4108, FR_SUCT_1, FR_SUCT_2, FR_SUCT_3, FR_PUMP_3, FR_DIS_3, FR_TCV_3, 21080, 5999, 6000, FR_DIS_5, FR_DIS_4, FR_TCV_1, FR_DIS_1, FR_PUMP_1, FR_TCV_2, FR_DIS_2, FR_PUMP_2, 6030, 4099, 4129, 1139, 18049, 18062, 18072, 9645, 9816, 9815, ORLEANS_SUCT_1, ORLEANS_SUCT_2, ORLEANS_SUCT_3, ORLEANS_SUCT_4, ORLEANS_PUMP_1, ORL_PS_DIS_1, ORLEANS_TCV_1, 21054, ORL_PS_DIS_7, ORL_PS_DIS_6, ORL_PS_DIS_5, ORLEANS_TCV_4, ORL_PS_DIS_4, ORLEANS_PUMP_4, ORLEANS_TCV_3, ORL_PS_DIS_3, ORLEANS_PUMP_3, ORLEANS_TCV_2, ORL_PS_DIS_2, ORLEANS_PUMP_2, 6300, 6301, 4112, 4113, 6305, 4130	60
S(78)	11904, 11905, 14551, 20867, 20866, 20864, 19508, 19507, 20865, 20870, 20868, 20869, 20871, 20885, 19315, 19317, 20874, 20873, 20876, 20884, 20722, 20721, 19797, 19798, 20883, 20877, 20878, 20872, 19318, 17504, 17501, 17499, 17500, 17508, 17507, 17513, 20881, 17502, 19319, 20194, 20181, 20183, 20182, 20184, 20185, 20186, 20879, 20882, 20875, 20880, 19799, 20723, 19316, 15138, 15139, 15142, 15146, 15153, 15143, 15144, 15148, 15141, 15145, 14798, 14799, 15150, 15147, 15155, 15149, 15154, 15151, 15152, 15140, 20064	74
S(255)	17506, 19858, 19881, 19861, 19857, 19860, 19862, 19895, 19894, 19893, 19898, 19886, 19887, 19896, 19863, 19882, 19891, 19888, 19885, 19889, 19883, 19884, 19890, 19892	24

Table 9-10
Five segments having the largest unintended isolation (Ottawa)

Segment	Pipes	No. of pipes
S(78)	15508, 15509, 15510, 15511, 15512, 15513, 15718, 16961, 17038, 17494, 17495, 17498, 17503, 17509, 17510, 17511, 17512, 17514, 17515, 17516, 17517, 17518, 17519, 17520, 19506, 20187, 20188, 20189, 20190, 20191, 20192, 20193, 20195, 20196	33
S(689)	15420, 2653, 2654, 2655, 2656, 2657, 2658, 2659, 2660, 2661, 2662, 2663, 2664, 2665, 2666, 2667, 2668, 2669, 2670, 2671, 2672, 2673, 2674, 2675, 2676, 2677, 2678, 2679, 2680, 2681, 2682, 2683, 2684, 2685, 2686, 2687, 2688, 2689, 2690, 2691, 2692, 2693, 2694, 2695, 3490, 3492, 643, 646, 647, 648	50
S(717)	11107, 11108, 11109, 11110, 11111, 11112, 12509, 1424, 1437, 1438, 18468, 18469, 18470, 18471, 18472, 18473, 18474, 18475, 18476, 18477, 18478, 18479, 18480, 18481, 18482, 18483, 18484, 20933, 3488, 3489, 4924, 4925, 4926, 4927, 4928, 4929, 4930, 4931, 4932, 4933, 4934, 4935, 4936, 4937, 4938, 4939, 4940, 4941, 4942, 4943, 4944, 4945, 4946, 4947, 4948, 4949, 4950, 4951, 4952, 4953, 4954, 4955, 4956, 4957, 4958, 6311, 635, 636, 637, 638, 639, 649, 650, 651, 652, 653, 655, 656, 658, 664, 665, 666, 669, 670, 671, 672, 673, 674, 675, 676, 677, 678, 679, 688, 689, 690, 691, 692, 694, 695, 9910	101
S(751)	11107, 11108, 11109, 11110, 11111, 11112, 1424, 1437, 1438, 18468, 18477, 18481, 18482, 18483, 4924, 4925, 4926, 4927, 4928, 4929, 4930, 4931, 4932, 4933, 4934, 4935, 4936, 4937, 4938, 4939, 4940, 4941, 4942, 4943, 4944, 4945, 4946, 4947, 4948, 4949, 4950, 4951, 4952, 4953, 4954, 4955, 4956, 4957, 4958, 6311, 669	51
S(754)	11107, 11108, 11109, 11110, 11111, 11112, 1424, 1437, 1438, 18468, 18477, 18481, 18482, 18483, 4924, 4925, 4926, 4927, 4928, 4929, 4930, 4931, 4932, 4933, 4934, 4935, 4936, 4937, 4938, 4939, 4940, 4941, 4942, 4943, 4944, 4945, 4946, 4947, 4948, 4949, 4950, 4951, 4952, 4953, 4954, 4955, 4956, 4957, 4958, 6311	50

Table 9-11
Five segments having largest number of customers (Ottawa)

Segment	Number of customers within segment	Percent	Rank
S(717)	148	0.9%	1
S(689)	99	0.6%	2
S(78)	98	0.6%	3
S(696)	89	0.5%	4
S(751)	80	0.5%	5

Note: Total number of customers: 17,389.

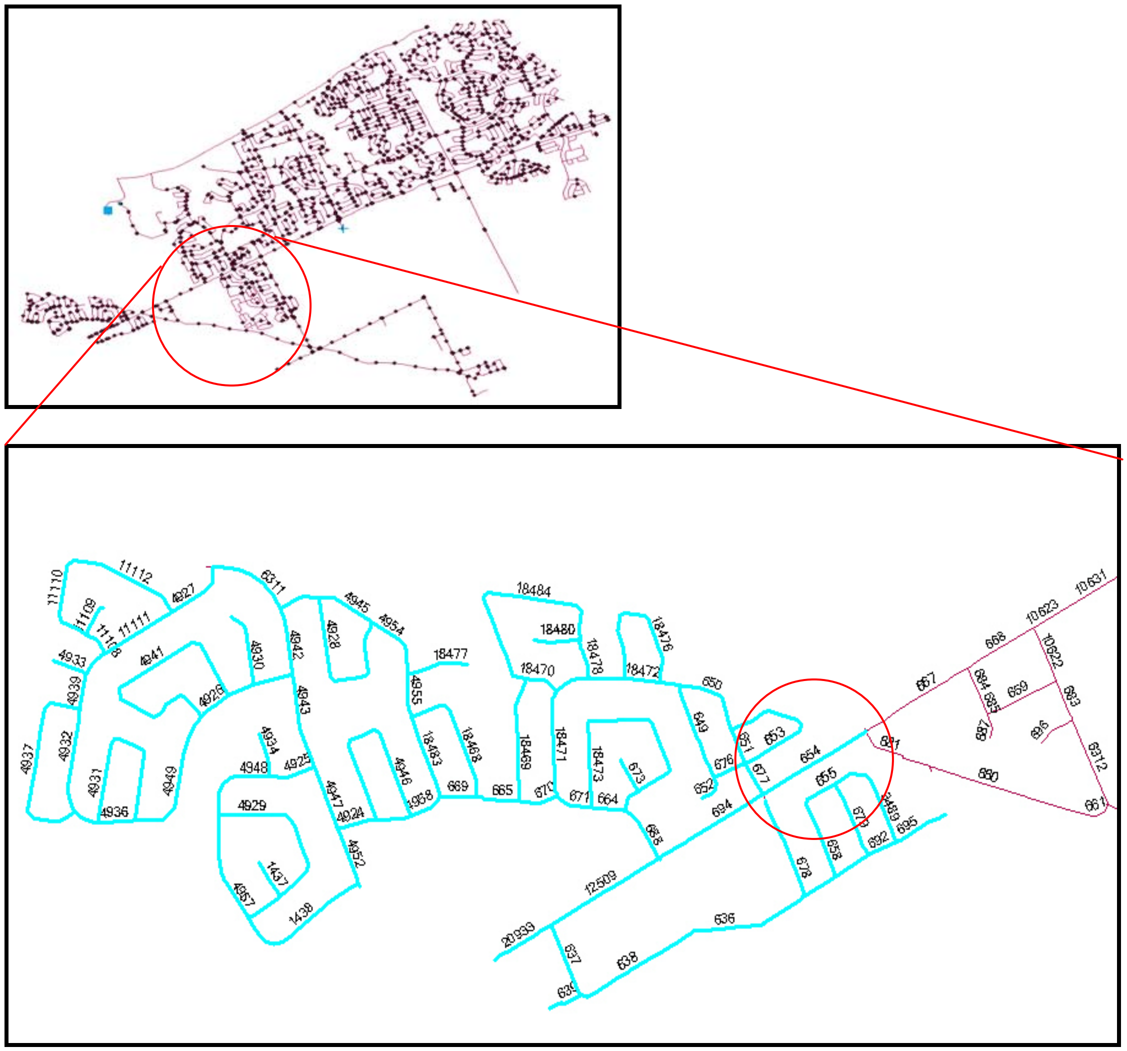


Figure 9-5 Segment S(717) and its unintended isolation

Table 9-12
Performance indicators

Performance indicators	Unit	Ottawa network	Ideal network
Average Length of Segment	length/segment	230.31 m	-
Average Number of Valves per Pipe	valve/pipe	0.85	2.00
Average Number of Valves to Be Closed to Isolate a Segment	valves/segment	2.71	2.00
Length – Valve Ratio	length/valve	160.21 m	-
Average Impact of Failure of a Valve (additional customer equivalent out of service)	customers/valve	6.93	-
Average Reliability of Isolating a Segment with 90% (0.90) valve reliability for all valves	per segment	0.76	0.81
Average Number of Pipes in a Segment	pipes/segment	1.69	1.00

9.3.1 Results of Tier 1 Valve-by-Valve simulation/Valve Importance Index

Table 9-13 shows the five critical valves having the highest VII values. The highest value is only 6.57%, or 150 customers, again substantiating a well looped layout. Figure 9-6 shows the locations of these valves. As would be anticipated, rank 1 to 4 valves are located around pipe 654.

9.3.2 Tier 2 and Tier 3 probabilistic analyses

Pipe 17505 is selected to demonstrate the results of Tier 2 simulation. Segment S(254) has the following components:

- Pipes: 17505
- No unintended isolation
- Nodes: 13188, 14450
- Valves: (13188, 15717), (13188, 17496), (14450, 17505)
- Customers: 1

If valve (14450, 17505) does not operate, the failure propagates to segment S(78), which is one of the critical segments shown in Tables 9-9, 9-10, and 9-11. For 90% probability of successful closure, there should be about 22 replications out of 30 trials in which pipe 17505 can be isolated. There are 24 such runs. For 50% probability of success, there should be a successful operation of all three valves 0.125, i.e., only about 4 replications should indicate successful closure of all 3 valves. In this simulation, there are 3 such replications.

Tier 2 simulation has an ensemble average number of customers without service of 11 for a valve reliability of 90%, and 80 for a valve reliability of 50%. These averages are very close to the systemwide simulation averages from Tier 3. A total of 1,500 Tier 3 replications were generated per sample run, and 50 such sample runs were made. The systemwide simulation results are shown in Table 9-15 and the averages are 10.6 and 40.7 for 90% and 50% valve reliabilities, respectively.

Table 9-13
Five most critical valves (Ottawa)

Valve ID	Node ID	Pipe ID	No of customers	VII	Rank
628,667	628	667	150	6.57%	1
628,681	628	681	150	6.57%	2
627,677	627	677	148	6.48%	3
627,694	627	694	148	6.48%	4
627,9910	627	9910	148	6.48%	5

Table 9-14
Tier 2 results (pipe 17505 from 30 simulations)

	Valve reliability	
	90%	50%
Average number of customers out of service per pipe 17505 failure		
Mean	11	80
Median	1	6

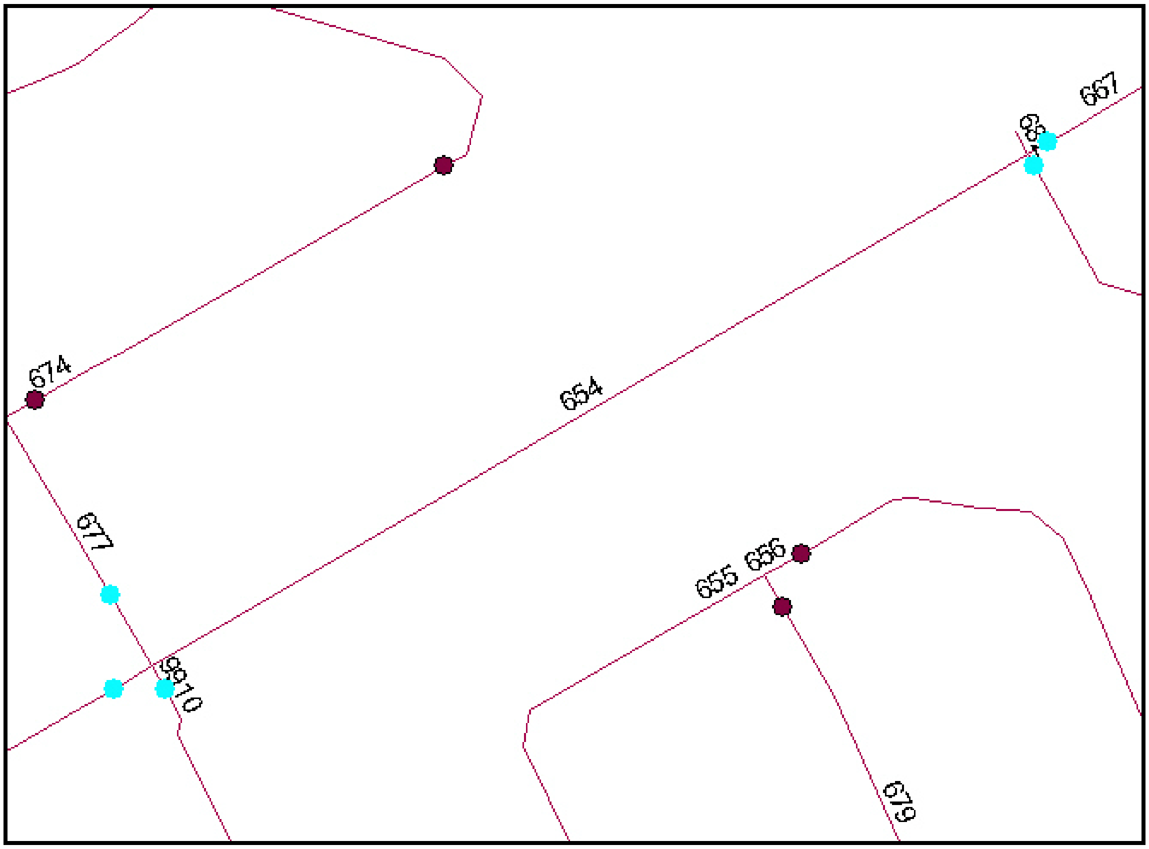


Figure 9-6 Five highest VII valves

Table 9-15
Tier 3 simulation results (Ottawa)

		Valve reliability		Difference (%)
		90%	50%	
The number of samples		50	50	-
The confidence level		0.95	0.95	-
Population mean	Sample mean	10.6	40.7	284%
	L. confidence interval	10.4	39.9	284%
	U. confidence interval	10.9	41.5	281%
Population median	Sample mean	3.0	14.6	387%
	L. confidence interval	2.9	14.3	393%
	U. confidence interval	3.1	15.0	384%
90^{th} percentile of population	Sample mean	33.2	107.2	223%
	L. confidence interval	32.3	105.2	226%
	U. confidence interval	34.0	109.1	221%
95^{th} percentile of population	Sample mean	63.2	148.5	135%
	L. confidence interval	57.8	146.0	153%
	U. confidence interval	68.8	150.9	119%

10. SUMMARY

This chapter summarizes the key findings of this dissertation.

Valves are the devices through which operational control is exercised in a water distribution system. The key issue is how to distribute valves to maximize the reliability of water distribution systems. In this research an efficient matrix analysis technique is put forward for delineating contained pipes and nodes within the set of closed valves. When such a segment delineation is carried, there may be unintended isolations elsewhere within the network. A "breadth first" matrix search scheme is offered to identify such unintended isolations.

A major drawback that has been repeatedly emphasized by the practitioners is the inability to identify or to close a valve. This inability is addressed by assigning a level of uncertainty in terms of the reliability of a valve. The matrix based segment analysis leads itself very well for tracking the growth of failure pattern resulting from progressively failing adjacent valves.

Two broader empirical valve placement schemes of (N-1)-valve and N-valve rules at junctions of N-incident pipes are evaluated in a systematic manner using probability theory. It is clear that the best protection is offered by the N-valve rule due to redundancy in the scheme.
The (N-1) valve rule that also enables containment of a failure pipe but requires more valves to do so lacks redundancy. From cost considerations a combination N and N-1 valve rules (called the mixed strategy) has been explored and the crucial recommendation is to have at least one valve on each pipe and some critical pipes to receive two valves.

From a methodology standpoint, the proposed techniques offer the following advantages regardless of valve distribution:

(1) Delineate segments containing failed pipes for a water distribution system.

(2) Track propagating failure pattern induced by progressively failing valves as they might occur in an emergency situation.

(3) Provide numerical performance measures for assessing failure impacts in terms of the number of customers out of service.

(4) Pinpoint new valve placement locations for the desired level of control.

(5) Perform all calculations in an automated, user-friendly manner with the provision to display results using a GIS technique.

(6) Utilize the industry standard EPANET freeware to perform hydraulic calculations to combine both topological and hydraulic failures. Because only matrix additions and search evaluations are involved in the calculations, even very large size networks can be easily handled.

Two kinds of matrices namely the valve deficiency matrix and segment-valve matrix can be employed in assessing failure propagation in a water distribution system. The totality of segments and valves cover the network traditionally represented by nodes and pipes. This dual nature of the same network should be fully explored as a future research topic. Both Tier 2 and Tier 3 simulations serve as powerful tools in assessing the valve reliability. The closeness of the statistics and minimum variance are employed to terminate the simulations. However, this area offers major potential for future research in terms of not only minimum number of needed simulations but also the level of looping (say in terms of the ratio of number of pipes to number of loops) can be considered to suggest the best locations for valves when budgetary constraints dominate.

Appendix 1: Introduction to valves

A-1-1 Introduction

Valves are a component to control flow and pressure for network systems in gas, oil and water industries. In the waste-water and water distribution systems, valves provide several functions to keep a network in the designed service conditions. The most important function of valves is the on-off function which is critical to repair broken components or to perform regular maintenance tasks like cleaning pipes. When a subsystem is isolated by closing valves, flow is diverted to minimize service interruption.

Valves have a long history and have been developed for various types, materials, and purposes (Skousen, 1997). A valve is made from steel, iron, plastic, bronze or other special alloys. Its weight is from about 1 lb to over 10 tons (Mead, 1986). Depending on the way to close or the closure member, there are many different types of valves designed and made for specific purposes. Today, the most widely used valves are gate, check, butterfly, globe, and pressure-reducing valves. Although many different types of valves have been developed, the basic structure or components of valves are found in most valves. As shown in Figure A-1, a valve consists of five major parts; operator, stem, packing, disk or closure member, and body. Operator is a unit to close or to open valves by manual or automatic device. In a water distribution system, since pipes are buried underground at several feet or more than 20ft, only operator can be shown where the valve is placed. Thus, stem which delivers the motion of operator to disk or closure member to be inserted is long enough to reach the body of valves. Packing made from rubber or other materials prevents leakage of fluid. There are several types of closure members such as ball or plate. Body confines a closure member and connects in and out pipes using end connection.

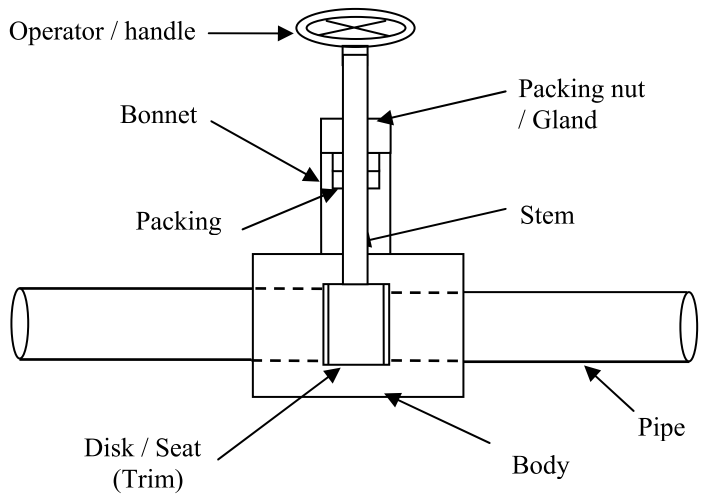


Figure A-1 Basic valve elements

A-1-2 The classifications of valves

Valves can be categorized by various ways. First, it can be classified by the operating method; manual or automatic operation. Most on-off valves are operated manually and pressure-reducing valves are automatically operated. The meaning of "by-manual" is that an operator determines when valves are opened and closed. However, in terms of how to operate a valve, some manual valves are operated by a powered gear or other mechanical devices. Electric, pneumatic, and hydraulic devices are used to close or open a valve.

Another criterion used to classify valves is the structure of a closure member and how it works such as disk, ball, globe and so on. In general, however, valves can be categorized by operating purposes (Hammer et al, 2001). We classify the operating purposes of valves in four major categories; on-off, check, throttling, and pressure-reducing. Using the operating purposes to classify valves, it may be confusing when a valve with specific body design can be used for a few purposes (Skousen, 1997). For example, a butterfly valve can throttle flow rate and / or can close flow if the surface of the disk is faced against flow direction perpendicularly. Thus, it is important to understand the structure of a valve and how it can be used for a specific purpose.

On-off valves are most widely used in a water distribution system. As mentioned above, subsystem isolation is done by closing valves. Basically, a water distribution system can be sectioned by locations of on-off valves. Properly sectioned water distribution system can minimize service default when a component failure occurs and maintenance tasks are performed. Gate valves are commonly used but rotary butterfly valves may be used when large diameter pipes are required to be isolated (Skousen, 1997).

Check valves allow water to flow in only one direction. If the direction of flow changes, it is automatically closed to prevent backflow. Check valve is generally installed in the discharge pipe of a pump so it prevents backflow after the pump stops (Mead, 1986). Lift type and swing type of check valves are abundant but diaphragm valves are installed for this purpose, too (Zappe, 1991).

Throttling valves regulate the flow. To obtain this function, the closure member can be moved to any position and kept at the position including fully open and close so that throttling valve can do on-off function. It is butterfly and globe valves that are widely used as throttling valves.

Pressure-reducing valves control the pressure difference from inlet to outlet of a valve so that they are able to maintain outlet pressure which is designed. Pressure-reducing valves are generally installed at a connecting point where branch pipes are connected to a main pipe so it is required to reduce high pressure in the main pipe to lower designed pressure in branch pipes (Hammer et al, 2001).

A-1-3 Valves in water distribution system

For a water distribution system, valves are installed on pipes to make sections, around pump stations to prevent backflow or reverse flow and around storages such as reservoirs and tanks to control flow into and out. The on-off function is the most important function for a water distribution system. According to the KIWA report (AWWARF and KIWA, 2001), isolation or sectioning which is obtained by the on-off function takes 87% of the purposes of valves used in a water distribution system. The dominant valve type is the gate valve which accounts for 96%. Butterfly valves take 1% and other types 3%. The KIWA report shows more than 99% of valves are installed to on-off and less than 1% of valves are used for throttling and preventing backflow. Therefore, most of valves in a water distribution system are installed for isolation and sectioning of a pipe network.

Appendix 2: Artificial Node Simulation

A-2-1 Sample network structure and five simulation scenarios

Based on the sample network, several scenarios were simulated to estimate flow condition changes. Two artificial nods were added into the existing network. First, A1(artificial node 1) is put between node 2 and node 3 which means pipe 2 is divided into two parts (N1 and N2 pipes). Second A2 is put between node 7 and node 9 so that pipe 12 is divided into two parts (N3 and N5 pipes). Except A1 and A2, other nodes have base demand and the flow is provided by the reservoir.

The tested scenarios are

1. No closed pipe so the normal flow condition will be simulated.
2. Close pipe N1 yet open pipe N2, which means a half of pipe 2 is closed.
3. Close pipe N2 yet open pipe N1, the same network condition of scenario 2.
4. Open pipe N1 and pipe N2 and close pipe N3 so that the part of pipe 12 is closed.
5. Add 1 GPM base flow to A2. With this simulation, we can see what happens when a part of pipe 12 is closed but if A2 has base flow (of course in this case, A2 is no longer an artificial node)

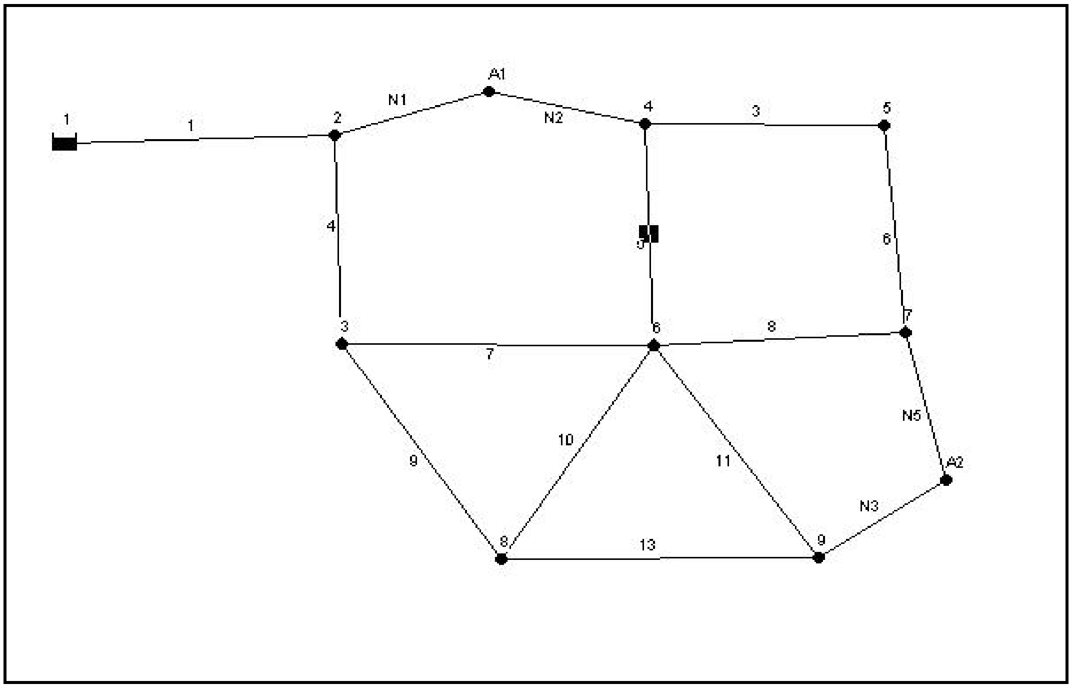


Figure A-2 Sample network diagram

Link ID	Flow GPM	Velocity fps	Unit Headloss ft/Kft	Friction Factor	Reaction Rate mg/L/d	Quality	Status
Pipe 3	-305.31	0.22	0.01	0.040	0.00	0.00	Open
Pipe 4	-244.12	0.17	0.01	0.050	0.00	0.00	Open
Pipe 5	250.57	0.18	0.01	0.048	0.00	0.00	Open
Pipe 6	250.31	0.18	0.01	0.048	0.00	0.00	Open
Pipe 8	39.55	0.11	0.01	0.050	0.00	0.00	Open
Pipe 10	-34.24	0.10	0.01	0.044	0.00	0.00	Open
Pipe 11	51.19	0.15	0.02	0.050	0.00	0.00	Open
Pipe 7	74.41	0.21	0.03	0.049	0.00	0.00	Open
Pipe 9	91.71	0.26	0.05	0.046	0.00	0.00	Open
Pipe 13	5.95	0.07	0.01	0.069	0.00	0.00	Open
Pipe N1	655.88	0.47	0.08	0.047	0.00	0.00	Open
Pipe N2	655.88	0.47	0.06	0.035	0.00	0.00	Open
Pipe N3	10.15	0.03	0.00	0.000	0.00	0.00	Open
Pipe N5	-10.15	0.03	0.00	0.000	0.00	0.00	Open
Pipe 1	950.00	0.17	0.00	0.035	0.00	0.00	Open

Figure A-3 Simulation results of Scenario 1

As shown above, normal flow condition is established and all pipes have flow.

Link ID	Flow GPM	Velocity fps	Unit Headloss ft/Kft	Friction Factor	Reaction Rate mg/L/d	Quality	Status
Pipe 3	-203.25	0.14	0.01	0.061	0.00	0.00	Open
Pipe 4	-900.01	0.64	0.12	0.037	0.00	0.00	Open
Pipe 5	-303.25	0.22	0.02	0.044	0.00	0.00	Open
Pipe 6	148.25	0.11	0.00	0.046	0.00	0.00	Open
Pipe 8	79.07	0.22	0.04	0.050	0.00	0.00	Open
Pipe 10	243.90	0.69	0.30	0.040	0.00	0.00	Open
Pipe 11	83.09	0.24	0.04	0.050	0.00	0.00	Open
Pipe 7	421.51	1.20	0.83	0.037	0.00	0.00	Open
Pipe 9	400.50	1.14	0.76	0.038	0.00	0.00	Open
Pipe 13	36.60	0.42	0.26	0.049	0.00	0.00	Open
Pipe N1	0.00	0.00	0.00	0.000	0.00	0.00	Closed
Pipe N2	0.00	0.00	0.00	0.000	0.00	0.00	Open
Pipe N3	72.69	0.21	0.03	0.049	0.00	0.00	Open
Pipe N5	-72.69	0.21	0.03	0.049	0.00	0.00	Open
Pipe 1	950.01	0.17	0.00	0.035	0.00	0.00	Open

Figure A-4 Simulation results of Scenario 2

No flow is in the pipe N1 and pipe N2 when pipe N1 is closed. With the closure of pipe N1, there is no flow in pipe N2 when the status of pipe N2 is “Open”. The reasons are

- First, water cannot flow through pipe N1 since it is closed.
- Second, there is no actual demand at node A1 so that no hydraulic condition is established between node A1 and node 4.

Link ID	Flow GPM	Velocity fps	Unit Headloss ft/Kft	Friction Factor	Reaction Rate mg/L/d	Quality	Status
Pipe 3	-203.25	0.14	0.01	0.061	0.00	0.00	Open
Pipe 4	-900.00	0.64	0.12	0.037	0.00	0.00	Open
Pipe 5	-303.25	0.22	0.02	0.044	0.00	0.00	Open
Pipe 6	148.25	0.11	0.00	0.046	0.00	0.00	Open
Pipe 8	79.07	0.22	0.04	0.050	0.00	0.00	Open
Pipe 10	243.89	0.69	0.30	0.040	0.00	0.00	Open
Pipe 11	83.09	0.24	0.04	0.050	0.00	0.00	Open
Pipe 7	421.51	1.20	0.83	0.037	0.00	0.00	Open
Pipe 9	400.49	1.14	0.76	0.038	0.00	0.00	Open
Pipe 13	36.60	0.42	0.26	0.049	0.00	0.00	Open
Pipe N1	0.00	0.00	0.00	0.000	0.00	0.00	Open
Pipe N2	0.00	0.00	0.00	0.000	0.00	0.00	Closed
Pipe N3	72.69	0.21	0.03	0.049	0.00	0.00	Open
Pipe N5	-72.69	0.21	0.03	0.049	0.00	0.00	Open
Pipe 1	950.01	0.17	0.00	0.035	0.00	0.00	Open

Figure A-5 Simulation results of Scenario 3

As shown above, the same result is obtained when pipe N2 is close instead. By the same reasons in scenario 2, no flow is in both pipes N1 and N2. From the results of scenario 2 and 3, it can be said that closing any pipe emanating from an artificial node with zero demand results in no flow in both pipes. Thus, both pipes emanating from an artificial node can be thought as a single pipe when we simulate the hydraulic condition.

Link ID	Flow GPM	Velocity fps	Unit Headloss ft/Kft	Friction Factor	Reaction Rate mg/L/d	Quality	Status
Pipe 3	-311.69	0.22	0.01	0.039	0.00	0.00	Open
Pipe 4	-242.57	0.17	0.01	0.051	0.00	0.00	Open
Pipe 5	245.74	0.17	0.01	0.041	0.00	0.00	Open
Pipe 6	256.69	0.18	0.01	0.046	0.00	0.00	Open
Pipe 8	43.32	0.12	0.01	0.056	0.00	0.00	Open
Pipe 10	-33.54	0.10	0.01	0.093	0.00	0.00	Open
Pipe 11	42.68	0.12	0.02	0.071	0.00	0.00	Open
Pipe 7	73.79	0.21	0.03	0.043	0.00	0.00	Open
Pipe 9	90.78	0.26	0.05	0.047	0.00	0.00	Open
Pipe 13	4.32	0.05	0.00	0.066	0.00	0.00	Open
Pipe N1	657.43	0.47	0.08	0.046	0.00	0.00	Open
Pipe N2	657.43	0.47	0.06	0.035	0.00	0.00	Open
Pipe N3	0.00	0.00	0.00	0.000	0.00	0.00	Closed
Pipe N5	0.00	0.00	0.00	0.000	0.00	0.00	Open
Pipe 1	950.00	0.17	0.00	0.035	0.00	0.00	Open

Figure A-6 Simulation results of Scenario 4

The same flow condition obtained in scenarios 2 and 3 is obtained again when pipe N3 is closed. Although pipe N3 is located at different location of the network, it generates the same flow condition of scenarios 2 and 3.

Link ID	Flow GPM	Velocity fps	Unit Headloss ft/Kft	Friction Factor	Reaction Rate mg/L/d	Quality	Status
Pipe 3	-312.43	0.22	0.01	0.038	0.00	0.00	Open
Pipe 4	-242.72	0.17	0.01	0.051	0.00	0.00	Open
Pipe 5	245.85	0.17	0.01	0.041	0.00	0.00	Open
Pipe 6	257.43	0.18	0.01	0.045	0.00	0.00	Open
Pipe 8	43.57	0.12	0.01	0.055	0.00	0.00	Open
Pipe 10	-33.48	0.09	0.01	0.093	0.00	0.00	Open
Pipe 11	42.68	0.12	0.02	0.072	0.00	0.00	Open
Pipe 7	73.88	0.21	0.03	0.043	0.00	0.00	Open
Pipe 9	90.84	0.26	0.05	0.047	0.00	0.00	Open
Pipe 13	4.32	0.05	0.00	0.065	0.00	0.00	Open
Pipe N1	658.28	0.47	0.08	0.046	0.00	0.00	Open
Pipe N2	658.28	0.47	0.06	0.035	0.00	0.00	Open
Pipe N3	0.00	0.00	0.00	0.000	0.00	0.00	Closed
Pipe N5	1.00	0.00	0.00	0.000	0.00	0.00	Open
Pipe 1	951.00	0.17	0.00	0.035	0.00	0.00	Open

Figure A-7 Simulation results of Scenario 5

In Scenario 5, node A2 is assigned 1 gpm (gallon per minute) base demand. We consider 1 gpm as small amount of base demand for a demand node. With 1 gpm base demand of A2, pipe N5 has flow when pipe N3 is closed. Therefore, if an artificial node has base demand, the flow condition will be different depending on a closed pipe which is one of two pipes emanating from the artificial node is closed. Also, it is obvious that both pipes should be considered individually.

A-2-2 Conclusions of the artificial node simulation

In reality, intermediate valves are usually introduced on long pipes and it does not fit our assumption, that is, only two valves can be placed on each end of a pipe. However, we introduce the artificial node with a positive demand for the intermediate valve if a positive demand can be assigned to the intermediate valve. With the artificial node with a positive demand, intermediate valves can be successfully represented and become fit for the assumption. If no positive demand is assigned to an artificial node (intermediate valve), two pipes emanating from the intermediate valve act as if they are a single pipe from the view point of the hydraulic analysis. In other words, in case of one of the pipes is closed and no positive demand at the artificial node, closing any one of both pipes produces no flow in the other side pipe. It is the same flow condition that is established when both pipes are closed.

Appendix 3: Summary of Literature Review

Reference	Area	Abstract
Billinton and Allan (1983)	Reliability/Minimal Cut Sets	Provide a definition of the minimal cut set.
Su et al. (1987)	Reliability/Minimal Cut Sets	Provide a clear methodology for addressing pipe failures in terms of minimal cut sets.
Shea (1990)	Valve in WDS	Report the Boston Water and Sewer Commission's valve program.
Bouchart and Goulter (1991)	Valve in WDS	Present a model to select a set of valve locations to minimize the demand of volume deficit.
Walski (1993)	Segment	Suggests a segment and the segment-valve diagram.
Jowitt el al. (1993)	Reliability	Under the abnormal condition, pipe failure consequences are predicted in terms of the number of demand nodes which don't have sufficient water flow with adequate hydraulic pressure head.
Deb et al. (1995)	Performance Indicators	Develope a methodology to quantify the performance of WDS.
Coelho (1995)	Performance Indicators	Provide four main categories for the performance of WDS: assessment frame work, hydraulic performance, water quality performance, and reliability performance.
Khomsi et al. (1996)	Reliability	A comprehensive review of issues involved in reliability analysis.
Hoff (1996)	General Valve	Addresses practical considerations related to valve maintenance, selection, storage, and installation.
Mays (1996)	Reliability	A comprehensive review of the water distribution reliability.
Yang et al. (1996)	Reliability/Minimal Cut Sets	Using the minimal cut set, the mechanical reliability is estimated.

Reference	Area	Abstract
Whittaker (1997)	General Valve	Describes potential problems in identifying, selecting, operating, monitoring, and record keeping of valves.
Skousen (1997)	General Valve	A comprehensive reference on valve selection, type, and sizing. It also addresses the various problems associated with valves and costing.
Jones and Tenera (1998)	Valve in the power plant industry	State that a comprehensive valve practice includes design practice as well as maintenance.
Goulter et al. (2000)	Reliability	A comprehensive review of issues involved in reliability analysis including valve location analysis.
Ysusi (2000)	Valve in WDS	A comprehensive reference on valves in WDS. Also, the practical valving rules, N- and (N-1) rules are addressed.
Kovan (2000)	Valve in the power plant industry	Reports a valve maintenance practice adopted by Siemens one of the largest service providers for the nuclear power plant industry.
Hammer and Hammer (2001)	General Valve	Details on the valves in general.
Monteiro (2001)	Performance Indicators	Report their recent case study performed in Portugal to apply performance indicators to water distribution systems.
Karjalainen (2001)	Valve in the power plant industry	States that valve maintenance and exercising programs should be carried out for assuring operability of emergency valves.
AWWARF and KIWA (2001)	Valve in WDS	Report common valve problems and solutions. Problem prevention strategies are also given.
Walski (2002)	Segment/Simulation	Based on segments, a fire flow simulation is modeled.
Ozger and Mays (2004)	General Valve	Recommend a rule of thumb to place valves and an issue involved in finding optimal valve locations.

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