Analysis and Design of an Intermittent Water Distribution Network

Ramani Katineni[1*] and Umamahesh V.Nanduri[2]
[1]*Department of Civil Engineering, National Institute of Technology-Warangal 506004, Telangana State, India.*
[2] *Water and Environment Division, National Institute of Technology-Warangal 506004, Telangana State, India.*
*(*Email:* ramaniketeneni@gmail.com, *mahesh@nitw.ac.in)*

Abstract

In many urban areas of the developing countries, piped water is supplied only intermittently, as valves direct water to different parts of the water distribution system at different times. One of the major problems associated with an intermittent water distribution networks is "Equity". A new index "Uniformity Coefficient" is considered to measure the Equity in distribution of water within the network, which may be useful for performance evolution of water distribution networks (WDNs). Developed a methodology for optimal design of an intermittent WDN using multi objective Genetic Algorithm incorporating Uniformity Coefficient, Cost and Reliability and studied the interdependence among the various network performance indicators and found this method is simple, quick and reliable.

Keywords: Equity, Intermittent water distribution networks, Uniformity Coefficient, Reliability and Cost .

1. Introduction

Water Distribution Network (WDN) is a system containing pipes, reservoirs, pumps, valves of different types, which are connected to each other to provide water to consumers. It is a vital component of the urban infrastructure and requires significant investment (Abebe *et al.*, 1998).

The primary objective of a water distribution network is to provide required quantity of water with sufficient pressure at required times to all its users.

Most of the design models are based on the assumption of a continuous system of supply. In India and many other developing countries, intermittent system of supply has been in use, in which water is supplied only for a fixed duration and consumers tend to collect water and store it for use during the non supply period. As the outlets are uncontrolled and the discharge is proportional to the head, nodes with higher available head get more water than required and the nodes with lower available head will get less water in a given duration which means unequal distribution of water takes place in a network.

One of the major problems associated with an intermittent water distribution networks is "Equity". A new index "Uniformity Coefficient" is introduced to measure the Equity in distribution of water within the network, which may be useful for performance evolution of water distribution networks (WDNs). Developed a methodology for optimal design of an intermittent WDN using multi objective Genetic Algorithm NSGA-II and EPANET Network solver incorporating Uniformity Coefficient, Cost and Reliability and studied the interdependence among the various network performance indicators.

During conditions involving excessively high demands for firefighting or failure of some network elements, a demand driven analysis can yield nodal pressures that are lower than the required minimum or which can become negative. This condition of the network is termed pressure deficient (Wu *et al.,* 2006). The demand driven analysis may generate unrealistic hydraulic results under the abnormal operating conditions (Baek *et al.,* 2010), it gives accurate results under normal operating conditions, because it considers fixed demands regardless of the pressure variation. In this study, the HDA model based on the source head method suggested by (Tanyimboh *et al.,* 2001) used to simulate an intermittent water distribution system.

Reliability of water distribution system is becoming of increasing concern to water system designers and operators. Many researchers have tried to incorporate reliability in the design of water distribution systems to be optimized without increasing the cost. There is no well defined meaning for reliability; it is concerned with the capability of providing adequate supply under both normal and abnormal operating conditions. A heavily redundant, highly looped network with large pipes provides a very reliable system with in- built resilience under exceptional loading conditions such as firefighting and pipe breakage. Such a system is very expensive to construct. There is a clear need to design a procedure which is able to strike an acceptable compromise between reliability/resilience and cost. Hence in this work a reliability measure called Network Resilience (Deviprasad *et al.,* 2004) is introduced based on the concept by providing excess pressure available at the nodes of a water distribution system as a possible subject to monetary constraints and is incorporated in the optimal design of water distribution network.

2. Formulation of the problem

2.1 Problem definition

Minimization of the total cost of the network (concentration on the pipes only) and maximization of reliability and uniformity coefficients are considered as three objectives and hence the problem is multi objective problem. In such a situation one gets several solutions with different costs and having different values of reliabilities and uniformity coefficients. Our aim is to obtain a best pareto-optimal front, consisting of several pareto-optimal solutions.

2.2 Objective function:

i) Minimization of network cost

$f_1 = \sum_{i=1}^{N_p} C_i(D_i, L_i)$ …………………… (1)

ii) Maximization of Uniformity Coefficient

$f_2 = UC$ -------------------------(2)

iii) Maximization of Network Resilience

$f_2 = I_n$ ------------------------------------- (3) Where C_i (D_i, L_i) = Cost of the ith pipe with diameter D_i and length L_i

N_p = Number of pipes in the system

UC = Uniformity Coefficient

I_n = Network resilience

.

3. Methodology:

3.1 Network Analysis:

The quantity of water that a distribution network can actually deliver at adequate pressure is one of the principal factors determining the performance and reliability of the system. Therefore the relationship among the actual nodal outflows and heads used here is as follows.

$$Q_j = Q_{jreq} X \sqrt[n]{\frac{H_s - H_{sj}^{min}}{H_{sj}^{des} - H_{sj}^{min}}} \qquad if \qquad H_{sj}^{min} \leq \mathrm{H_s} \leq H_{sj}^{des}$$

$$\mathrm{Qj}=0 \qquad \mathrm{if} \qquad \mathrm{H_s} \leq H_{sj}^{min}$$

$$\mathrm{Q_j}= \mathrm{Q_j^{req}} \qquad \mathrm{if} \qquad \mathrm{H_s} \geq H_{sj}^{des}$$

Where,

H_s = head available at source .

H_{sj}^{min} = head at source at which flow at node j will just begin.

H_{sj}^{des} = head at source at discharge at node j is equal to the demand .

Q_j = discharge at node j.

Q_j^{req} = demand at node j.

Developed a methodology for optimal design of an intermittent WDN using multi objective Genetic Algorithm NSGA-II and EPANET solver incorporating Uniformity Coefficient, Cost and Reliability. We studied the interdependence among the various network performance indicators The GA Parameters used were Population Size: 200, Probability of Cross over: (0.6-1.0), Probability of Mutation: (1/no of real variables), Number of Generations: 200. Seed value (0.0-1.0). The distribution index for crossover is 5-20 and distribution index for mutation is5-50.

3.2 Reliability Measure or Network Resilience I_n

The following reliability measure, called network resilience (I_n), incorporates the effect of surplus power and reliable loops and is a measure of combined effect of surplus power and nodal uniformity.

$$I_n = \frac{X}{X_{max}} = \frac{\sum_{j=1}^{nn} C_j Q_j (H_j - H_j^l)}{\left[\sum_{k=1}^{nr} Q_k H_k + \sum_{i=1}^{npu} (P_i/\Upsilon)\right] - \sum_{j=1}^{nn} Q_j H_j^l}$$

n_r =Number of reservoir nodes

nn= Number of nodes.

Q_k, H_k=Discharge and head corresponding to each reservoir node.

Where $X_{max} = (P_{inp} - \sum_{i=1}^{nn} Q_j H_j^l)$ = Maximum surplus power

Theoretically, the value of network resilience may vary between 0 and 1. However, for real systems it never attains a value of 1.

3.3 Uniformity Coefficient:

$$\text{UC} = 1 - \left[\frac{\text{ADEV}}{\text{ASR}}\right]$$

SR = Supply Ratio of the node, is the ratio of actual quantity of water delivered at a node to the demand at that node.

ASR = Average Supply Ratio, the mean of supply ratios of the all nodes in the network.

ADEV = Deviation of supply ratio at the node from the ASR is computed at each node and the average of these deviations is ADEV.

If the demand is exactly satisfied at all the nodes then the supply ratios at all the nodes will be one and hence UC would also be one. While designing a water distribution network, the objective is to maximize the uniformity coefficient, so that all the nodes will have an equal level of demand satisfaction.

4. Results and Discussion

Non Dominated Sorting Genetic Algorithm –II is used as an optimization tool with the objective of minimization of network cost, and maximization of Uniformity Coefficient and Network Resilience. Before applying the simulation tool, simulations are run with different values for various parameters of NSGA like number of generations, number of individuals per generation, probability of crossover, probability of mutation, seed value, distribution indices like mutation distribution index and crossover distribution index. After obtaining the results of trails made with different values the developed program has been executed by taking seed value as 0.6, number of individuals per generation as 200, probability of crossover 0.8, probability of mutation = 1/ (no of real variables), distribution indices namely, mutation distribution index = 15 and crossover distribution index = 25.

The applicability and efficiency of the proposed reliability-based optimization model is demonstrated by its application to the following example problem. Figure.1 was previously used as Tanyimboh network. The network consists of 18 links, 12 demand nodes and one source node. The node and link data for this network is given in Tables 1.0 and 1.1. The elevation of each demand node is 700m. The minimum residual pressure head at each demand node is 30m. The Hazen-Williams roughness coefficient is taken as 100 for all pipes. The same set of GA parameters as the previous model is applied here

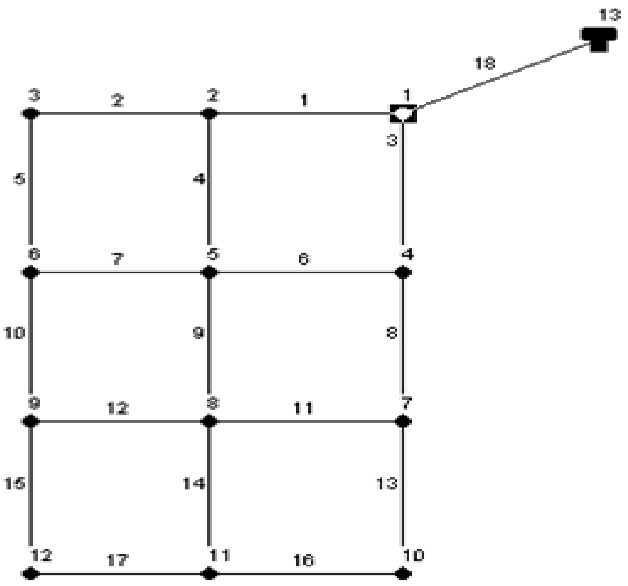

Fig 1.Layout of Network

Table 1.0 Node data for network

Node ID	**Elevation, m**	**Demand, lps**
1	700	27.8
2	700	27.8
3	700	41.7
4	700	41.7
5	700	41.7
6	700	27.8
7	700	55.5
8	700	55.5
9	700	55.5
10	700	27.8
11	700	41.7
12	700	27.8

Table 1.1 Link data for network

Link ID	**Start Node**	**End Node**	**Length, M**	**Diameter, mm**	**Roughness coefficient**
3	1	4	1000	750	100
4	2	5	1000	900	100
5	3	6	1000	500	100
8	4	7	1200	600	100
9	5	8	1200	750	100
10	6	9	1200	450	100
13	7	10	1200	300	100
14	8	11	1200	600	100
15	9	12	1200	350	100
1	1	2	1500	100	100
6	4	5	1500	350	100
11	7	8	1500	300	100
16	10	11	1500	200	100
2	2	3	1200	600	100
7	5	6	1200	450	100
12	8	9	1200	400	100
17	11	12	1200	300	100
18	13	1	10	1000	100

The Pareto fronts obtained are as shown in the following figures.

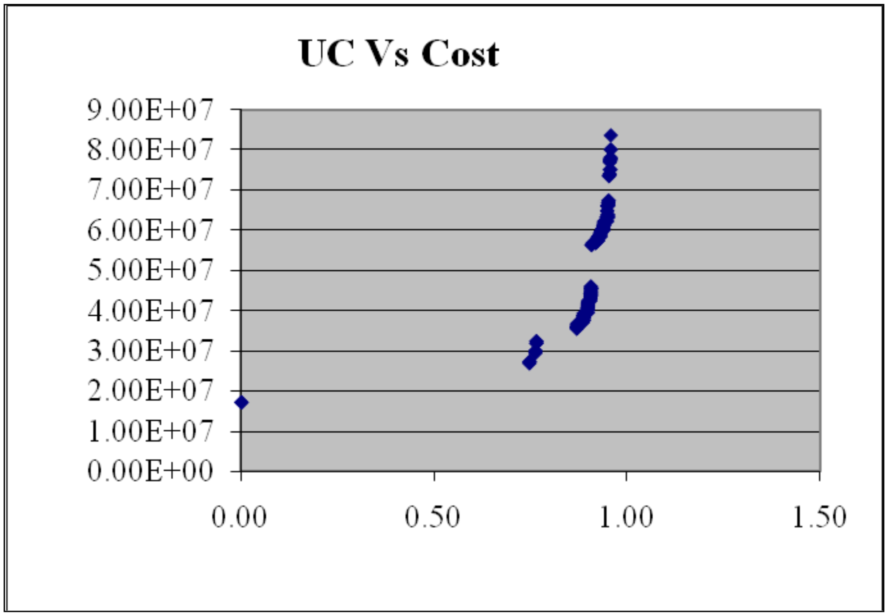

Fig 2.Variation of Uniformity Coefficient with cost.

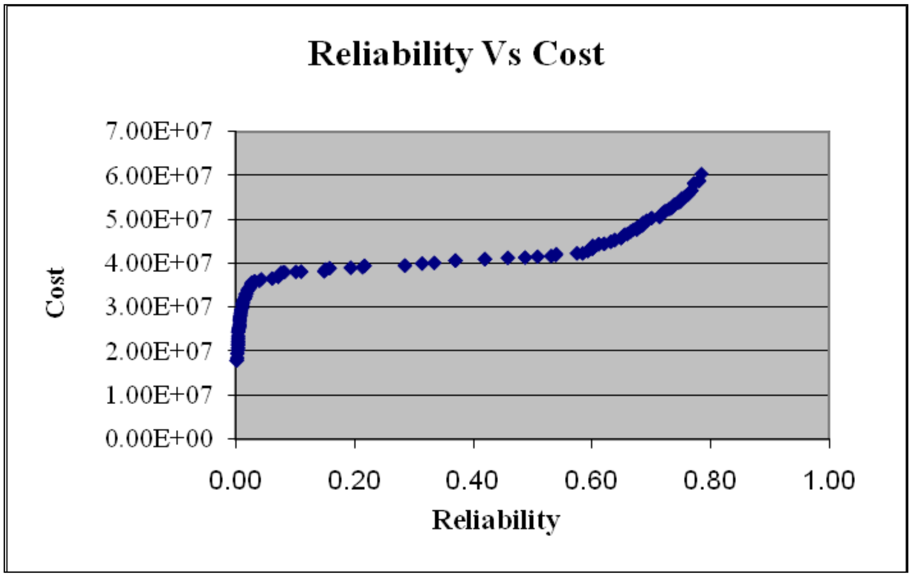

Fig 3.Variation of Reliability with cost.

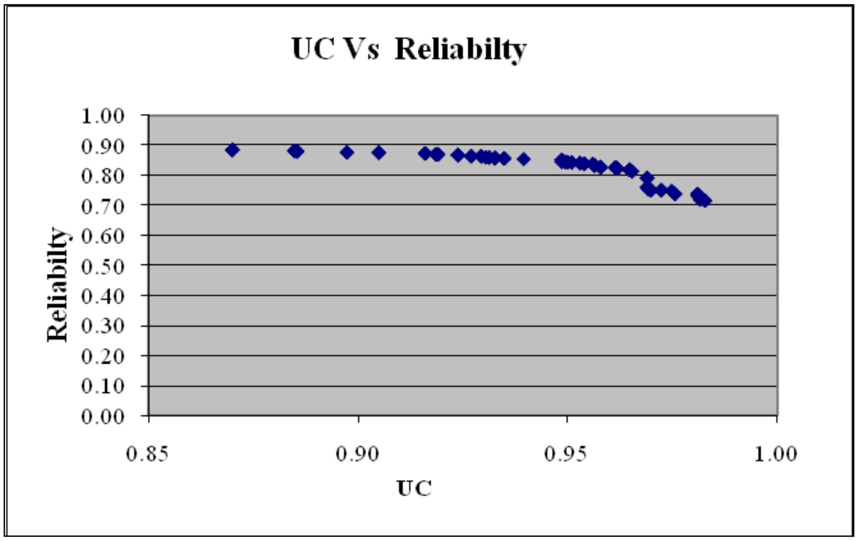

Fig 4.Variation of Uniformity Coefficient with Reliability.

Fig.2 illustrates that cost increases with increase in UC, while Fig.3 shows the increase of cost with respect to reliability. Comparatively, the increase of cost as a function of UC is more than that of reliability. Fig.4 shows that reliability decreases slightly with increase in UC.

6. Conclusions and Inferences

The present work emphasizes the need of computing the Uniformity coefficient and it can be used for quantifying the equity in distribution of water among various nodes within zone of distribution. Staggered water supply may improve the equity in water supply.

NSGA-II gives a comparatively better constraint handling technique that does not require a penalty coefficient and is applicable to water distribution networks. This technique ensures that a feasible solution is better than any infeasible solution in the population. The method produces a set of Pareto-optimal solutions in the search space of cost, UC and reliability. From the results obtained from different networks, we infer that maximizing the UC alone makes the cost of the network maximum, which is uneconomical. By maximizing the reliability the UC is low and cost becomes higher. In order to ensure uniform supply of water and economical network, the reliability of the network should be decreased. By minimizing the cost alone, we cannot obtain satisfactory results from any network. Compromising the cost to some extent will yield better UC and reliability.

A methodology for optimal design of WDN for intermittent systems using different evolutionary techniques and making comparative studies is being continuation of this study.

References

Abebe, A.J. and Solamatine, D.P. (1988). Application of global optimization to the design of pipe networks. 3rd international conference on hydroinformatics, Copenhagen.

Baek, C.W., Jun, H.D. and Kim, J.H. (2009). Development of PDA model for water distribution systems using Harmony Search Algorithm. Journal of Civil Engineering. KSCE 14(4), 613-625.

Bhave, P.R. (1981). Node Flow Analysis of Water Distribution Systems. Journal of Transportation Engineering, ASCE, 107(4), 457-467.

Bhave, P.R (2003. Optimal design of water distribution networks.

Deviprasad, T. and Nam-sik park, M. (2004). Multiobjective Genetic Algorithms for Design of Water Distribution Networks. Journal of water resources planning and management, ASCE 130(1), 73-82.

Moneim, M.A., Moawad, A.K., Molla, A.A. and Selawy, A.A. (2010). Model Application for Reliability-based optimization of water distribution networks. World Engineering and Applied Sciences Journal 1(1):01-08.

Tabesh, M., Tanyimboh, T.T. and Burrows.R. (2002). Head driven simulation of water supply networks. IJE Transactions A: Basics, 15(1), 11-22.

Tanyimboh, T., Tahar. B., and Templeman.A. (2003). Pressure –driven modeling of water distribution systems. Water science and technology:water supply, 3(1-2),255-261.

Tanyimboh, T.T., and Templeman. A.B. (1993). Optimum design of flexible water distribution networks. Civil engineering systems 10(3),243-258.

Tanyimboh, T.T., Tabesh, M. and Burrows, R. (2001). Appraisal of source head methods for calculating reliability of water distribution networks. Journal of water resources planning and management, ASCE 127(4), 206-213.

Wah,K.A.and Paul, W.J. (2006) . Solution for Water Distribution Systems under Pressure Deficient Conditions. Journal of water resources planning and management, ASCE 132(3), 175-182.