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Resilience Enhancement Methods for Water Distribution Networks

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ABSTRACT

Water is a basic necessity of all living beings for their survival on Earth. Hence, it has to be ensured to be distributed effectively. A water distribution system is a mesh of pipelines that distribute water to consumers. They are designed to satisfy adequately the water requirements for a combination of domestic, industrial and commercial purposes. A network designed with extreme care regarding pressure, losses, supply, quality of pipes and workmanship usually satisfies adequate water pressure at the consumer's taps for a specific rate of flow in an economical manner. But, due to the unexpected vertical growth and horizontal expansion, the designed network may not supply the assessed demand. This ultimately affects the supply level of low pressure zones, as well as remote places that are far away from the source. Hence, it is necessary to consider resiliency of the network at the design level of the water distribution system which can represent the capability of the network to meet additional demands or withstand demand fluctuations that may occur during peak hours. The basic principle used to improve the resilience is to increase the diameter of the pipe to the pipeline to achieve maximum flow velocity. Increasing the diameters of the various pipes of an optimally designed network or an existing network considerably increases the efficiency of the system due to the increase in its resilience index. Parallel piping system is another option adopted to enhance resilience, in which a stretch experiencing maximum velocity is chosen. An additional pipe is installed parallel to the existing pipe in that stretch, thereby increasing the flow of water from the source and decreasing the velocity in that stretch. This ultimately increases the resilience index of the system, thereby meeting the additional demand incurred on that system. This is illustrated using two benchmark networks available in literature. The results of the study indicate that the parallel pipe approach is found to be better than increasing the pipe size approach both in terms of resilience enhancement as well as economy.

KEYWORDS: Water distribution network, Resilience, Low pressure zone.

INTRODUCTION

The water distribution system is one of the major requirements in urban and regional economic development. A water distribution network usually contains water distributing pipes, junctions and sources which include reservoirs and water storage tanks. For any agency dealing with the design of water distribution networks, an economic design will be an objective. The funds needed for the construction, maintenance and operation of these systems require the achievement of a good compromise between technical and economic aspects. Several methods are available to design a water distribution network in which rule of thumb and trial and error are the most popular methods. With the development of high speed digital

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computers and improved optimization techniques, the optimal design of water distribution networks was attempted since the 1970s. Numerous works were reported in literature for optimal design and some of them considered certain reliability aspects too. The past two decades witnessed a growing interest in adopting evolution-based algorithms, which overcome such a problem. A straightforward approach to the solution of such a problem would be the enumeration of all possible solutions and choosing the best one. The present day water distribution networks are complex and require huge investments in their design, construction and maintenance. The need to improve their efficiency by minimizing their cost and maximizing the benefit accrued from them is essential.

The problem of optimal design of water distribution networks usually has an objective of minimizing the total capital cost. For a given layout, details like demand and elevation of the node, tank size and its bottom level are assumed as known variables. The objective is to find a combination of different sizes of pipes that gives the minimum cost. These pipes should not exhibit a capacity shortage that will increase energy losses to satisfy demand. Hence, selecting a balanced pipe size for each link is a challenging task for network modellers. Optimization techniques for selecting the pipe diameter from a set of commercially-available diameters have been attempted for more than three decades. This paper proposes a heuristic-based approach, in which flow velocity is considered as implicit information in selecting the appropriate size for each link to improve the resilience of the network. This paper uses three existing resilience measures available in literature for measuring resilience and its efficiency in handling the additional demand.

Resilience Index

Todini (2000) proposed a resilience index to relate the intrinsic capability of a system to overcoming failures. Hence, a resilient design of a water distribution system strongly relates the intrinsic capability of the system to overcoming failures. The water distribution network designed based on a resilient point of view should reduce failure probabilities, yield minimum or reduced failure consequences and be able to recover quickly from failure. Resilience can also be defined as a measure of capability of the system to absorb shocks or to perform under perturbation. Wu et al. (2011) demonstrated the application of surplus power factor as a resilience measure for the optimization of water transmission systems. Yazdani and Jeffray (2012) considered robustness and redundancy to address the resilience of water distribution systems. Liu et al. (2012) defined resilience for water resource systems as the capacity of water resource system to maintain its essential functions as before during the event of unexpected stresses and disturbances.

Resilience index (RI) proposed by Todini (2000) is the ratio of the sum of residual power of all the nodes and the sum of potential residual power of all the nodes.

$$\mathrm{RI} = \frac{\sum_{j=1}^{N} q_{i(h_{avl},j - h_{min,j})}}{\left(\sum_{i=1}^{R} Q_r h_{res,i} + \sum_{b=1}^{B} \frac{P_b}{\nu}\right) - \sum_{j=1}^{N} q_j h_{min,j}} \tag{1}$$

where

q_i = demand at node i.

$h_{avl,j}$ = available pressure head at node j.

$h_{min,j}$ = minimum pressure head at node j.

Q_r = flow from reservoir i.

$h_{res,I}$ = sum of elevation and water level of reservoir i.

P_b = power of pump b.

N = specific weight of the liquid.

Modified Resilience Index

Jayaram and Srinivasan (2008) proposed a resilience index which is the ratio between the sum of residual power of all the nodes and the sum of minimum power required to all the nodes. Since it is a modification to the Todini (2000) resilience index, Jayaram and Srinivasan (2008) named it as the modified resilience index (MRI). MRI can be applied directly to networks having pumps and reservoirs.

$$\mathrm{MRI} = \frac{\sum_{j=1}^{N} q_i(h_{avl,j} - h_{min,j})}{\sum_{j=1}^{N} q_j h_{min,j}} \qquad (2)$$

While Todini (2000) resilience index theoretically varies between 0 and 1 (poor and good), the modified resilience index of Jayaram and Srinivasan (2008) can exceed one. Though both indices quantify the intrinsic capability of the system to overcome failures while satisfying demand and pressure at the nodes, it is difficult to fix the numerical value within the range mentioned above. The nodes near the source will have more surplus power than the critical nodes. Utilization of available surplus power in those nodes will certainly affect the supply at critical nodes. Critical nodes can be defined as those nodes having meagre (or negligible) surplus power or zero surplus power. Such nodes do not satisfy the consumer demands of pressure and discharge during abnormal conditions. Hence, availability of minimum surplus power at critical nodes is crucial in quantifying the intrinsic capability of the system. The major advantage of Todini and Jayaram and Srinivasan's resilience indices is that they do not involve statistical considerations on failures. Network reliability can be enhanced if the network is designed to have higher values of those indices. Resilience of the network can be increased only if the flow is distributed more evenly among all pipes rather than allowing flow concentrically in a spanning tree (Todini, 2000). If the network is designed in such a way to have an even flow distribution to all the pipes, there is a chance of diverting water through other pipes easily under abnormal conditions.

Power Efficiency

Suribabu and Neelakantan (2012) proposed a performance index called the power efficiency index. It is based on power availability at the source and power delivered at the demand nodes. The power efficiency index is defined as the ratio of power delivered at the demand nodes and the total power available at the source reservoirs, while satisfying the constraints on nodal demands and nodal heads. In this power efficiency indicator, since the total power available is taken as denominator, the ratio appears simpler than other power based performance measures. The power efficiency theoretically ranges between 0% and 100% (poor and good).

$$\eta = \frac{\sum_{k=1}^{nn} Q_k H_k}{\sum_{s=1}^{nr} Q_s H_s} \times 100 \qquad (3)$$

where

Q_s = discharge from reservoir s.

H_s = head of water available at the service reservoir with respect to ground level.

nr = number of reservoirs.

Q_k and H_k = demand and available head at node k.

nn = number of demand nodes.

Though the demand factor value varies with respect to time due to the diurnal nature of demand, it is common that the network is designed for peak demand. When peak demand is assigned for the node, the demand factor should be set as one. Demand factor is a parameter in EPANET used to analyze the amount of demand that the network could satisfy. Initially, the demand factor is set to 1 which means that the network could satisfy the peak (maximum) demand which the network is designed for. If the demand factor is increased to 1.1, this shows that an additional 10% of the actual demand can be satisfied by that network.

Methodology

Minimum cost design of water distribution networks using optimization techniques usually results with a network configuration to just satisfy the nodal demand under normal operating conditions. The optimization model most likely opts shortest path to satisfy the nodal demand from the source and assigns a least possible pipe size to all en-route pipes to that node, and the same way is executed to other demand nodes. There is a greater chance to assign smaller pipe size to almost all the redundant pipes in the looped network in view of cost minimization as a prime objective. Though loops ensure better connectivity to the nodes to the source, but the undersized redundant pipes cannot satisfy consumer demand which depends directly on these pipes. Hence, it is essential to design the network based on resilience as a point of view rather than minimum cost alone, and at the same time this reduces failure probabilities, yields minimum or reduced failure consequences and is able to recover quickly from failure. This paper uses three existing resilience measures available in literature and proposes two approaches to enhance the resilience of optimally designed networks or existing networks.

Increase in Pipe Size Approach

The proposed approach makes an assumption that velocity is the primary contributing factor to head loss in the pipes, despite the fact that head loss is a function of length, diameter and roughness. The optimal designed network or existing network should be simulated using any Hydraulic Simulation Engine (e.g., EPANET Software, Rossman, 2000). Pick up the link having maximum flow velocity and increase its size to the next commercial size. If the existing pipe has maximum size and maximum velocity, then such a pipe should not be selected. Instead, the pipe possessing maximum velocity and size next to the maximum size needs to be selected. Again, simulating the network for a new configuration, the pressure and velocity of the flow can be noted. For the revised network configuration, the values of resilience indices can be obtained.

Parallel Piping Approach

Parallel piping is another method to improve the resilience of the network in a cost-effective manner. Similar to the change in diameter method, velocity is taken into consideration, since it contributes to head loss in the pipe. In this method also, the pipe stretch experiencing maximum velocity is taken into account. To minimize the effect of head loss that occurs due to the increase in discharge and velocity, a pipe is added parallel to the existing pipe in that stretch which in turn reduces the flow velocity and increases the nodal pressure in the water distribution network. The size of the pipe to be added is selected either starting from minimum available size or on the basis of engineering judgement. The improvement of resilience of the network depends on the size of the pipe selected. Hence, the size of the pipe adopted is varied from least diameter to maximum. Each stage of this change in diameter is considered as an iteration, and for each iteration resilience index, modified resilience index and demand factor are found. These parameters help in evaluating the efficiency of the methodology.

Another approach of parallel piping is by deciding the number of pipes to be added to the network. The number of pipes that are added to the network influences the efficiency, cost and resilience of the water distribution network. The stretch to which this additional pipe is to be installed has to be chosen carefully. If the stretch is not selected properly, the cost of the network increases much faster than the efficiency and resilience index. Whenever two or more pipes are to be added to the network, the pipes having higher velocity have to be chosen. Generally, the pipe connecting the source and the node experiencing maximum velocity, when compared to other pipes in the network, will be always a better choice for improvement. Hence, additional pipes have to be installed parallel to those pipes having higher velocity. The outflow from the source can increase only if the parallel piping is done between the source and the immediate node.

Applications to Benchmark Networks

Two-Source Network

A 2-reservoir network with 26 nodes, 34 pipes and 9 loops presented by Kadu et al. (2008) was used here to demonstrate the proposed approach. Fig. 1 shows the layout of the network. The pipe and node details are presented in Table 1. The Hazen-Williams coefficient for all pipes is set to 130. The cost of 14 commercial pipes is presented in Table 2. Kadu et al. (2008) optimized this network through a modified genetic algorithm and the same network is improved for better resilience through increasing its diameter. Table 1 also provides an optimal diameter of the network obtained by Suribabu (2012) using the heuristic method. This network configuration is used to study the proposed approaches for improving the resilience of the network.

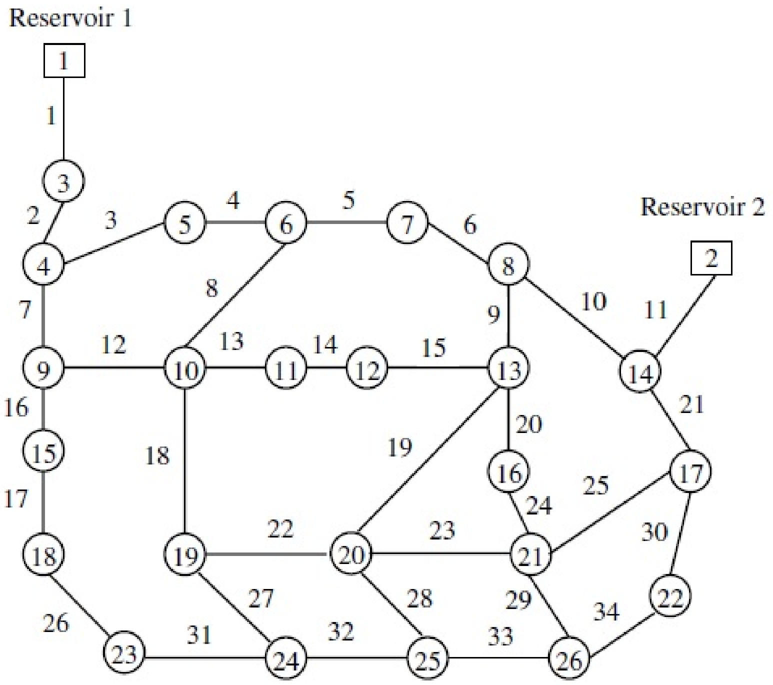

Figure (1): Two-source network

Table 1. Node and link properties for two-source network

Node No.	Demand (m^3/min)	Minimum HGL (m)	Pipe ID	Length (m)	Optimal Diameter (mm)
1	-	100	1	300	1000
2	-	95	2	820	1000
3	18.4	85	3	940	400
4	4.5	85	4	730	200
5	6.5	85	5	1,620	150
6	4.2	85	6	600	250
7	3.1	82	7	800	1000
8	6.2	82	8	1,400	150
9	8.5	85	9	1,175	450
10	11.5	85	10	750	600
11	8.2	85	11	210	1000
12	13.6	85	12	700	800

13	14.8	82	13	310	500
14	10.6	82	14	500	350
15	10.5	85	15	1960	150
16	9.0	82	16	900	500
17	6.8	82	17	850	300
18	3.4	85	18	650	450
19	4.6	82	19	760	150
20	10.6	82	20	1,100	150
21	12.6	82	21	660	900
22	5.4	80	22	1,170	150
23	2.0	82	23	980	450
24	4.5	80	24	670	300
25	3.5	80	25	1,080	750
26	2.2	80	26	750	150
			27	900	300
			28	650	250
			29	1,540	150
			30	730	300
			31	1,170	150
			32	1,650	150
			33	1,320	150
			34	3,250	150

Table 2. Pipe cost data for two-source network

Diameter (mm)	Unit Cost (In Indian Rupees)
150	1,115
200	1,600
250	2,154
300	2,780
350	3,475
400	4,255
450	5,172
500	6,092
600	8,189
700	10,670
750	11,874
800	13,261
900	16,151
1000	19,395

Hanoi Network

The second network considered in this study is Hanoi city water distribution network (Fig.2) which consists of thirty-two nodes, thirty-four pipes and one reservoir. It is used in this work to illustrate the crux of a resilient design of a water distribution network as the optimally designed network shows large head loss in some segments of pipelines. The input data for this problem is obtained from Fujiwara and Khang (1990) and is presented in Tables 3 and 4. Hazen Williams coefficient for all the pipes is assumed to be 130. The network is designed for peak demand as given in Table 3 and for a minimum nodal pressure head of 30 m. The cost corresponding to the optimal design of the network is $6.081 million (Suribabu, 2010). Table 3 provides the optimal pipe size of the network.

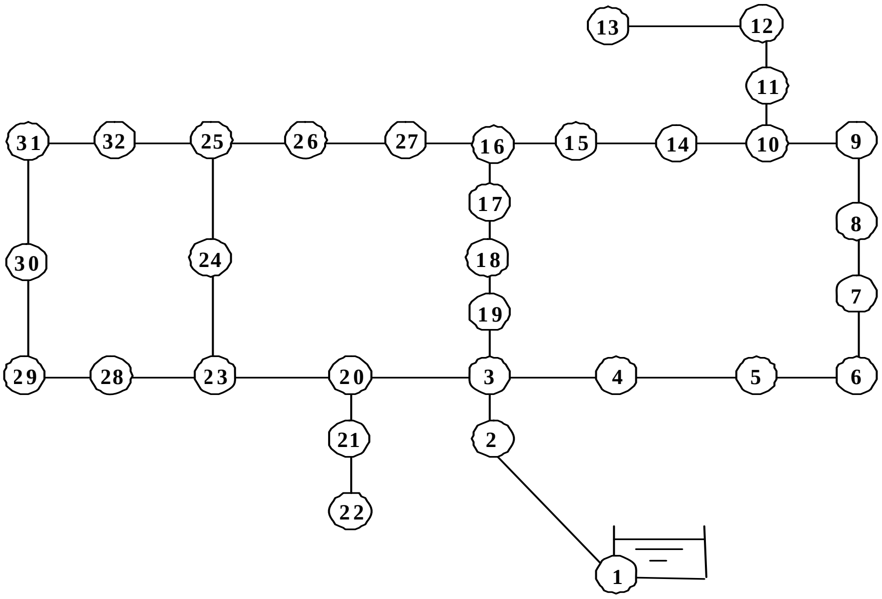

Figure (2): Layout of Hanoi network

Table 3. Node and link properties for Hanoi network

Node No.	Demand (m^3/hr)	Link Index	Arc	Length (m)	Optimal Diameter (mm)
1	-19,940	1	(1,2)	100	1016
2	890	2	(2,3)	1,350	1016
3	850	3	(3,4)	900	1016
4	130	4	(4,5)	1,150	1016
5	725	5	(5,6)	1,450	1016
6	1,005	6	(6,7)	450	1016
7	1,350	7	(7,8)	850	1016
8	550	8	(8,9)	850	1016
9	525	9	(9,10)	800	1016
10	525	10	(10,11)	950	762
11	500	11	(11,12)	1,200	609.6
12	560	12	(12,13)	3,500	609.6
13	940	13	(10,14)	800	508
14	615	14	(14,15)	500	406.4
15	280	15	(15,16)	550	304.8
16	310	16	(16,17)	2,730	304.8

17	865	17	(17,18)	1,750	406.4
18	1,345	18	(18,19)	800	609.6
19	60	19	(19,3)	400	508
20	1,275	20	(3,20)	2,200	1016
21	930	21	(20,21)	1,500	508
22	485	22	(21,22)	500	304.8
23	1,045	23	(20,23)	2,650	1016
24	820	24	(23,24)	1,230	762
25	170	25	(24,25)	1,300	762
26	900	26	(25,26)	850	508
27	370	27	(26,27)	300	304.8
28	290	28	(27,16)	750	304.8
29	360	29	(23,28)	1,500	406.4
30	360	30	(28,29)	2,000	304.8
31	105	31	(29,30)	1,600	304.8
32	805	32	(30,31)	150	406.4
		33	(31,32)	860	406.4
		34	(32,25)	950	609.6

Table 4. Cost data for pipes for Hanoi network

Diameter (in.)	Diameter (mm)	Cost ($)
12	304.8	45.73
16	406.4	70.400
20	508.0	98.380
24	609.6	129.333
30	762.0	180.8
40	1016.0	278.300

RESULTS AND DISCUSSION

The methodologies of increase in diameter, adding parallel pipelines to an existing system and optimally designed networks were experimented using EPANET (Rossman, 2000) software. Initially, one pipe with maximum velocity was considered for this process, and the process was continued for a number of times by changing the diameter of the link in every iteration. Also, the number of pipes considered was increased in each iteration to test the resilience of the network (for N number of iterations, where 'N' is the number of pipes considered). Iterative increase in pipe diameter is terminated based on the number of pipes that has attained the maximum available size.

During the first trial in the two-source network, it has been seen that pipe identity (ID) number 14 of diameter 350 mm experienced the maximum velocity of 2.32 m/s when compared to other links. Hence, the diameter of that pipe was modified to the next standard diameter 400 mm. Any increase in the size of the pipe certainly brings an increase in nodal delivery pressure, as head loss is inversely proportional to almost 5th power of diameter according to any head loss formula. Three measures to address the resilience of the network; namely, resilience index, modified resilience index and power efficiency of that network are calculated based on the data. Also, the increase in the cost of the modified network is calculated for each increase in the pipe size.The above process is carried out for 10 iterations, since at that iteration 25 pipes out of 34 reached the maximum diameter of 1000 mm. In Fig. 3, results obtained from the increase in pipe size are presented. It is noted that the resilience index and the modified resilience index increase with each iteration. Fig.3 shows the percentage increase in the resilience of the network when the cost of the network is increased by increasing the pipe diameter whose flow velocity is found to be maximum. From Table 5, it can be seen that around 8% increase in cost brought around 51% increases in both RI and MRI. The lines showing the increase in RI and MRI in Fig. 3 coincide.

Another important aspect that needs to be noted here is that the 8% increase in the network cost is able to deliver 68% more supply than actually required as per design. This is because, in each iteration, the diameter of the pipe increases, thus easing the velocity of water and pressure at each node. Such improved network design is indeed useful to tackle uncertainty in the demand. As the optimally designed network shows, the maximum velocity is less than 3 m/s which is usually taken as a threshold value for design.

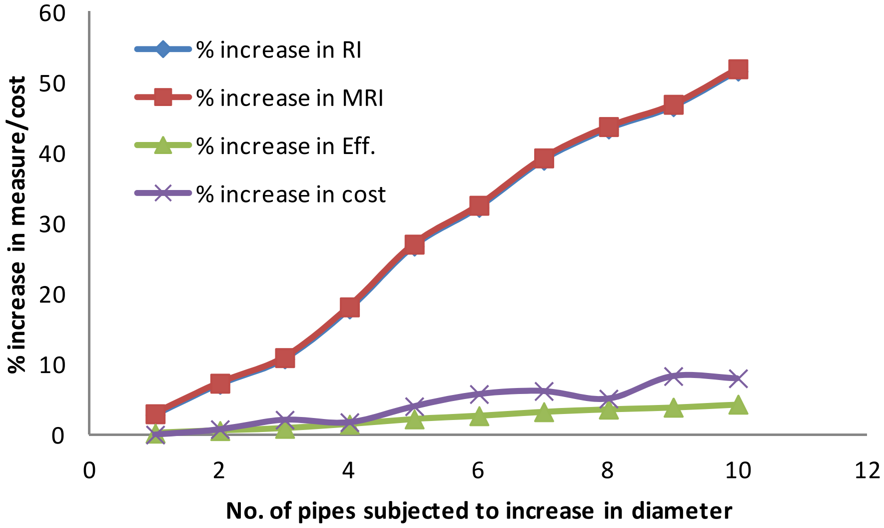

Figure (3): Plot showing the percentage increase in cost and resilience measures

Table 5. Two source network using the increase in pipe size approach

No. of pipes	Percentage increase in R.I. (%)	Percentage increase in M.R.I. (%)	Percentage increase in efficiency (%)	Percentage increase in cost (%)	Demand factor
1	2.837	2.991	0.2333	0.027	1.0001
2	7.168	7.32	0.598	0.796	1.0001
3	10.784	10.96	0.902	2.144	1.008
4	17.87	18.17	1.5	1.79	1.009
5	26.79	27.08	2.25	4.05	1.05
6	32.29	32.59	2.71	5.79	1.09
7	38.99	39.32	3.277	6.22	1.1
8	43.43	43.77	3.65	5.14	1.24
9	46.59	46.94	3.918	8.34	1.27
10	51.64	51.98	4.344	8.024	1.68

The optimal design solution for Hanoi network provided by Suribabu (2012) is used to enhance its resilience. The maximum velocity of the optimally-sized network is found to be 6.62 m/s in pipe ID 1. But, this pipe cannot be selected for size increase because it reached maximum size within the given options of optimal design. While searching other pipes, several pipes are sized with the maximum available size and therefore cannot be considered to increase their diameters for the same reason. Hence, the next maximum velocity of pipeline having diameter less than the maximum commercial size is selected. In the first trial, it has been seen that pipe 19 of 508 mm diameter experiences the maximum velocity of 3.27 m/s when compared to other links. Hence, the diameter of that pipe is modified to the next standard diameter from 508 mm to 609.6 mm. Once after the modification, the network is tested for flow and pressure at each node. Resilience index, modified resilience index and efficiency of that network are calculated based on the data tabulated. Also, the increase in cost of that modified network is also worked out to bring out the percentage increase in cost. Demand factor has to be varied accordingly in each iteration, and again check has to be carried out for the nodal pressure in each iteration. The above process is carried out for 7 iterations, since at that iteration out of 34 pipes, 20 pipes attained maximum diameter; i.e, 1016 mm. Results drawn out from Hanoi network using this approach and the same are presented in Table 5. From Table 6, it is evident that there is much less increase in efficiency when compared to the cost incurred for each iteration. Also, from the 3rd iteration, the percentage increase in cost takes a steep rise while the efficiency of the network shows a gradual increase resulting in maximum efficiency of 18.38% at the final iteration. For the 1st two iterations, the efficiency of the network increases marginally over the cost, thus proving that increase in diameter method is most suitable for less number of iterations. In terms of demand factor, change in diameter method achieves a maximum of 1.08, which implies that 8% of additional demand can be satisfied by this network. Similar to the two-source network, the percentage increases in RI and MRI coincide with each other though their numerical values are different. Hence, both the RI and MRI measures account to the same level of parameters of the network though their expressions are distinct. Despite seven pipes are increased in diameter, the increase in demand factor is insignificant. This is mainly due to the inability of increasing the pipe size to those pipes having maximum flow velocity as the selection options restrict to do so. In such a case, it is possible to introduce parallel pipes to augment the flow easily to other demand nodes without higher head loss.

In the first iteration, pipe ID 1 of 1016 mm diameter connecting the source and the node is chosen. This is because it possesses a maximum velocity of 6.62 m/s and also attained its maximum diameter. So, an additional pipe of lowest standard diameter; i.e., 304.8 mm is installed parallel to pipe 1. This additional pipe eases the rate of flow that occurred in pipe 1, thus decreasing the head loss. Available head at each node is noted, and RI, MRI, efficiency and cost of the network are calculated. Demand factor is also evaluated for the new layout and again check is made for the nodal pressure. In the second iteration, as discussed earlier, the second pipe is added parallel to the pipe experiencing next maximum velocity. In Hanoi network, it is noticed that pipe 2 of 1016 mm diameter possesses a velocity of 6.53 m/s, which is next maximum to pipe 1. Hence, the 2nd pipe of lowest standard diameter; i.e., 304.8 mm is added parallel to pipe number 2 and is tested for pressure. Here, the diameters of both added pipes are simultaneously increased to the next standard diameter and the corresponding available head at each node is calculated. Resilience measures, as well as the increase in cost and demand factor are evaluated. Table 7 shows the results obtained from parallel piping approach. It is evident that throughout the process there has been a steep increase in RI and MRI. This happens because for every pipe added to the network, there will be an increase in discharge and a simultaneous decrease in the velocity in the pipe. Unlike in diameter increase method, the efficiency of the network has always been high when compared to the cost incurred. This linear growth in the efficiency of the network implies that iterations involving the addition of 2 pipes produce more efficiency than iterations involving the addition of a pipe. In terms of demand factor, parallel piping system achieves a maximum value of 1.1 which implies that 10% of additional demand can be satisfied by this network. The quantum of increase in the efficiency of network denotes that a considerable reduction in head loss is achieved due to the addition of parallel pipes.

Table 6. Resilience improvement for Hanoi network using increase in pipe size

No. of Pipes	Pipe ID	Change in Diameter (mm)	Increase in RI (%)	Increase in MRI (%)	Increase in Efficiency (%)	Increase in Cost (%)	Demand Factor
1	19	(508-609.6)	3.55	3.55	1.09	0.21	1.01
2	19 18	(609.6-762) (609.6-762)	8.52	8.52	2.63	1.06	1.01
3	17 24 21	(406.4-508) (762-1016) (508-609.6)	22.96	22.96	7.09	12.12	1.01
4	22 17 25 19	(304.8-406.4) (508-609.6) (762-1016) (762-1016)	29.52	29.52	9.11	17.74	1.02
5	18 26 16 11 21	(762-1016) (508-609.6) (304.8-406.4) (609.6-762) (609.6-762)	39.14	39.14	12.08	31.36	1.04
6	17 34 33 10 29 16	(609.6-762) (609.6-762) (406.4-508) (762-1016) (406.4-508) (406.4-508)	49.01	49.01	15.13	43	1.06
7	17 16 15 28 32 26 34	(762-1016) (508-609.6) (304.8-406.4) (304.8-406.4) (406.4-508) (609.6-762) (762-1016)	59.54	59.54	18.38	47.44	1.08

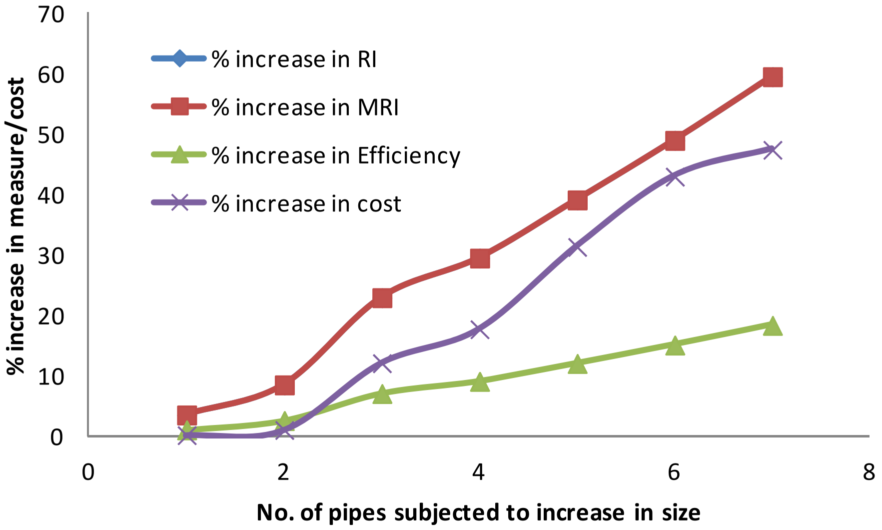

Figure (4): Percentage increase in cost and resilience measures for Honai network

Table 7. Resilience improvement for Hanoi network using parallel piping approach

No. of pipes added	Diameter of 1st pipe added	Diameter of 2nd pipe added	Increase in RI (%)	Increase in MRI (%)	Increase in efficiency (%)	Increase in cost (%)	Demand factor
1	304.8	Nil	3.55	2.3	0.71	0.08	1.01
2	304.8	304.8	15.64	14.23	4.43	1.14	1.02
2	406.4	406.4	31.91	30.31	9.44	1.77	1.03
2	508	508	53.47	51.6	16.07	2.47	1.06
2	609.6	609.6	56.01	73.94	12.88	3.25	1.09
2	762	762	91.81	116.58	23.91	4.54	1.1

CONCLUSIONS

This paper concentrated on designing a resilient water distribution network to handle additional demand. This design was carried out based on two methods; namely, the increase in pipe size method and the parallel piping method. From the results obtained above, it is evident that both methods were successful in designing a resilient water distribution network. Increase in pipe size method is more preferable in the networks having low velocity like two-source networks. As the velocity is less, pressure developed in the nodes will also be higher, thus satisfying more demand. The increase in pipe size can be adopted easily to enhance the resilience of the network at minimum increase in cost. Parallel piping system helps the network in bringing more discharge at the nodal points due to the additional pipe installed in the process. Unlike increase in pipe size method, parallel piping method makes meagre increase in cost as very few pipes are installed additionally to the network, but it results in a notable increase in efficiency. Thus, parallel piping system is more reliable and efficient for networks experiencing high velocity like Hanoi water distribution system. In these cases, the velocity in the pipes is greatly reduced, consequently increasing the nodal pressures. In terms of demand factor, parallel piping system satisfies much higher demand than the other method.

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