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Proceedings of ninth International Conference on Hydro-Science and Engineering (ICHE 2010), IIT Madras, Chennai, India.
2 - 5 August 2010

RELIABILITY INDICES USED IN DESIGN OF WATER DISTRIBUTION NETWORKS

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***Abstract**: Various reliability indices used for design of water distribution network are discussed. These indices are expected to represent the performance of the network under failure conditions. Actual performance of network under failure conditions can be represented in terms of supply-demand ratios at nodes and network. The supply at each node and the whole network are determined using head dependent flow analysis. Simultaneous failure of more than one pipe is ignored.*

Various indices of a bench mark problem having five different solutions are determined. It is observed that the indices do not represent the actual performance of network under failure conditions. This is contrary to the general belief among the researchers regarding the indices used for design of water distribution networks. In the absence of proper index representing robustness to handle failure conditions, it is necessary to carry out a detailed analysis of failure conditions to study the performance of the network at least at the final selection process.

***Keywords**: Water distribution network, reliability, resilience, index, failure condition.*

INTRODUCTION

Water distribution networks are basically used to convey water from source to consumer premises or intermediate storage tanks. The hydraulic requirement of any network is to convey the quantity of water at the required time to the consumers. When the distribution system is not designed up to the delivery locations, designers prescribe certain minimum pressure at the branching location. Hence out flow rate, (usually at the peak demand condition) and pressure at different nodes becomes the hydraulic requirement.

Like any design, cost minimization becomes the main objective in the case of water distribution networks also. During the operation period of the distribution network, planned shutdowns and unexpected outages of pipelines occur due to various reasons. In order to overcome these failure conditions, distribution networks are designed with higher resilience or higher reliability even though it may be costlier than the minimum cost solution. While designing a system with higher reliability, enough care should be taken to ensure that the system can really handle the failure conditions successfully. Otherwise, sufficient benefits cannot be ensured for the additional investments.

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Indices used for representing reliability are quite important while designing a network. Several indices to denote reliability were reported in the past (Fontanazza C M et al 2007). Different indices can give different designs. Designers have to ensure that they are getting maximum benefits out of the investments proposed. Hence the indices representing reliability should be capable of representing the performance of the entire network even in deficit conditions which are likely to happen in certain failures.

During failure conditions, network may not be able to meet the demand at certain nodes. So the actual supply at those nodes will be less than the demand. In this paper, "demand" is referred as the water requirement and "supply" is referred as the actual water delivered. Both are referred in terms of flow rate instead of quantity.

Some of the surrogate indices reported was found inadequate later. This paper deals with the merits and demerits of various indices reported.

RELIABIITY

As mentioned earlier the basic function of the distribution network is to convey water at desired flow to various nodes. Reliability index should be a quantified measure of the extent to which a distribution system can perform the required function (Tanyimboh 2001). Hence reliability should be regarded as the ratio of actual flow delivered to the required flow (Fujiwara O et al 1998) or the same can be represented as follows:

$$Reliability = \frac{Supply}{Demand} \quad \text{--- ---- --- --- --- --- --- --- --- ----} \ (1)$$

The supply and demand referred above are in flow rate. Similar ratios were reported earlier in terms of volume (Gupta R et al 1994). The supply-demand ratio related to each node is referred as "node reliability factor" and for the entire network, it is called "volume reliability factor".

Even though simultaneous failures of more than one pipeline are possible, the probability of occurrence of the same is quite small and can be disregarded in practice (Farmani R et al 2005, Agrawal M L et al 2007). Hence, network which can sustain single pipe failure (called as Level 1 redundancy) can be considered adequate. The failure condition referred in this paper relates only to the single pipe failures.

Under failure conditions, performance of network can become below satisfactory level. In such deficit conditions, the conventional fixed demand analysis will give a wrong picture (Chandapillai 2001). Instead, head dependent outflow analysis is necessary (Reddy S et al 1989, Chandapillai J 1991, Gupta R et al 1996, Zheng Y W et al 2009). In head dependent analysis, a relationship between pressure and supply at every node is also incorporated in addition to the conventional equations used in the fixed outflow analysis.

For head dependent flow analysis, the following relationship (Reddy S et al 1989, Chandapillai J 1991, Gupta R et al 1996, Zheng Y W et al 2009) is used:

$$Q = kH^n \quad \text{--- ---- ---- ---- ---- ---- -----} \; (1)$$

where Q is Node Outflow in cu.m/hr, K is the emitter or Outflow coefficient, H is pressure in m, n is the emitter or outflow exponent which is taken as 0.5 in this paper. Outflow coefficients were derived based on the assumption that 30m pressure corresponds to demand flow rate (Todini 2000). Eq.1 is valid up to a node corresponding to the node demand. When the node pressure is higher, the node flow is restricted to the node demand (Chandapillai J 1991).

OTHER INDICES

Least cost design of looped network under single loading condition result in some of the pipes having minimum diameter and heads at some of the nodes being barely satisfied. Hence least cost designs are meant for the normal operation and they are not meant to have the robustness to handle failure conditions. Attempts have been made to designs with capability of network to handle the failure conditions. Indices used for representing the reliability are quite important. It may be noted that the supply-demand ratio mentioned in previous section is the true representation of the performance. The other indices are developed mainly to avoid the detailed analysis.

An index called “Network reliability factor” is also reported (Gupta R et al 1994) which is a product of “Volume reliability factor”, “time factor” and “node factor”. Time factor is the ratio of duration in which node supply is within acceptable level to the total duration of supply. Node factor is the geometric mean of node reliability factors. Time factor and node factor have the deficiency of same weight to all demand nodes(Tanyimboh 2001). The network reliability factor which is a triple product of the factors between 0 and 1 and hence the value will be quite low. Due to these draw-backs the factors like “Network reliability factor”, “Time factor”, ”Node factor” are not widely used.

Various indices adopted by different researchers with merits and demerits are discussed below:

Minimum surplus head

The surplus head is difference in head between the actual head H_j and minimum head required H_j^l to supply the demand at any node. The minimum surplus head (I_m) among various nodes is considered as the available energy for dissipation during failure conditions. Maximization of the minimum surplus head is expected to increase the reliability. In mathematical form:

$$I_m = min\{H_j - H_j^l\} \quad j = 1,2 \ldots .nn \quad \text{--- --- --- --- ---} \; (2)$$

This index is conceptually related to the fixed demand analysis, which gives pressures at various nodes based on the fixed demand (Mays L W 2000). In fact there is no relationship between the pressure obtained through the fixed demand analysis and actual supply obtained through the head dependent analysis. Hence it may not be proper to give much emphasis on the head instead supply at every node.

When minimum surplus head is considered as index, surplus head in one node alone gets reflected. Since the importance of this particular critical node, under failure condition is not clear, this index cannot be considered as the true representation of the performance of the entire network under failure condition.

Total surplus head index

Summation of surplus head in various nodes (I_t) is also considered as a measure of reliability.

$$I_t = \sum_{j=1}^{nn} \{H_j - H_j^l\} \quad j = 1,2 \dots .nn \quad \text{--- --- --- --- --- (3)}$$

Instead of a single critical node (in the case of minimum surplus head), sum of surplus head of all nodes are considered in the case of total surplus head index. Hence it gives an indication regarding the overall excess head. Since the head obtained has no relation to the supply, this index does not ensure supply at various nodes. Moreover, arithmetic summation of heads may not reflect the ability to meet failure conditions when excessive heads at various nodes are not uniform.

Resilience index

One of the widely used indices representing the reliability of the network is resilience index (Todini 2000). Resilience index (I_r) is defined as:

$$I_r = 1 - \left(\frac{P_{int}^*}{P_{ext}^*}\right) \quad \text{--- --- --- --- --- --- (4)}$$

Where P_{int}^* is the power dissipated in the network to meet the demand and P_{ext}^* is the maximum power that would be dissipated internally in order to satisfy the constraints in terms of demand and head at the nodes. It can be represented as:

$$I_r = \frac{\sum_{j=1}^{nn} Q_j (H_j - H_j^l)}{\left(\sum_{k=1}^{nr} Q_k H_k + \sum_{i=1}^{npu} {P_i}/{\gamma}\right) - \sum_{j=1}^{nn} Q_j H_j^l} \quad \text{--- --- --- --- --- --- --- (5)}$$

nn, nr, npu are number of nodes, number of reservoirs and number of pumps. Q_i and h_i corresponds to the flow and head at each node. $\boldsymbol{\gamma}$ is the specific weight of water. Q_k and H_k are the discharge and head of each reservoir. P_i is the power introduced into the network.

By opting higher resilience index, more power than that is required will be getting provided at each node. This surplus is expected to provide intrinsic capability of overcoming sudden failures. The increase in resilience index is expected to give better network reliability (Todini E 2000). However it is reported that this is not always true (Reca J et al 2008) especially where the surplus power is not uniformly distributed. Excessive power available at certain nodes may not be useful to handle failure conditions. This is the weakness of the resilience index to account for reliability. Hence resilience index in two different problems cannot be compared.

When there are multiple reservoirs, resilience index may not reflect the increased reliability (Jayaram N et al 2008). This aspect is explained in detail in the section on "Modified Resilience Index". Even though the maximization of resilience Index improves reliability, it will not ensure delivery of water at different nodes (Prasad D. T et al 2004). Poor performance of network under failure condition was reported when resilience index was considered as objective function (Farmani R et al 2005). This problem was rectified by considering one additional objective of minimum surplus head. It may be noted that the concept of resilience index does not involve statistical considerations of failures.

Network Resilience

Maximization of minimum surplus head, summation of heads or resilience index may increase surplus head or power at nodes. But they do not reflect the effect of redundancy. In order to accommodate redundancy, resilience index is modified with a weightage factor (Prasad D T et al 2004). It is assumed that reliable loops are ensured if the pipes connected to a node are not widely varying in diameter. The weightage factor can be defined as:

$$C_j = \frac{\sum_{i=1}^{npj} D_i}{np_j X \; max\{D_i\}} \qquad \text{--- --- --- --- --- --- (7)}$$

Hence the network resilience can be expressed as:

$$I_r = \frac{\sum_{j=1}^{nn} C_j Q_j (H_j - H_j^l)}{\left(\sum_{k=1}^{nr} Q_k H_k + \sum_{i=1}^{npu} P_i/_\gamma\right) - \sum_{j=1}^{nn} Q_j H_j^l} \qquad \text{--- --- --- --- --- --- (7)}$$

The value of C_j will be 1 when all pipelines connecting to a node are having same diameter or the node is connected by a single pipeline. Assigning higher resilience value to a node with single connecting line is against the reported necessity of more than one line connecting to a node.

Modified resilience network

In the case of single reservoir feeding the network, the term used for input power $\sum_{k=1}^{nr} Q_k H_k$ remains same irrespective of pipe diameters and hence the resilience index is proportional to the surplus power. In the case of multiple reservoirs, the term $\sum_{k=1}^{nr} Q_k H_k$ depend on the pipe diameters or hydraulic capacities, as the flow from each reservoir depend on the diameters. In the case of multiple reservoirs, an increase in hydraulic capacity may not be reflected as increase in resilience index.

For instance, when diameter of pipes connected to a reservoir, which operates at higher HGL value as compared to other reservoirs, is increased, it is likely that a larger portion of the total demand would be served by this reservoir than before. This would increase the value of $\sum_{k=1}^{nr} Q_k H_k$ in addition to the possible increase in the value of $\sum_{j=1}^{nn} Q_j (H_j - H_j^l)$. The net effect would be a distortion of resilience index. In worst case, $\sum_{k=1}^{nr} Q_k H_k$ could even result in a decrease in resilience index despite the increase in hydraulic capacity.

In order to overcome this difficulty, modified resilience index(MI_r) is introduced (Jayaram N et al 2008) which is the ratio of surplus power available at outflow nodes to the sum of minimum required power at the output nodes. It can be expressed as:

$$MI_r = \frac{\sum_{j=1}^{nn}(H_j - H_{min,j})}{\sum_{j=1}^{nn} Q_j^{req} H_{min,j}} \quad --- \quad --- \quad --- \quad --- \quad --- \quad --- \quad --- \quad (8)$$

It may be noted that the modified reliance index provides alternate representation of network in the case of multi-reservoirs. However other problems related to resilience index are prevailing in the modified resilience index also.

COMPARISON

From the indices mentioned above, it is clear that all indices are just surrogate measures of reliability and they don't have any direct relationship with the performance under failure conditions. It is also clear that the increase in above indices will lead to increase in diameter of pipe in the network and hence the investment will also increase. However, the quantum of actual improvement in performance in failure condition is not clear.

These indices are tried in benchmark problems and the same cannot be considered as general performance indicators which can be used for comparison of different networks. Since there is no direct relation between the indices and the actual performance of distribution network under failure conditions, it is necessary to compare the indices with the actual performance. It is true that the determination of actual performance will lead to additional computational efforts. Considering the accuracy of the results, it may be worth taking the additional computational efforts. If the cost for computational effort and the cost of investment are compared, anyone will go for detailed computations. In the recent past, faster computers are made available at a very competitive price. This trend is likely to continue in future also.

	Ground level (m)	Minimum head (m)	Water Demand (Cu.m/hr)	Outflow Coefficient
Node 2	150	180	100	18.257
Node 3	160	190	100	18.257
Node 4	155	185	120	21.909
Node 5	150	180	270	49.295
Node 6	165	195	330	60.249
Node 7	160	190	200	36.515

Table 1 Two loop network data

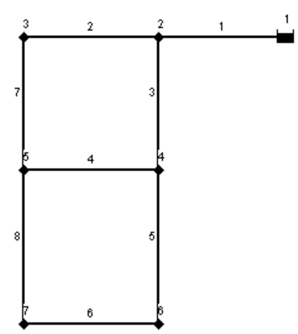

Fig 1 Two loop network

In order to understand the relationship between the indices and the actual performance of the network under failure condition, it is better to evaluate both of them for a particular network.

A two loop network which is used for illustrating resilience index (Todini 2000) is considered for comparison. This two loop problem is referred by several researchers for the last couple of decades. The schematic diagram of the network is given in Fig 1. The node data is given in Table 1.

The node 1 is supplying water at a head of 210m to the remaining nodes. Diameters of links are given in Table 2 under Optimum Cost solution (Todini 2000). All pipelines have a length of 1000m and Hazen-William's C-value 130. Outflow coefficients were derived based on the assumption that 30m pressure corresponds to demand flow rate (Todini 2000).

	Diameter of links in different solutions (mm)				
	Opt cost Solution	Sol A	Sol B	Sol C	Sol D
Pipe 01	457	457	457	457	457
Pipe 02	254	406	406	406	406
Pipe 03	406	356	356	356	356
Pipe 04	102	152	152	152	152
Pipe 05	406	356	356	356	356
Pipe 06	254	25	25	25	25
Pipe 07	254	356	356	356	356
Pipe 08	25	254	254	254	254

Table 2 Diameter of two loop network for different solutions

Performance of two-loop Cost optimum solution is given in Table 3. In order to determine the performance under failure condition, head dependent flow analysis is carried out without the particular pipeline. Results contain actual supply (flow rate) from each node. Similar analysis is repeated by deleting respective pipelines and the out flow rates were obtained. The supply-demand ratio is determined based on demands mentioned in Table 1. Last row in Table 3 indicates the total demand and supply-demand ratio of the entire network.

	Water Demand (m^3/hr)	Supply-Demand ratio at different failure conditions							
		Pipe 01 failed	Pipe 02 failed	Pipe 03 failed	Pipe 04 failed	Pipe 05 failed	Pipe 06 failed	Pipe 07 failed	Pipe 08 failed
Node 2	100	0	1	1	1	1	1	1	1
Node 3	100	0	0	1	0.97	1	1	1	1
Node 4	120	0	1	0.34	1	1	1	1	1
Node 5	270	0	0.24	0.99	1	1	1	0.24	1
Node 6	330	0	1	0	1	0	1	1	1
Node 7	200	0	1	0	1	0.01	0.01	1	1
Total	**1120**	**0**	**0.73**	**0.45**	**1**	**0.53**	**0.82**	**0.82**	**1**

Table 3 Performance of two-loop cost optimum solution

Table 3 gives a clear picture of the actual performance of the network. It may be noted that the supply and demand are presented in terms of flow rate. Hence it represents the instantaneous flow rate at failure condition. Duration of such failure may depend on the nature of failure, facility to repair etc. As the focus is to reduce the disparity in instantaneous flow rate, supply –demand ratio is represented. If the duration of such failure is not extended until demand in at least one node is completely met, supply-demand ratio in terms of flow rate and volume are same.

It can be observed that the last column in Table 3 indicating the supply-demand ratio is 1 when Pipe 08 is failed. This shows that the performance of the network is not affected even if the line 08 is failed. In other words, pipe 08 is not necessary for normal operation of network. Performance of network when pipe 04 is failed is also similar except a marginal 3% deficiency at node 3.

When pipe 01 is failed, no supply is received in any node. It is evident in Fig.1 that all nodes in the network is getting isolated from the source. It explains the need for another additional route connecting the source to other nodes. It may be noted that this observation is in line with the reported necessity of at least two lines connecting every node in a network (Agrawal M.L 2007).

Except the failures of lines 04 and 08, all other failures give low supply-demand ratios less than 25% at nodes. Some are not getting any water in certain failures. These situations are quite serious and hence require attention. Among different nodes node 2 gets the demand flow rate in all single failure cases except the failure of pipe 01. The deficiency in supply in all other nodes is quite less and zero in certain cases. Hence node 2 is in a comfortable position compared to other nodes, as far as availability of water is concerned.

The aim of the designer should be to avoid the non-supply situations and raise the minimum supply demand ratio above a certain level. The level can be decided based on the time required to rectify the failure, storage capacity with each consumer etc. The improvement in supply demand ratio can be achieved by providing additional pipe lines or replacing the lines with lines having higher diameter.

Table 4 to 7 gives the similar performance of the two loop network when different diameters (mentioned in table 2) were used. These alternate designs (solutions A to D) other than optimum cost solution are reported in literature (Todini E 2000) as solutions with higher reliability. The same example is selected to verify the real performance under failure condition.

	Water Demand (m^3/hr)	Supply-Demand ratio at different failure conditions							
		Pipe 01 failed	Pipe 02 failed	Pipe 03 failed	Pipe 04 failed	Pipe 05 failed	Pipe 06 failed	Pipe 07 failed	Pipe 08 failed
Node 2	100	0	1	1	1	1	1	1	1
Node 3	100	0	0.02	1	1	1	1	1	1
Node 4	120	0	1	0.61	1	1	1	1	1
Node 5	270	0	0.58	1	1	1	1	0.58	1
Node 6	330	0	1	0.19	1	0	1	1	1
Node 7	200	0	0.02	0.99	1	1	1	0.02	0.01
Total	**1120**	**0**	**0.64**	**0.72**	**1**	**0.71**	**1**	**0.72**	**0.82**

Table 4 Performance of two-loop solution A

	Water Demand (m^3/hr)	Supply-Demand ratio at different failure conditions							
		Pipe 01 failed	Pipe 02 failed	Pipe 03 failed	Pipe 04 failed	Pipe 05 failed	Pipe 06 failed	Pipe 07 failed	Pipe 08 failed
Node 2	100	0	1	1	1	1	1	1	1
Node 3	100	0	0.03	1	1	1	1	1	1
Node 4	120	0	1	0.6	1	1	1	1	1
Node 5	270	0	0.58	1	1	1	1	0.58	1
Node 6	330	0	1	0.17	1	0	1	1	1
Node 7	200	0	0.03	0.95	1	1	1	0.04	0.01
Total	**1120**	**0**	**0.64**	**0.7**	**1**	**0.71**	**1**	**0.73**	**0.82**

Table 5 Performance of two-loop solution B

	Water Demand (m^3/hr)	Supply-Demand ratio at different failure conditions							
		Pipe 01 failed	Pipe 02 failed	Pipe 03 failed	Pipe 04 failed	Pipe 05 failed	Pipe 06 failed	Pipe 07 failed	Pipe 08 failed
Node 2	100	0	1	1	1	1	1	1	1
Node 3	100	0	0.41	1	1	1	1	1	1
Node 4	120	0	1	0.72	1	1	1	1	1
Node 5	270	0	0.71	1	1	1	1	0.76	1
Node 6	330	0	0.99	0.4	1	0	1	0.99	1
Node 7	200	0	0.37	0.89	1	1	1	0.45	0.01
Total	**1120**	**0**	**0.76**	**0.77**	**1**	**0.71**	**1**	**0.84**	**0.82**

Table 6 Performance of two-loop solution C

	Water Demand (m^3/hr)	Supply-Demand ratio at different failure conditions							
		Pipe 01 failed	Pipe 02 failed	Pipe 03 failed	Pipe 04 failed	Pipe 05 failed	Pipe 06 failed	Pipe 07 failed	Pipe 08 failed
Node 2	100	0	1	1	1	1	1	1	1
Node 3	100	0	0.03	1	1	1	1	1	1
Node 4	120	0	1	0.6	1	1	1	1	1
Node 5	270	0	0.58	1	1	1	1	0.58	1
Node 6	330	0	1	0.17	1	0	1	1	1
Node 7	200	0	0.03	0.99	1	1	1	0.04	0.01
Total	**1120**	**0**	**0.64**	**0.71**	**1**	**0.71**	**1**	**0.73**	**0.82**

Table 7 performance of two loop solution D

Table 8 gives different indices and the cost of all solutions of the two loop network. Minimum surplus head, Total surplus head, Resilience Index, Network resilience, Modified Resilience Index are presented for all the solutions of the two loop problem.

Minimum supply-demand ratio at node and entire network which are called as node reliability and total reliability respectively, are found to be zero (Table 3 to 7). Even though the designers are expected to increase these indices, it is not reflecting the improvement in reliability between different solutions. However it indicates the possibility of getting all nodes isolated from source under failure condition.

Sl. No.	Indices	Cost opt solution	Solution A	Solution B	Solution C	Solution D
1	Min surplus head (m)	0.39	1.01	1.82	2.88	3.48
2	Total surplus head (m)	41.81	65.32	74.19	75.72	77.04
3	Resilience Index	0.21	0.40	0.46	0.47	0.48
4	Network resilience	0.17	0.31	0.35	0.37	0.37
5	Modified Resilience Index (%)	2.49	4.72	5.50	5.64	5.77
6	Min. Node reliability	0	0	0	0	0
7	Min. total reliability	0	0	0	0	0
8	Average Node Reliability	0.70	0.72	0.73	0.76	0.73
9	Average Total Reliability	0.67	0.69	0.70	0.74	0.70
10	Cost (thousand $)	419	450	460	467	478

Table 8 Indices and cost of different solutions of two loop network

In order to represent the network as single index, average of all node reliability and total reliability are calculated and presented in Table 8. Costs of all solutions are also presented. The first five indices in Table 8 show that the reliability increases when cost of the network is increased. However average node reliability and average total reliability shows that solution D is inferior in reliability to solution C, even though the cost of solution D is more than solution C. Comparison between supply-demand ratios of all nodes described in table 7 and table 6 also shows that solution C is better than solution D. All values of supply-demand ratios of table 6 are more than table 7 except a marginal increase of 1% in node 6 when pipe 07 is failed. Hence solution C can be considered superior to solution D, in terms of reliability. It is reported that (Reca J et al 2008) the resilience index cannot be used for comparing different networks and it can be used for comparing different designs of the same network. However, resilience index mentioned for solution C and solution D shows that it cannot be used even in the same network.

It is reported that (Todini E 2000) that resilience index doubles when Solution A is opted instead of cost optimum solution and solution D is suggested as solution with highest reliability. This is not true. Even though solution A is having higher reliability than cost optimum solution, performance cannot be termed as double. It is evident from the table 3 and table 4. Node reliability and network reliability mentioned in table 8 also illustrates the same. Moreover solution D is not the solution with highest reliability. Among different solutions Solution C can be considered as the solution with highest reliability.

CONCLUSIONS

Reliability indices, minimum surplus head, total surplus head, resilience index, network resilience and modified resilience index were computed for five alternative designs of a benchmark problem. The actual performance of the networks in terms of supply-demand ratios at every node was also determined. The comparison between the indices and the actual performance show that the indices are not representing the performance of the network under failure conditions. The increase in cost and diameter need not produce better performance of a network under failure conditions. Hence it will be better to derive actual supply-demand ratios in all nodes and network, instead of depending on surrogate measures. It is true that the determination of supply-demand ratios in all failure conditions require more computational effort. However, designers are advised to explore the possibility of detailed analysis of failure conditions, especially due to the availability of computers with increased memory and speed. In the case of difficulties, it is better to analyze the failure conditions of at least the final solutions before taking a final decision.

ACKNOWLEDGEMENT

The authors wish to express sincere gratitude to their colleagues and family members who helped in the work directly or indirectly.

REFERENCES

1. Agarwal M L, Rajesh Gupta, Pramod R Bhave (2007) "Reliability based strengthening and expansion of water distribution networks", *Jl. of Water Resources Planning and management* Nov/Dec 2007 pp 531-541.
2. Chandapillai J. (1991) "Realistic simulation of Water Distribution System" *ASCE Journal of Transportation Engineering,* Vol. 117, No.2
3. Chandapillai J., Narayana Iyer, R. (2001) "Equitable distribution of water though pipe network under low supply situation" *Proc. of the 4th international conference on WATER PIPELINE SYSTEMS*, BHR Group 28-30 March 2001, York, U.K.
4. Farmani Raziyeh, Godfrey A Walters and Dragan A Savic (2005) "Trade off between total cost and reliability for Anytown water distribution network", *Jl. of Water Resources Planning and management* May/June 2005 pp 161-171.
5. Fontanazza C.M, G Frei, G La loggia and V. Notaro (2007) " Definition of performance indicators for urban water distribution systems in drought conditions" Performance assessment of Urban Infrastructure services, edited by Enrique Cabrera Jr and Miguel Angel Pardo, IWA publishing.
6. Fujiwara Okitsugu and Jun Li (1998) "Reliability analysis of water distribution networks in consideration of equity, redistribution and pressure dependent demand" *WATER RESOURCES RESEARCH, VOL. 34, No.7 July 1998 pp 1843-1850.*
7. Gupta R, Pramod R Bhave (1994) "Reliability analysis of water distribution systems", *Jl. of Environmental Engineering* March/April 1994 pp 447-460.
8. Gupta R, Pramod R Bhave (1996) "Comparison of Methods for predicting deficient network performance", *Jl. of Water Resources Planning and management* May/June 1996 pp 214-217.
9. Jayaram Nirmal , Srinivasan K, (2008) "Performance-based optimal design and rehabilitation of water distribution networks using life cycle costing" *WATER RESOURCES RESEARCH, VOL. 44, W01417, doi:10.1029/2006WR005316, 2008.*
10. Mays L .W(2000) " Water Distribution Systems Handbook" McGrawHill, New York.
11. Prasad D T, Nam Sik Park (2004) "Multiobjective Genetic Algorithms for design of water distribution networks", *Jl. of Water Resources Planning and management* Jan/Feb 2004 pp 73-82.

12. Reca J, Martinez J, Banos R and Gil C, (2008) "Optimal design of gravity fed looped water distribution networks considering the resilience index", *Jl. of Water Resources Planning and management* May/June 2008 pp 234-238.
13. Rossman L.A(2000) EPANET Users Manual, U.S Environmental Protection Agency, Cicinnati, Ohio.
14. Reddy Srinivasa L., and Elango, K. (1989) "Analysis of Water distribution networks with head dependent outlets", *Civil Engg. Systems,* Vol.6, No.3, 1989, pp102-110.
15. Tanyimboh TT, M Tabesh and R Burrows (2001) "Appraisal of source head methods for calculating reliability of water distribution networks", *Jl. of Water Resources Planning and management* July/Aug 2001 pp 206-213.
16. Todini Ezio (2000) "Looped water distribution networks design using resilience index based heuristic approach" Urban Water 2 (3), 115-122
17. Zheng Y. Wu, Rong H Wang, Thomas M Walski, Shao Y Yang, Danniel Bowdler, Christopher C Bhaggatt (2009) "Extended Global Gradient Algorithm for pressure-dependent water distribution analysis" *Jl. of water resources planning and Management, ASCE", Vol 135, No.1 pp 13-22.*