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Identifying Pipes and Valves of High Importance for Efficient Operation and Maintenance of Water Distribution Systems

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Abstract Failure of a pipe or valve in a water distribution system causes service disruption and other inconveniences to the customers at or downstream of the failure location. To minimize the impact of such a pipe or valve failure, it is crucial to identify those pipes or valves whose failure will have the most severe consequences in degrading the performance of the system relative to that of other pipes or valves. In this paper, we develop two failure analysis methodologies, Pipe-by-Pipe and Valve-by-Valve, to prioritize the importance of pipes and valves in a water distribution system. The relative importance of individual pipes and valves is evaluated according to the number of customers who are forced out of service as a consequence of a pipe or valve failure. The methodologies are based on a segment-finding algorithm which defines a series of isolated pipes in the case of pipe or valve failure. A procedure based on the Breadth First Search is also developed to find sections of pipes that are unintentionally isolated in the isolation procedure for failed pipes. The number of unintentionally isolated customers is included in the Pipe-by-Pipe and Valve-by-Valve analyses in order to incorporate this negative effect of unintended isolation of pipes. The methodologies are applied to a case study of a water distribution system for which the most important pipe and valve are identified. The results are analyzed to form a guideline for improving the system reliability. The proposed methodologies were found to be a valuable tool for ensuring efficient operation and developing appropriate maintenance strategies, and thereby for improving the reliability of many water distribution systems.

Keywords Water distribution system · Vulnerability analysis · Simulation · Pipe failure · Valve failure

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1 Introduction

Most cities face deterioration of their water distribution systems with component failures not being a rare event. When a component such as a pipe or joint fails, it should be isolated from the rest of the system for repair or replacement. Since many utilities experience this inconvenience frequently, it is necessary to carry out on-going maintenance to reduce the impact of a component failure. To establish an efficient maintenance program, the system components whose failure causes greater impact than others should be identified. Because of limited resources for maintenance, the budgets should be allocated to the most vulnerable system components which could incur large losses such as the number of customers forced out of service.

The first step in establishing an effective maintenance program is to understand the failure consequences when a failure occurs. In a water distribution system, pipes and joints are the two most frequently failing components. Since a joint is considered as a part of a pipe, hereafter, pipe failure will imply a pipe itself or a joint failure. When a pipe failure occurs, it should be isolated from the water distribution system for repair. Isolation of the broken pipe is possible only after adjacent valves are closed. Therefore, a pipe failure and its adjacent valves cannot be considered separately. The locations and number of adjacent valves determine the range of pipe failure impact. Thus, Walski (1993a,b) suggests that the concept of "Segment," which is the portion of the network that can be isolated by closing adjacent valves, can be used to determine the range of a pipe failure. Such a segment is composed of only the broken pipe itself when the broken pipe has two valves at its ends. If it doesn't, then adjacent pipes of the broken one must be isolated by closing more valves. In this case, the whole isolated sections of pipes can be considered as a single segment. With the concept of segment, the pipe failure impact can be properly estimated. However, most of previous studies investigating pipe failure have assumed that a broken pipe is the only impacted area in a water distribution system (Su et al. 1987; Jowitt and Xu 1993).

Estimation of the pipe failure impact along with its adjacent valves (unless the pipe is supplying only one point, in which case no analysis is needed as there is only one, or one set of, affected customer, then there will always be a minimum of two valves) is associated with the reliability analysis for a water distribution system. Goulter et al. (2000) provided a detailed review of the reliability analysis for water distribution systems, including valve location analysis. Bouchart and Goulter (1991) presented a model to select a set of valve locations to minimize the demand volume deficit. Regarding the role of valves in a water distribution system, Hoff (1996) addressed the practical considerations related to valve maintenance, selection, storage, and installation. Whittaker and Arscott (1997) described potential problems in identifying, selecting, operating, monitoring, and record keeping of valves. Skousen (1997) provided a comprehensive reference on valve selection, type, and sizing, and also addressed the various problems associated with valves and costing. Another effort to utilize valves to improve the reliability of the water distribution system is to minimize water losses by optimizing valve locations to control pressure (Jowitt and Xu 1990; Araujo et al. 2006).

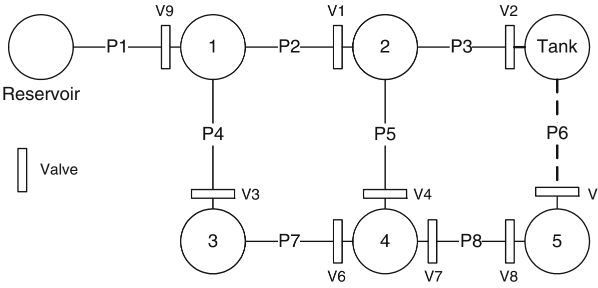
To analyze a pipe failure impact for the entire water distribution network, it is necessary to determine the failure impact of each segment or pipe in order to identify the more important segments. Then, an efficient maintenance program can be established based on the analysis. When a pipe fails, depending on adjacent valve locations, a large portion of the system might have to be isolated if an insufficient number of valves were installed or if the valves are sparsely distributed. To evaluate the relative importance of each pipe and its corresponding segment, all possible segments in the entire system should be identified. Identifying all segments for a large and complicated water distribution system, however, is exceedingly time consuming and may not be possible in some occasions without a systematical methodology.

Therefore, utilities need an efficient methodology to identify all segments in complicated systems. In this respect, Jun (2005) suggests a matrix-based, segment-identifying algorithm which can easily identify a segment caused by a pipe failure. In this paper we expand on the matrix-based algorithm of Jun (2005) to develop a methodology capable of identifying all possible segments in a water distribution system corresponding to each pipe or valve failure. The methodology may be considered a deterministic pipe failure analysis and is termed Pipe-by-Pipe Failure Analysis (PPFA) in this paper.

Valves also play a critical role in the event of a pipe failure. A pipe failure impact is successfully confined within the broken pipe only when all adjacent valves work properly. In other words, the reliability of each adjacent valve should be 100% to confine the pipe failure impact within the broken pipe. However, previous reports have indicated that the reliability of valves in real water distribution systems is typically less than 100%. KIWA and AWWARF (2001) reported that about 4% of on–off valves were malfunctioning. The Boston Water and Sewer Commission (Shea 1991) reported a valve reliability of 95.8% with 120 out 2,800 (=4.3%) inoperable valves . They also reported a large number of valves with packing leaks which further reduced the valve reliability rate. Based on those studies, it is clear that it may not be possible to isolate a segment successfully, especially, when more than four adjacent valves need to be closed. In case of closing four adjacent valves, the reliability of isolating a segment with 95% valve reliability is $(0.95)^4=0.0.8145$, giving a nearly 20% chance that a segment may not be isolated. Thus, the possibility of valve failures cannot be ignored for successful PPFA.

When a pipe fails, crews will try to close all valves around the broken pipe. If crews are unable to close one or any of the valves, the adjacent segment, which is supposedly separated by the malfunctioning valve, will be merged to the original segment resulting in the growth of the size of segment. Furthermore, to isolate the merged segment from the rest of the system, all valves which are located around the merged segment, should be closed. If one or any of these valves is malfunctioning too, then the next segment, which is separated by the malfunctioning valve, will be merged to the currently merged segment. In the worst case scenario, multiple segments may have to be merged to the original segment simultaneously, leading to the merging of a large section of the network. However, the probabilities of multiple or sequential valve failures are too low to be considered for practical purposes. In most cases, it is a reasonable assumption that only one valve among the adjacent valves can fail. Therefore, this suggests a deterministic approach to valve failure analysis. In deterministic valve failure analysis, which is termed Valve-by-Valve Failure Analysis (VVFA) in this paper, each valve is sequentially assumed to be malfunctioning one at a time while all others are functioning. Then, the failure impact of a selected valve is quantified as the number of customers affected by the loss of service. After the selected valve failure impact is quantified, the next valve is assumed to be failed

Fig. 1 Sample network



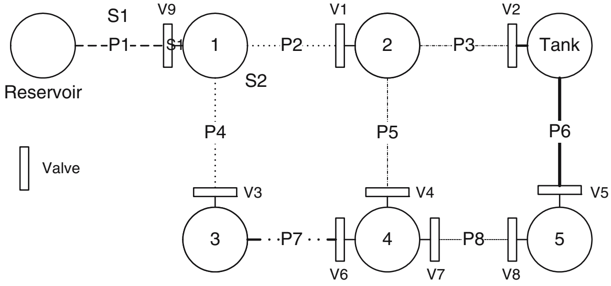


Fig. 2 Segment delineation

and its failure impact is quantified. This procedure is continued until all of the valves have been considered.

In VVFA, the relative importance of each valve is quantified by the number of customers out of service due to a valve failure. As a result, the valves of greater importance can be identified and therefore receive greater maintenance attention in line with a more efficient valve maintenance program.

2 Illustration of Pipe Failure Impact

To illustrate the segment approach to analyzing the component failure impact in a water distribution system, it is useful to show how a segment is created when a pipe failure occurs. Figure 1 presents a network consisting of seven nodes, numbered 1 through 5 and two water sources, a reservoir and a tank, eight pipes denoted by P_i, where i=1, 2, ..., 8, and 9 valves denoted by V_j, where j=1, 2, ..., 9. Figure 2 shows the segments of the network in Fig. 1. When pipe P2 fails, segment S2 made up of pipes P2 and P4 must be isolated to conduct repairs on P2. Because pipe P8 has two valves, segment S5 is just pipe P8.

Strictly following the definition of segment, a segment without a pipe is possible. A segment consisting only of a node without any pipe is created by closing all of the valves around it. These segments are referred as “Node Segments.” In Fig. 1, nodes 4 and 5 become the Node Segments of the sample network by closing V4, V6, and V7 for node 4 and V5 and V8 for node 5. Node Segments, however, do not incur any pipe failure impact

Table 1 Number of customers for each segment of the sample network

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

Total number of customers=360

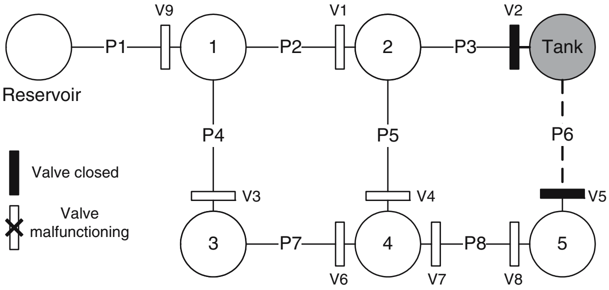


Fig. 3 Case 1: V2 and V5 operating and segment S6 isolated

since these segments lack any pipes. For this reason, in this paper, only segments having at least one pipe are analyzed and discussed.

Assessing the pipe failure impact relies on identifying the pipes and nodes belonging to a segment and on estimating their working condition status. The matrix-based algorithm suggested by Jun (2005) is used for identifying a segment. The algorithm can identify pipes and nodes along with adjacent valves associated with a segment. For the sample network in Fig. 1, eight segments are found by the matrix-based algorithm, as shown in Fig. 2. Once pipes within a segment are identified, the number of customers within a segment is considered as the pipe failure impact. Usually, customers are distributed along pipes so that the number of customers is easily obtained from a GIS(Geographic Information System) or other database maintained by utilities. For the sample network, we assume the number of customers for each pipe. Table 1 shows the number of affected customers for each pipe, and the number of customers for each segment is obtained as the sum of the customers belonging to the respective pipes for that segment.

3 Illustration of Valve Failure Impact

The same sample network in Fig. 1 is used to explain the valve failure impact. Similar to the quantification of the pipe failure impact, the number of customers out of service is used to quantify the valve failure impact.

The isolation of segment S6, consisting of the Tank node and pipe P6, is used as an example. Two valves, V2 and V5, must be closed to isolate segment S6, as shown in Fig. 3. If valve V5 operates but V2 does not, two more valves, V1 and V4, should be closed to isolate the broken pipe, as shown in Fig. 4. Because valves V1 and V4 belong to segment S4, segment S4 will be isolated along with segment S6. In the case that valve V2 operates

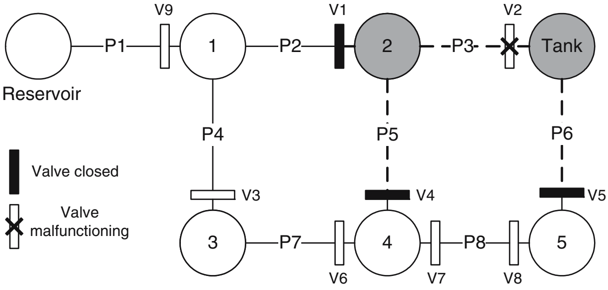


Fig. 4 Case 2: V2 not operating and segments S4 and S6 isolated

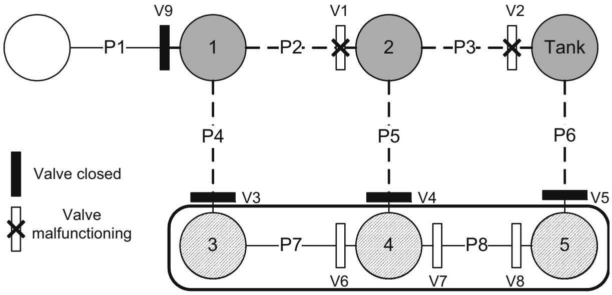


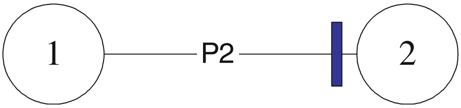
Fig. 5 Case 3: V2 and V1 malfunctioning and segments S2, S4, and S6 isolated

properly, only segment S6 is isolated and S4 remains in service, as shown in Fig. 3. Due to a failure of valve V2, 80 customers in segment S4 are additionally forced out of service. Therefore, the failures of pipe P6 and valve V2 put 140 customers (= 60+80) out of service.

This procedure can be expanded. Now, the currently isolated segments are S4 and S6, and if V4 operates but V1 does not, two valves of segment S2, V9 and V3, should be closed as shown in Fig. 5. In this case, because of S6, V2, and V1 failures, 200 customers (= 60+80+60) are forced out of service. It is noticeable that by closing the valves V1, V3, V4, V5, and V9, the pipes P7 and P8, which are shown in the rectangle in Fig. 5, are disconnected from the two water sources. Therefore, it is observed that even if Pipes P7 and P8 are not a part of those merged segments consisting of S2, S4, and S6, the customers within pipes P7 and P8 are unexpectedly forced out of service. Since the pipe failure impact is quantified as the number of customers out of service, customers within the pipes P7 and P8 should be included in the assessment of the failure of P6, V1 and V2. An area in a pipe network which is unexpectedly disconnected from the water source(s) due to isolation of a segment is termed "Unintended Isolation" in this paper, and a detailed explanation of this event is presented in later sections of this paper.

4 Segment-finding Algorithm

The suggested failure analyses explained later use the segment-finding algorithm suggested by Jun (2005), which is used to identify a segment resulting from a pipe failure. The algorithm is performed on three matrices, namely, Node-Arc Matrix, Valve Location Matrix, and Valve Deficiency Matrix. The matrices have the same structure in which the row represents each node and the column represents each pipe. The cells of the matrices contain either "1" or "0." Node-Arc Matrix contains network topology information so that, if a node is connected to a pipe, a cell corresponding to the row of the node and the column of the pipe has a "1." If not, it contains a "0." In the Valve Location Matrix, a "1" is stored when a valve is placed on a pipe and next to a node. A "1" stored in the valve deficiency matrix means that there is no valve placed on a pipe and next to a node. The following example explains the structure of the matrices.



Node-Arc Matrix

Node	Pipe
	P2
1	1
2	1

Valve Location Matrix

Node	Pipe
	P2
1	0
2	1

Valve Deficiency Matrix

Node	Pipe
	P2
1	1
2	0

Once the matrices are established, the segment-finding algorithm is performed on the Valve Deficiency Matrix to identify the nodes and pipes within a segment. It is a searching algorithm to search for "1"s in the Valve Deficiency Matrix starting at the column of a pipe which fails. The following example (Table 2) shows how the algorithm searches for "1"s in the Valve Deficiency Matrix. Table 2 is the Valve Deficiency Matrix of the sample network in Fig. 1 and the algorithm searches for "1"s to identify segment S4 which is to be closed in case of failure of P3. Because pipe P3 fails, it starts the P3 column to find a "1." A "1" is found at the N2 row and then it searches for "1"s in the N2 row. A "1" is found at the P5 column. Then, it searches for "1"s in the P5 column but no more "1" is found in the column. Thus, the algorithm stops at this point and segment S4 is identified: two pipes {P3, P5} and one node {N2}.

5 The Definition and Developed Algorithm for Unintended Isolation

As briefly explained earlier, when isolation of a segment is considered there may be other parts of the network, in addition to the segment that is isolated intentionally, that are

Table 2 C matrix of the sample network and an example for identifying a segment

	P1	P2	P3	P4	P5	P6	P7	P8
Reservoir	1	0	0	0	0	0	0	0
1	0	1	0	1	0	0	0	0
2	0	0	1	0	1	0	0	0
Tank	0	0	0	0	0	1	0	0
3	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0

Table 3 Node–Node adjacent matrix of the sample network

Node	Node						
	Reservoir	1	2	Tank	3	4	5
Reservoir	0	1	0	0	0	0	0
1	1	0	1	0	1	0	0
2	0	1	0	1	0	1	0
Tank	0	0	1	0	0	0	1
3	0	1	0	0	0	1	0
4	0	0	1	0	1	0	1
5	0	0	0	1	0	1	0

unexpectedly disconnected from the sources. For example, in Fig. 5, the section within the black rectangular is an unintended isolation. Due to the isolation of S2, S4 and S6, the four segments, S3, S5, S7 and S8 do not have a path from the two water sources, the Reservoir and Tank. Since customers within the unintended isolation do not have water supply, they must also be counted as customers affected by the pipe failure. The unintended isolation occurs only after isolation of a segment is completed.

Since the number of customers out of service resulting from an unintended isolation may be more than the one from an intended isolation, a corresponding unintended isolation should be identified for each segment. Based on the Breadth-First search algorithm, an algorithm identifying an unintended isolation is developed. It is operated on a Node–Node Adjacent Matrix. Table 3 shows the Node–Node Adjacent Matrix of the sample network. A "1" or "0" in a cell of the matrix indicates that two nodes are or are not linked, respectively. Before the algorithm is performed, the nodes and pipes within a segment should be identified since isolation of those nodes and pipes change the current network topology. For example, pipes within a segment become disconnected links. Reflecting those disconnected links on the Node–Node Adjacent Matrix, "1"s representing the disconnected links are replaced with "0"s in the matrix. Then, the Breadth-First search algorithm is performed, beginning with water sources. In Tables 4 and 5, the updated node–node adjacent matrix is shown when

Table 4 Updated node–node matrix when segments S4, S5, and S6 are isolated and the Unintended isolation search procedure from the Reservoir

Search Order	Node Node	Reservoir	1	2	Tank	3	4	5
	Reservoir	0	1	0	0	0	0	0
↓	1	1	0	***0***	0	1	0	0
	2	0	***0***	0	***0***	0	***0***	0
	Tank	0	0	***0***	0	0	0	***0***
↓	3	0	1	0	0	0	1	0
↓	4	0	0	***0***	0	1	0	***0***
	5	0	0	0	***0***	0	***0***	0

Table 5 Updated node–node matrix when segments S4, S5, and S6 are isolated and the Unintended isolation search procedure from the Tank

Search Order	Node Node	Reservoir	1	2	Tank	3	4	5
	Reservoir	0	1	0	0	0	0	0
	1	1	0	***0***	0	1	0	0
	2	0	***0***	0	***0***	0	***0***	0
	Tank	0	0	***0***	0	0	0	***0***
	3	0	1	0	0	0	1	0
	4	0	0	***0***	0	1	0	***0***
	5	0	0	0	***0***	0	***0***	0

segments S4, S5 and S6 are isolated, and two different procedures for identifying an unintended isolation, which are initiated from the Reservoir or the Tank, are demonstrated. From the rows of the water sources, the algorithm traces a "1" in a row of each node. If a "1" is found, the corresponding row of the node is searched after the current row search is completed. When there is no remaining node to be searched, the procedure is completed and the unintended isolation has been identified. Any nodes which have not been searched by the algorithm are the unintended isolation. In the example, node 5 is not searched by the algorithm indicating that it is an unintended isolation shown in Tables 4 and 5.

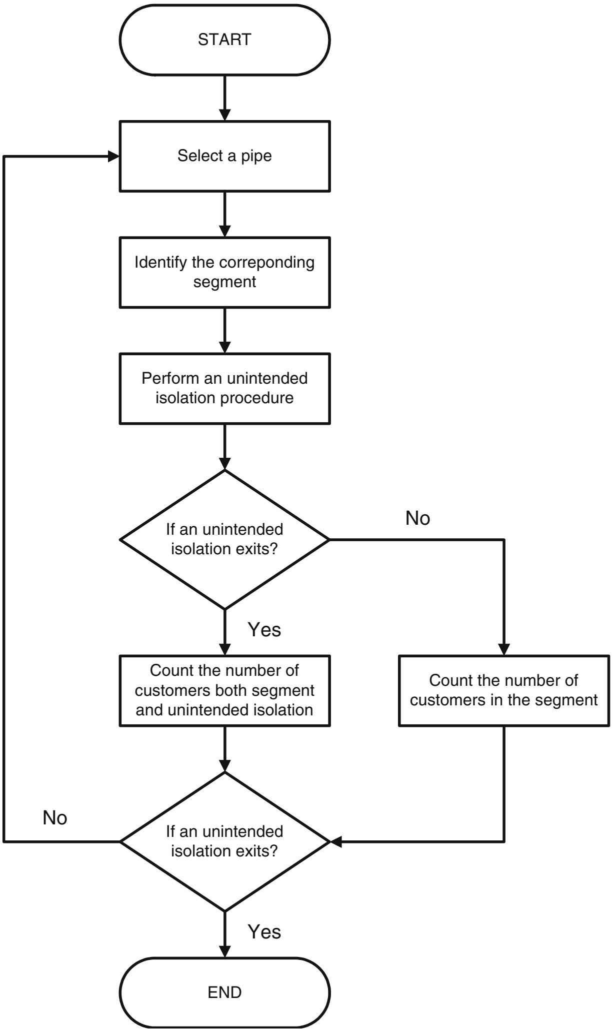
6 The Suggested Failure Analyses of a Water Distribution System

6.1 Pipe-by-Pipe Failure Analysis (PPFA)

PPFA accounts for each pipe failure impact on a water distribution system. The purpose of PPFA is to assess the relative importance of a pipe or a segment on a water distribution system. For maintenance purposes, it is possible to prioritize the maintenance order of pipes to minimize the number of affected customers due to a pipe failure. Moreover, a utility can determine where they place new pipes or rehabilitate existing pipes for improving the entire system reliability. For example, if a pipe failure forces a large number of customers out of service, utilities may place additional pipes alongside the pipe to add an alternative water path to the customers within that area.

In PPFA, it is assumed that the reliability of each valve is 100%. Each pipe is sequentially assumed to fail and then the corresponding segment is identified by the segment-finding algorithm. Isolating that segment places customers within the isolated section out of service and the pipe failure impact is quantified. Once a segment is identified, an unintended isolation is explored. If isolation of a segment creates an unintended isolation, the failure impact is estimated using the number of customers within the segment and a corresponding unintended isolation. Regarding the assessment of pipe failure impact on a water distribution system, the number of customers out of service is used for this research. However, there is a room for using other criteria to assess the impact such as hours of suspension of water supply, amount of water loss, and/or economical loss such as a reduction of revenue in nearby businesses and social cost due to traffic congestion incurred by broken pipe. In case these criteria are considered along with the number of customers criterion used in this paper, it is conjectured that the order of importance of the pipes and valves may change corresponding to the relative degree of importance among the criteria. In addition, types of customers are also very important to assess pipe failure impact. For example, if hospitals, schools, and industrial facilities are out of service due to a pipe failure, their impact will be more severe than that on households. For those critical customers, their impact may be considered using the equivalent customers, i.e. a hospital maybe considered to be equivalent to 1,000 households. Once an equivalent number of customers are established for each critical customer group, one could assign them to an individual pipe that serves the critical customers. The methodology of this paper may, then, be used to evaluate the importance of the valves and pipes of a given water distribution system based on the more elaborate measures for the critical customers.

Fig. 6 Flow-chart for a PPFA

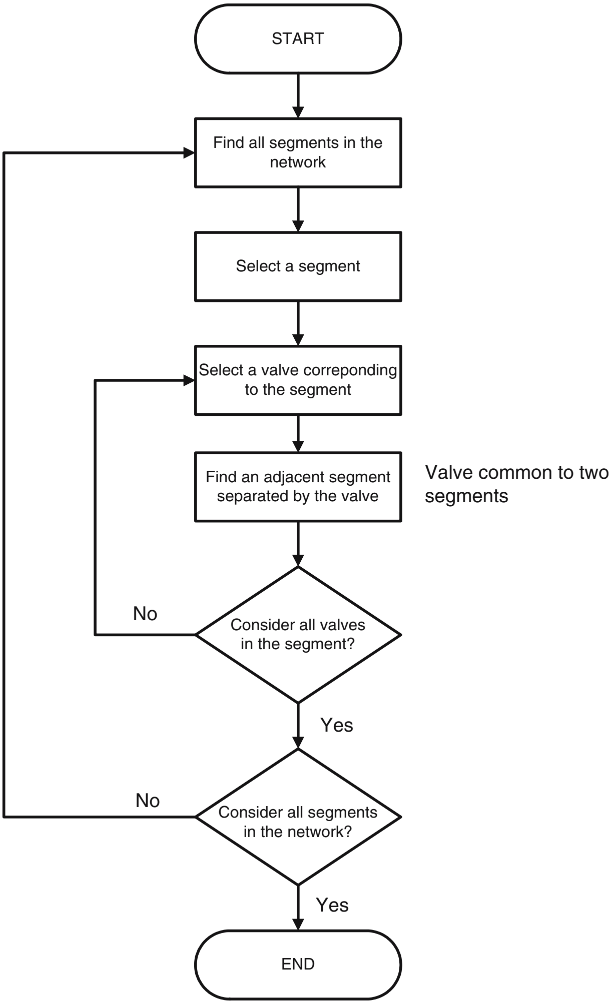


Every segment in a water distribution system is delineated and each pipe failure impact is assessed. Then, all segments are ordered according to the assessed impact and critical segments are found for a network. The PPFA procedure is illustrated in Fig. 6.

6.2 Valve by Valve Failure Analysis (VVFA)

VVFA accounts for the valve failure impact between adjacent segments. Each valve within a segment is sequentially assumed to fail. As a consequence, the adjacent segment of the original segment linked by the failed valve is merged with the original segment into a newly expanded segment. The valve failure impact is quantified by the number of customers within the new segment. This procedure continues until the failure impact of each of the valves belonging to the original segment is estimated. The procedure then moves to the next segment and eventually the valves of all the segments in the network are

Fig. 7 Flow-chart for a VVFA



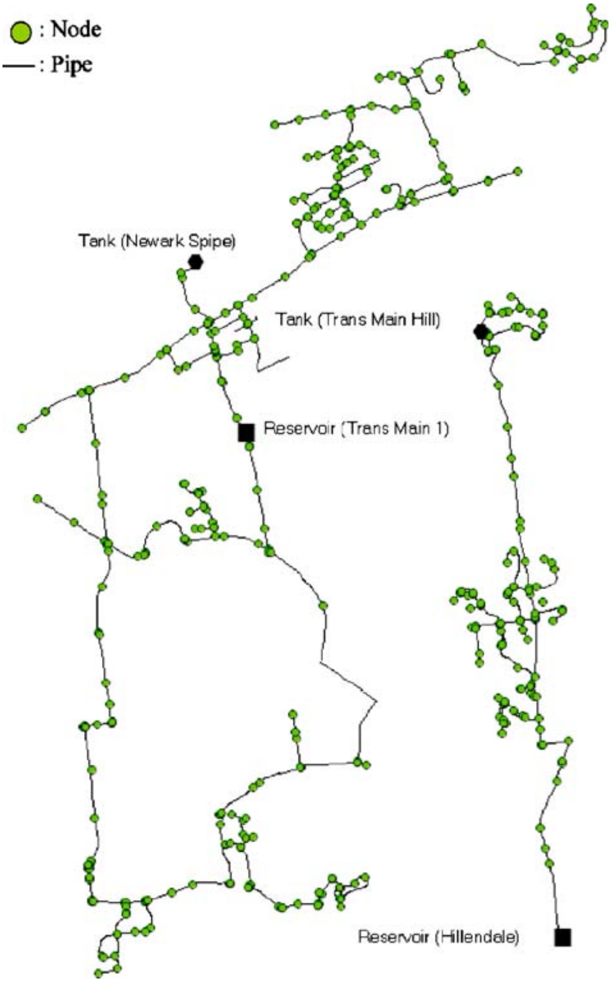


Fig. 8 Chester water authority water main network

examined. To determine the relative importance of each valve, a standardized index is used: the Valve Importance Index (VII). VII calculates the proportion of customers affected by a valve failure relative to the total number of customers in the network using Eq. 1.

$$\mathrm{VII}(\mathrm{Valve}_i) = \frac{\mathrm{VC}_i}{C_{\mathrm{Tot}}} \tag{1}$$

Where,

VC_I The number of customers relying on valve i
C_{Tot} The total number of customers in the network

VII is a standardized index to be used to evaluate or to compare the relative importance of each valve in a system. Valves with higher VII should be kept in good working condition to minimize the pipe failure impact. Therefore, VVFA can be used to establish the maintenance order for valves. Since each valve has different VII, valves with higher VII should be considered first for maintenance. By using VVFA, utilities will be able to allocate their resources more efficiently for valve maintenance. A flow chart of VVFA is shown in Fig. 7.

Table 6 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

7 Real Network Example: Chester Water Authority, PA, USA

To verify the applicability of the suggested methodology, a real network, one of the five sections of the Chester Water Authority (CWA) network, was selected. The network has 566 pipes, 537 nodes, and 354 valves. Actually, there are more than 354 valves installed in

Table 7 Five segments having the 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

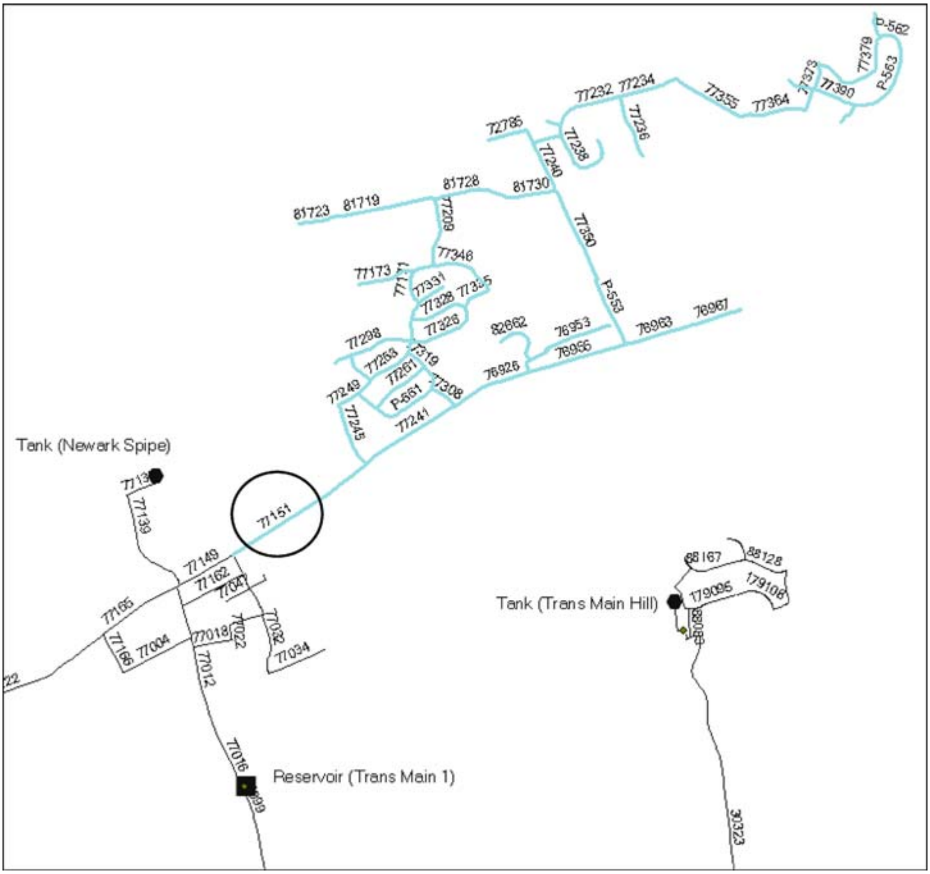


Fig. 9 Location of segment S(223) and isolated pipes

the selected section, but the valves installed on hydrants and laterals were not included in the analysis since they cannot be used to isolate a subsystem when a pipe fails. There are four water sources: two reservoirs and two tanks. Because of the unavailability of customer data per pipe, the number of customers in the network is estimated by Eq. 2.

$$\mathrm{NC}_i = \frac{\mathrm{PL}_i}{L_{\mathrm{Tot}}} \times C_{\mathrm{Tot}} \tag{2}$$

Where,

NC_i Number of customers of pipe i
PL_i Length of pipe i
L_{Tot} Total length of pipes in the network
C_{Tot} The total number of customers in the network

Figure 8 shows the network lay-out and valve location.

7.1 Results of PPFA

From PPFA analysis, 314 segments are identified, including 84 Node Segments which implies 84 out of the 537 nodes are fully valved. Of 229 normal segments, 53 have

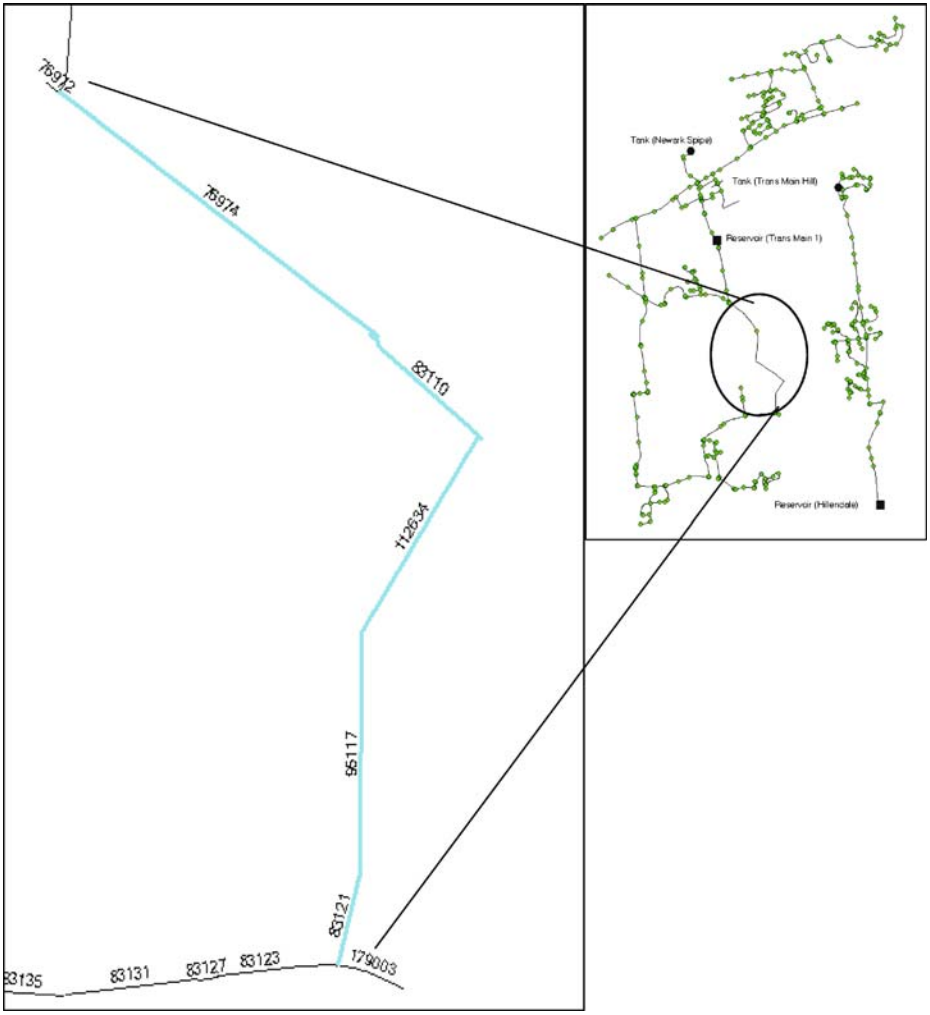


Fig. 10 Segment S(7) and its components

unintended isolations. From Table 6, among the segments, it is seen that some consist of a large number of pipes such as segments S(7) and S(107) comprising 16 and 12 pipes, respectively. Segment S(223) consists of only one pipe, 77151, but as shown in Table 7, the unintended isolation of S(223) produces a segment comprising 124 pipes. Figure 9 shows that pipe 77151 connects two components of the network. The downstream components of pipe 77151, which are shown on the right of pipe 77151 in Fig. 9, are disconnected from the water sources, Tank whose ID is "Newark Spipe" and Reservoir whose ID is "Trans Main 1." This is because pipe 77151 is the only path from the water sources to the downstream components so that they become disconnected when segment S(223) is isolated. In contrast, Fig. 10 shows that segment S(7) has the largest number of pipes (16) but no unintended isolation. Therefore, when pipe failure impact is estimated, the segment and its unintended isolation should be considered together. Table 8 lists the five largest segments, of which failure of segment S(223) forces 27.2% of the total number of

Table 8 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

customers out of service. To avoid creating these large segments, placing more valves or providing multiple water paths along these sections is necessary. Moreover, new water sources such as emergency tanks to provide water to customers during the isolation or additional valves in an effort to reduce the size of those large segments could also be another reinforcement options to minimize pipe failure impact. The potential for PPFA as a valuable tool in identifying critical pipes in a water distribution network and thus establishing an effective plan for reinforcement of critical pipes is demonstrated in subsequent sections of this paper.

7.2 Results of VVFA

Table 9 lists the five valves with the highest VII. Valve V(JT050AV16, 77149) is located on the left side of segment S(223) containing 2,146 customers. This valve has the largest VII of 27.7%. The second highest VII is found around the node JT050AV16 and other valves in Table 9 are also nearly as significant as S(223). This suggests that all valves around S(223) should be maintained well to prevent S(223) from merging to adjacent segments.

From VVFA, the most critical valves for the network are identified. For efficient maintenance, valves with higher VII values should be well maintained to guarantee their operation when required. Ranked by VII, the relative importance of a valve is quantified which enables the maintenance schedule for these valves to be better prioritized. The VVFA results are useful to establish an annual valve maintenance program. In general, real networks may have many thousand valves and it is not possible to regularly maintain all valves in a large network. If utilities plan their valve maintenance for the next 10 years, the VVFA results would be able to provide critical information to determine the optimum portion of valves to be maintained in the first year. Then, the order of maintenance activities for the rest of the valves could be based upon the VII values for each of the remaining valves for the following years.

Table 9 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	2,188	27.75	1
JT050AV16,77575	JT050AV16	77575	2,172	27.55	2
JT001AP13,77241	JT001AP13	77241	2,146	27.22	3
JT001AP13,77243	JT001AP13	77243	2,146	27.22	4
JL170AP14,81740	JL170AP14	81740	848	10.76	5

8 Reinforcement Options for Critical Sections

Using the suggested failure analyses, critical sections in a network can be identified efficiently. Once critical sections are found, reinforcement plans are required to improve the system reliability. Usually, there are several options for reinforcement of critical sections:

- New pipes

– Replace old pipes
– Establish double water paths by placing parallel pipes in addition to existing pipes
– Make a new water path for a downstream section

- New emergency water sources such as Tanks

– Supply water for emergency as an additional water source

- New valves

– Reduce the length of a pipe when it is isolated

- Valve maintenance program

– Improve the valve reliability

To establish an efficient reinforcement plan, the reason for the section's criticalness should be evaluated, along with the relative benefits of applying different options, since each option has its own advantages and disadvantages. For example, parallel new pipes will be a good reinforcement for a pipe if it is the only water path for a section of an unintended isolation. However, if the pipe is placed under a commercial building, placing parallel pipes may be impossible, therefore supporting the better option of a new tank around the section.

As an example of reinforcement, an example is presented of how to determine reinforcement options for critical sections and important valves. From PPFA, segments S(7) and S(223) are two critical sections. S(7) consists of 16 pipes and no unintended isolation, while S(223) consists of one pipe but 124 pipes of unintended isolation. For S(7), additional pipes are not suitable since it does not cause an unintended isolation when it is isolated. In addition, a new water source for S(7) may be not suitable since the cost of a tank for only S (7) would be excessive. To minimize the impact of the isolation of S(7), new valve(s) may be the best choice to divide S(7). If a valve is placed between pipes 83110 and 112634, S(7) is divided into two segments, only one of which is isolated, as shown in Fig. 10, if a failure occurs in one of the two pipes. On the contrary, a new valve for S(223) cannot be an reinforcement option. Suppose a new valve is placed on pipe 77151 of S(223). When this pipe fails, the downstream of S(223) remains disconnected regardless of the new valve. For S(223), replacing the pipe with a new one or parallel pipes will be a good option for reinforcement. Moreover, a new tank will be another option for reinforcement, as the cost of a tank in this case may not be prohibitive compared to the number of customers within the unintended isolation of S(223).

VVFA confirms that valve V(JT050AV16, 77149) is the most important valve in the system. When pipe 77149 fails, this valve stops propagation of the failure impact of S(223), which is the most critical segment. For this purpose, a new valve adjacent to valve V (JT050AV16, 77149) is the best reinforcement option since it almost guarantees the isolation of pipe 77149. Another possible option is replacing pipe 77149 with a new pipe.

9 Summary

Due to wide variations in the topology and operating conditions that may exist in a water distribution system, water utilities may need to spend tremendous efforts and resources to maintain their systems in a well and efficiently operating condition. In this paper, two methodologies for failure analysis, which will provide an essential tool for an efficient operation and maintenance of a water distribution system, one pipe based, PPFA, and the other valve based, PPFA, are developed to identify critical pipes and valves of a water distribution system. The methodologies are based on a matrix algorithm that can be easily implemented to any water distribution system. Moreover, the analyses can be performed very efficiently regardless of the size of the water distribution system by coupling with the EPANET.

The methodologies focus on identifying those pipes and valves which incur the largest losses when they fail. PPFA provides information about which section of the system suffers the greatest impact from a pipe failure in terms of the number of customers forced out of service both by the failed segment and unintended isolation area. PPFA simulates each valve failure impact and estimates the VII, which represents the index for quantifying the relative importance of each valve. Results of PPFA and VVFA can be used to prioritize the order of maintenance of a water distribution system. For example, the most critical pipe or valve should be maintained first during a scheduled maintenance period to minimize the failure probability and to maximize the reliability of the water distribution system.

The applicability of the suggested methodologies is demonstrated with an example application using a real water distribution system. A proper reinforcement plan is presented to minimize the failure impact of a critical section and to improve the serviceability and reliability of the example water distribution system.

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