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Upgrading Reliability of Water Distribution Networks Recognizing Valve Locations

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Abstract

An iterative procedure for upgrading water distribution network reliability is proposed by recognizing valve locations. In each iteration, three types of alternatives: (1) an addition of a valve(s) to pipe(s) without a valve; (2) an addition of a parallel pipe to an existing pipe; and (3) an increase in size of newly added pipes, are compared and the best is implemented. The iterative method is continued until no further improvement in reliability is possible, or a desired level of reliability is reached. This method is illustrated through an example taken from literature.

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Keywords: Design; Redundancy; Reliability; Segment analysis; Water Distribution System.

1. Introduction

Reliability of an existing water distribution network (WDN) can be improved in several ways, such as by providing parallel pipes to the existing pipes, adding new pipes between existing nodes, standby pumps and electricity generators at source and booster points, additional tanks and their proper distribution over the entire network, larger storage capacity at source nodes, and more isolation valves located so that only a small portion of the network is required to be isolated following a pipe failure. Walski [1] suggested many practical aspects of providing reliability in WDNs. Each measure for improving reliability has its own advantage and limitation.

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Several researchers suggested improving reliability by providing higher than required pipe sizes for additional flow capacities which can be utilized during failure of any pipe [2, 3, 4, 5]. Further, most of the earlier work on reliability-based design of a WDN is based on the assumption that valves are provided on either end of pipes, which can be closed to isolate that pipe during failure. This is not the usual practice. Bouchart and Goulter [6] proposed an algorithm in which valves are initia lly assumed at each end and the number of additional interior valves was determined to improve reliability. Mays [7] suggested placing valves at either ends of pipe. However, valves are not provided at both ends because of financial constraints and a segment of the distribution network is required to be isolated during failure of a pipe [8]. Some recent work on reliability-based analysis and design of WDNs includes methods for segment analysis [9-12], methods for segment based reliability/supply shortfall analysis [13-15], and methods of optimal location of valves [16, 17].

Giustolisi and Savic [16] proposed GA based methodology for selection of a minimum number of isolation valves in the network and minimizing the size of the largest segment (taken as the segment with the largest number of pipes with the assumption of same length for each pipe). Creaco et al. [17] suggested placement of isolation valves in water distribution systems based on minimization of valve cost and weighted average demand shortfall. In this paper, a novel methodology for upgrading the reliability of an existing WDN is suggested by incorporating redundancy through: (1) the addition of new links necessary for topological redundancy; (2) strengthening by parallel pipes; and (3) increasing the number of valves in the network.

2. Topological and hydraulic redundancy

To ensure reliable supply to all nodes of the network, it is minimum necessity that every node of the network is connected by at least two links, i.e., every node must at least be of degree two. The higher the degree of a node the greater is the topological redundancy at that node and the network may be able to sustain multiple-link failure at that node. However, since the probability of simultaneous failure of two or more links is quite small, a network with all nodes of a degree two has satisfactory topological redundancy, provided that isolation of each pipe during failure is possible. This requires provision of valves at either ends of a pipe, which is not a current practice. Further, providing topological redundancy does not ensure the reliability of water supply. A topologically redundant network must also have additional water carrying capacity to ensure satisfactory water supply during pipe failure condition. This introduces hydraulic redundancy. The reliability of an existing WDN can be improved by improving both topological and hydraulic redundancies.

3. Model development

3.1. Practical Assumptions

- Even though withdrawal points are distributed along links, these are aggregated and assumed to be concentrated at nodes.
- Not more than one valve is considered on each pipe. Herein, location is considered at middle of pipe. However, methodology proposed herein is general and can be extended for actual valve positions and multiple valves in each pipe.
- Nodal demands are known with certainty.
- No storage is considered to be available in the system, whether at the source or at the consumer point. This can be an important consideration when taking into the account hydraulic reliability of the system, because once storage is introduced the duration of fire loadings becomes important, since there is now a possibility that some tanks may drain. Further, with storages at consumer location there could be a possibility of extra supply during periods of low demands [18-19].

3.2. Options for Improving Reliability

An iterative methodology is used to improve the reliability by selecting one of the options under three different types of alternatives which is found to be most appropriate at that stage. The first type of alternative consists of adding a minimum diameter parallel pipe to existing link. Initially, all the existing links for which a parallel pipe can be provided are considered. Once a parallel pipe of minimum size is added to any link, the increase in size of this parallel pipe is considered as an option in subsequent iterations. The second type of alternative is increase in size of newly added minimum diameter links required for network expansion or achieving topological redundancy. The third type of alternative is to add one or more valves to increase the number of segments. Herein, there could be number of options. However, it is seen that the option of increasing the segment by one valve is better than that by two or more valves. Therefore, only options of addition of one and two valves at a time are considered which resulted in the increase of segments.

3.3. Segment Analysis

The methodology suggested by Kaldenbach and Ormsbee [12] for segment identification is used with slight modifications. The suggested modification avoids the duplication of nodes, pipes and valves in different segments. The suggested modifications in the methodology of Kaldenbach and Ormsbee to avoid duplication of nodes is to search both, the Skip List and the existing Search List, whenever a connection is found instead of searching only the Skip List. Similarly, duplication of pipes and valves can be avoided by checking the Segment's Pipe List and Segment's Valve List respectively, whenever a connection is found.

3.4. Reliability Analysis

Reliability is quantified and obtained by the method suggested by Gupta and Bhave [20]. Three reliability parameters are used: (1). Node reliability parameter, R_n; (2). Volume reliability parameter, R_v; and (3). System reliability parameter, R_s to describe the performance of a network over the period of analysis.

Node reliability parameter, R_n, is the ratio of the total available outflow volume at a node to the desired outflow volume at that node for all states during the period of analysis. Volume reliability parameter, R_v, is the ratio of total available outflow volume to required outflow volume of the entire network for all states during the period of analysis. System reliability parameter, R_s, is a single reliability parameter which is a product of volume reliability, node factor and time factor introduced to distinguish reliability values under different situations [1]. Available flows at different nodes are obtained using node flow analysis, using EPANET 2.0 with modifications [21].

4. Proposed methodology

An iterative methodology is suggested for improving the reliability of existing network. Initially, the reliability of an existing network is obtained. Now, all possible options of improving the reliability are considered one by one. As discussed earlier, we have three different alternatives with a number of options in each. With the implementation of each option, the cost of the network will increase, further the reliability may improve. These options are compared based on: (1) marginal capacity factor [22], ΔF_c, defined as the product of marginal increase in the volume reliability parameter and marginal increase in reliability of the least reliable node; and (2) marginal increase in cost of network (ΔC_T). The best option to implement is the one that provides the largest marginal capacity factor at minimum network cost. Therefore, the ratio of marginal capacity factor to marginal increase in cost is termed as MCFMIC ratio [22]. The ratio is obtained for each of the options and the option corresponding to largest MCFMIC ratio is selected for change. The iterative procedure is continued until desired level of reliability is reached.

The first step to improve the reliability of an existing network is to achieve topological redundancy. For a single source network, all nodes including the source nodes must be connected by two pipes. This can be accomplished using an algorithm first proposed by Kessler et al. [23]. New links provided for topological redundancy are considered of minimum size. This becomes the initial network. The step-wise procedure to improve this network further is as follows:

Step 1: Carry out Node Flow Analysis of this network to obtain available flows at different nodes under all-pipes-working condition (APWC) and one segment-failure condition (1-SFC).
Step 2: Find network cost and various reliability parameters, i.e. node, volume, and system reliability parameters.
Step 3: If obtained reliability values are more than designed values then end.
Step 4: Identify the node having minimum nodal reliability value.

Step 5: Find various available options to improve the reliability at this stage, i.e. a minimum size pipe parallel to existing pipes, increase the size of newly added pipes to higher size, and addition of one or two valves at a time within an existing segment to form one or more segments.
Step 6: Obtain MCFMIC ratio for each one of the options.
Step 7: Select the best option having maximum MCFMIC ratio, implement it, and go to step 1.

5. Illustrative example

A small network, [5] shown in Fig1, serving an area with large commercial/industrial customers is selected to explain the algorithm. The network has one source and 16 demand nodes. Ormsbee and Kessler [5] labelled Source Node as S (herein labelled 1) and Demand Nodes 1 through 16 (herein labelled 2 through 17). It is assumed that some valves are existing and are placed at mid length of the pipes 1,7,9,10,15,16,17,18 and 19 (Fig 1). Thus the total number of pipes is increased from 19 to 28 as valves are considered as nodes in the network model. Further, to achieve topological redundancy (nodes 1, 10, 11, and 13 are connected by one pipe), additional pipes are added between nodes 1 and 17 (Pipe 31) nodes 12 and 13 (pipe 30), and nodes 10 and 11 (pipe 29). The modified network with 17 nodes, 9 valves and 31 pipes is shown in Fig2. The network is upgraded by considering the peak hour nodal demands. The other details of the network (link and node data) can be seen from the original paper [5].

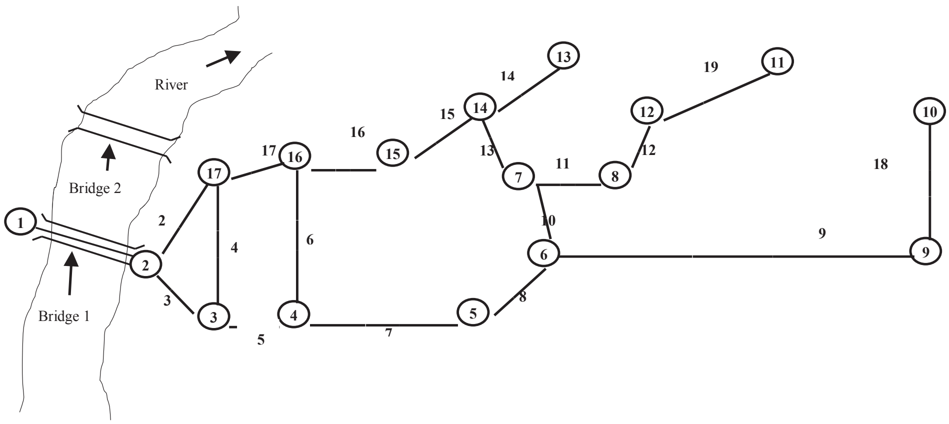

Fig 1. A water main system

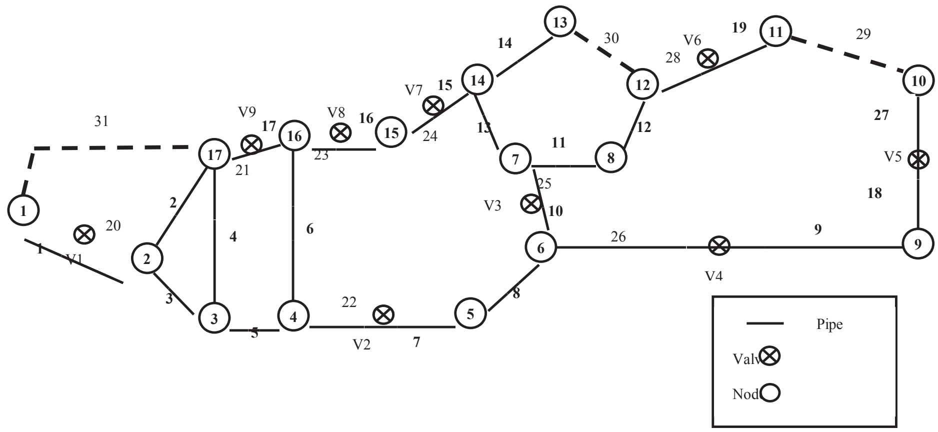

Fig 2. Topologically redundant water main system with existing valves

The cost of new pipes and valves are considered as per Maharashtra Jeevan Pradhikaran's Schedule of Rates. The available pipe sizes and their unit costs (given in parentheses) are: 254 mm (Rs 3348), 304.8 (Rs 3948), 355.6 (Rs 4317), 406.4 (Rs 4806), 455.6 (Rs 5794), 609.6 (Rs 8921), 762 (Rs 12897). The cost of valves (given in parentheses) of various sizes are: 203.2 mm (Rs 24101), 254 mm (Rs 37382), 304.8 (Rs 49699), 355.6 (Rs 72811), 406.4 (Rs 99720), 455.6 (Rs 123737), 508 (Rs 160146), 609.6 (Rs 243982), 762 (Rs 579078), and 812.8 (Rs 672599). Available pipe sizes (mm) and breakage data (breaks km-1 yr-1) are taken from Bhave [24] as follows: 150 mm (1.04 breaks km-1 yr-1); 200 (0.71); 250 (0.39); 300 (0.07); 350 (0.05); 400 (0.05); and for sizes greater than or equal to 450 mm (0.04 breaks km-1 yr-1). Repair time for a pipe is considered as two days.

5.1 Design Solution

Computer Programs/Software: To carry out the design as per the proposed methodology, three computer programs are used. (1) Segment Analysis Program - This program is prepared in C^{++} to generate segments based on the location of valves using the methodology of Kaldenbach and Ormsbee [12]. Various options to be considered for improving the reliability were obtained, and passed on to another program for node flow analysis. (2) Modified EPANET 2.0 - EPANET 2.0 with modifications suggested by Abdy Sayyed et al. [21] was used to determine the available flows under various conditions, i.e. APWC and 1-SFC. (3) Reliability analysis and selection of best option - Using the available flows obtained from modified EPANET 2.0 for different conditions, reliability parameters and the best option is determined using Excel based program.

Time of state for a segment: A segment consists of number of pipes. Since failure of any pipe in a segment will cause complete closure of the segment, the time of state for the segment is determined by the addition of the time of state of different individual pipe failure condition. For example, consider a segment consisting of pipes 7, 8, 10 and 26. Let time of states for individual failure of these pipes be t_7, t_8, t_{10} and t_{26}. The time of state for closure of this segment would be $t_7 + t_8 + t_{10} + t_{26}$.

Parallel pipes and Valve Additions: Parallel pipes are added between two nodes of original network. For an existing link without a valve, a parallel pipe will also not contain any valve, see left side of Fig. 3. For an existing pipe with a valve, the parallel pipe is connected in two parts as shown in the right side of Fig. 3 to avoid modifications in the segments.

Fig.3. Addition of parallel pipe to existing pipe with no valve (left); and with valve (right).

Reliability analysis of network and its modification: The reliability values for the initial network and iteration details are shown in Table 1. The following can be observed from Fig. 2 and Table 1.

1. In the initial network there were 7 segments. Segment 2 is the largest segment with 11 pipes and segment 1 is the smallest segment with only one pipe. Segments 3 and 7 have two pipes in each of them and they isolates node 15 and 9, respectively.
2. Initial values of Volume and System Reliabilities are 0.987656 and 0.964266 and the cost is 113.79 M Rs. Node 10 is the worst affected node with a nodal reliability value of 0.986252.
3. Valve costs are comparatively lower than the pipe costs, and therefore MCFMIC ratios are more with addition of valves. Valves were added in the network in first five iterations. With the addition of a valve in a link, the link splits into two pipes. In the first iteration valve is added in pipe 31 at its middle and it splits in to pipes 31 and 32. After addition of the valve, the size of both the portions of pipes was increased simultaneously. In the fourth, fifth and later in the eleventh iteration, a pair of valves were added.

Table 1. Iteration details for Illustrative Example

Iteration	Selected Option	Change Implemented	Critical Node	Minimum nodal reliability	Volume Reliability	System Reliability	Network Cost (Million Rs)
Initial			10	0.986252	0.987656	0.964266	16.43
1	Valve	Valve : Pipe 31	10	0.990127	0.991530	0.975657	16.46
2	Valve	Valve : Pipes 5&6	10	0.992074	0.993486	0.981472	16.59
3	Valve	Valve : Pipe 29	7	0.993025	0.993964	0.982349	16.62
4	Valve	Valve : Pipes 2&4	7	0.995938	0.997414	0.992595	17.30
5	Valve	Valve : Pipes 11&30	17	0.995490	0.997666	0.993450	17.44
6	Increase diameter	Pipes 31&32: 304.8 mm each	11	0.997657	0.998317	0.995622	19.65
7	Increase diameter	Pipes 29&35: 304.8 mm each	12	0.997936	0.998578	0.996149	20.21
8	Increase diameter	Pipes 30&39: 304.8 mm each	9	0.998130	0.998677	0.996448	20.42
9	Valve	Valve : Pipe 8	4	0.998254	0.998759	0.996613	20.47
10	Valve	Valve : Pipe 3	12	0.998339	0.998821	0.996770	20.57
11	Valve	Valve : Pipes 12&13	9	0.998350	0.998858	0.996897	20.91
12	Increase diameter	Pipes 31 & 32: 355.6 mm each	4	0.998473	0.998980	0.997248	22.29
13	Increase diameter	Pipes 31 & 32: 406.4 mm each	4	0.998582	0.999071	0.997549	24.10
14	Increase diameter	Pipes 31 & 32: 457.2 mm each	4	0.998684	0.999171	0.997760	27.74
15	Increase diameter	Pipes 31 & 32: 609.6 mm each	11	0.998723	0.999216	0.997838	39.30
16	Increase diameter	Pipes 29&35: 355.6 mm each	12	0.998741	0.999234	0.997873	39.66
17	Parallel pipe	Pipe 8 - 254 mm	4	0.998771	0.999238	0.997881	41.30
18	Increase diameter	Parallel pipe 8: 304.8 mm	4	0.998776	0.999405	0.998228	41.60
19	Valve	Valve : Pipe 14	-	-	0.999421	0.998285	41.70
20	Increase diameter	Parallel pipe 8: 355.6 mm	-	-	0.99945	0.998346	41.90
21	Increase diameter	Parallel pipe 8: 406.4 mm	-	-	0.999463	0.998372	42.17
22	Parallel pipe	Pipe 19 - 254 mm	-	-	0.999491	0.998336	43.35
23	Increase diameter	Parallel pipe 19: 304.8 mm	-	-	0.999523	0.998467	43.60
24	Increase diameter	Parallel pipe 8: 457.2 mm	-	-	0.999532	0.998487	44.11
25	Increase diameter	Pipes 30&39: 355.6 mm each	-	-	0.999535	0.998496	44.26
100	Rs=1.67 US$						

4. The diameter of new pipe 31 (and 32) is increased to 304.8 mm in the sixth iteration; and later consecutively in iterations 12, 13, 14 and 15 to a final size of 609.6 mm. The diameter of other newly added pipes 29 (and 39) and 30 (and 38) also increased in different iterations.
5. A parallel pipe to existing link 8 is added in the 17th iteration and its size is also further increased in different iterations. A parallel pipe to existing link 19is added in the 22nd iteration.
6. After 18th iteration, it is observed that there are no options which simultaneously increases both volume as well as minimum nodal reliabilities. Therefore, the iterative process was continued by considering the marginal increase in volume reliability instead of marginal capacity factor.
7. The process was terminated after the 25th iteration as the volume reliability remained same up to fifth place after the decimal point. However, the process could be continued. The increase in reliability would be because of increase in availability of pipe as the failure rate of higher diameter pipe is lesser.
8. With the addition of valve in pipe 14 in 19th iteration, valves were added in all the pipes. Thus, the number of segments became 18. Each segment contained one node and node 1 was common in two segments. The failure of any pipe in a segment thus isolated one node contained in that segment.
9. At the end of 25th iteration, it is observed that failure of pipe in segments containing nodes 14, 15, 16 and 17 affected other nodes in addition to the node in that segment.

6. Comparison of Results with other methods

The illustrative network has been designed earlier by Ormsbee and Kessler [9], Agrawal et. al. [22], and Gupta et al. [25] with the assumption that valves are provided at the either ends of each pipe. Considering their final design including the cost of valves, their cost of upgrading network reliability, using the cost values considered herein would have been 58.8, 56.5, 52.9Million Rs, respectively. The total cost of network expansion with the proposed methodology is 44.26 Million Rs, which includes the cost of existing valves. Even though earlier methodologies [9, 22, 25] assumes that there are no consumers affected due to isolation of pipe during failure, the consumers provided connection through the isolated pipe would certainly suffer.

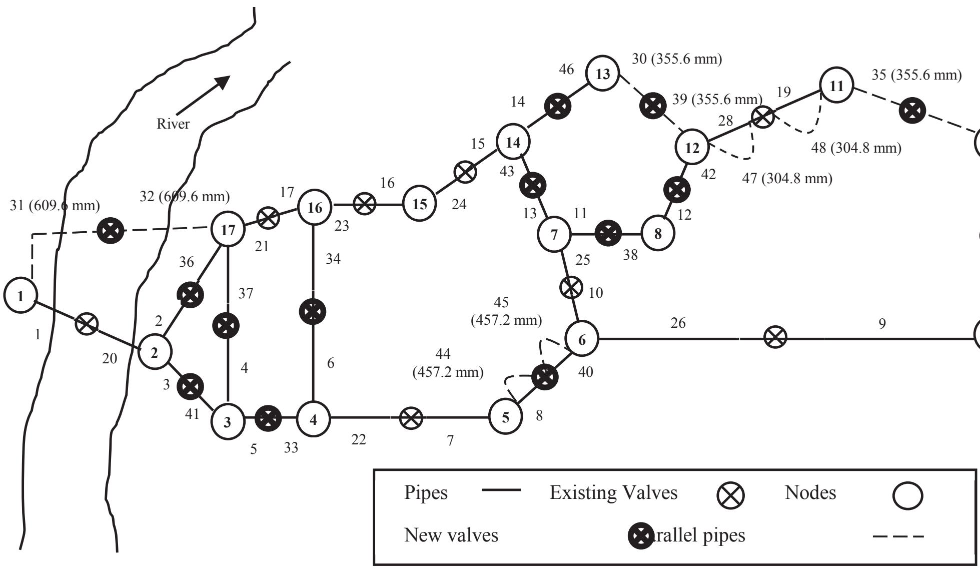

Fig.4. Upgraded water main system

Herein, the final design valves are provided on mid length of all the pipes. Further, demands of consumers on half of the pipe length can be lumped at the respective nodes and therefore during failure of any segment one node is isolated and consumers lumped at that node will automatically get isolated. Thus, the proposed methodology not only provides a cheaper solution but considers valves' and consumers' locations also. The final design solution is shown in Fig. 4.

7. Summary and conclusions

An iterative method which considers the trade-off between reliability and cost has been suggested for use in improving the reliability of existing systems. The application of this method can also be extended to design new networks. The proposed method has an advantage that it considers location of valves in obtaining reliability values and improves reliability not only through increasing pipe sizes or adding parallel pipes but also considers the location of new valves in pipes not provided with valves to reduce the size of segments. The proposed methodology is computationally extensive as it requires a large number of simulations before selecting any option. The application of methodology is shown in a water main system supplying water to a commercial-industrial township. The results are compared with those obtained by previous researchers. The proposed methodology provides a cheaper solution.

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