RELIABILITY BASED OPTIMAL DESIGN OF A WATER DISTRIBUTION NETWORK FOR MUNICIPAL WATER SUPPLY

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Abstract

The history of water supply and distribution is as old as the history of civilization. In the present society, water supply system has become an important and necessary element. It also gives an indication of level of advancement of society. Water Distribution Network (WDN) is an important component of water supply system which contributes to nearly 70% of the total cost. Optimal design of water distribution network is the aim of any agency dealing with water supply distribution. Consideration of reliability in water distribution networks has been received increasing attention over the past few years.

In the present research work, the main focus is on to develop a new parameter for assessing the overall network reliability using fuzzy logic concepts based on the excess pressures available at the demand nodes and to be incorporated in the optimal design and to incorporate this parameter in a two objective optimization model for design of water distribution network using the combination of Genetic Algorithms and EPANET tool kit in the MATLAB environment.

The best range of excess of minimum residual pressures is considered in the present study in such a way that the reliability of the network is maximum. The proposed methodology is applied on a two loop gravity network which is referred by most of the researchers. 54 optimal solutions are identified for the network. The Network Reliability Parameter (NRP), Cost Reliability Ration (CRR) and Cost per Unit Reliability and Unit Length (CURUL) parameters are used to compare the results with the previous researchers. It is found that the present study shows better results of when comparing with the results of the previous researchers.

Key Words: Optimal Design, NRP, Fuzzy Logic, Water Distribution Network, EPANET, MATLAB, CRR, CURUL

1. Introduction

Water is one of the fundamental necessities for sustaining life on the earth for all living entities. Man needs water for many of his activities in day to day life. Initially Man used to live near by water bodies such as rivers, lakes etc. This led to the development of water supply engineering, as a part of civil engineering, to develop a system for supplying protected water to all the people to meet their demands. The water distribution system consists of several components such as intake, pumping, transmission, treatment, storage, distribution network etc. Supplying water at required pressures to draw sufficient quantity of water.

Design plays vital role in the water distribution system. Optimal design of water distribution network is the aim of any agency dealing with water supply distribution. Through trial and error procedure and by the use of a simulation model, a water distribution network may be designed. Selecting a network configuration with minimum pipe cost and maximum reliability is a complex process. Consideration of reliability in water distribution networks has been received increasing attention over the past few years. If the network is designed with reliability alone as a prime objective, then the resulting system may be an uneconomical one.

Based on literature review, it is understood that most of the researchers preferred Genetic Algorithms (GAs) for the optimal design of water distribution networks as one of the best heuristic methods. Most of the researchers combined EPANET as analysis tool in their optimization algorithms. In the recent times, many researchers are focused on the reliability based optimal design of water distribution networks. But different researchers proposed different reliability parameters for the measure of network reliability and most of them concentrated on capacity reliability. Most of the researchers focused on satisfying the minimum requirements of the constraints of the optimization problem only. In satisfying the minimum requirements, the binary logic is only used by the researchers which are not practical. In any water distribution network, the pressures at demand nodes play a very important role. Hence the designer should take into consideration the excess pressures available than the minimum one in the design aspects.

In the present research work, the main focus is on to develop a new parameter for assessing the overall network reliability using fuzzy logic concepts based on the excess pressures available at the demand nodes and to be incorporated in the optimal design and to incorporate this parameter in a two objective optimization model for design of water distribution network using the combination of Genetic Algorithms and EPANET tool kit in the MATLAB environment. Genetic Algorithms functions and EPANET tool kit functions are linked in Matlab through generic DLLs.

Network reliability parameter is defined as the ratio of summation of the product of the nodal demand and satisfaction of the pressure at the node to the total demand of the network. The satisfaction is based on the excess pressures available at the demand nodes after satisfying the minimum requirement. Fuzzy logic is used to link the excess pressures at the demand nodes with the satisfaction index.

2. Review of Literature

Due to its practical importance and inherent complexity, the optimization of distribution Networks for supplying drinking water have been the subject of extensive study for the past 30 years (Edgar Reehuis-2010).

Saud A.Taher and John W.Labadie (1996) developed a decision support system for analysis and design of water distribution systems using Linear Programming (LP) technique and GIS. In the LP, basically the objective function and constraints are of linear in nature. But practically the equations involved in the analysis and design of water distribution networks are highly non linear and highly complex. Another drawback is the reliability aspects are not at all considered.

Wu Z Y and Simpson A. R. (2001) applied one of the competent genetic-evolutionary algorithms—a messy genetic algorithm to enhance the efficiency of an optimization procedure for the optimal design of water distribution networks. But Reliability aspects are not considered in the design aspects.

Muzzafer and Lansey (2003) developed Shuffled Frog Leaping Algorithm NET *(SFLANET)*, a computer model that links *SFLA* and the hydraulic simulation software *EPANET* and its library functions. No where the reliability is considered in the design.

Aklog D and Y.Hosoi (2003) aimed at to introduce a new reliability based optimal design of specifying minimum allowable pipe sizes during least cost design on system reliability. But the satisfaction of pressures at the demand nodes in the network has been not considered.

Huynh T. Luong and Nagen N. Nagarur (2005) developed a mathematical model that aims to support the decision to allocate funds among pipes of the network as well as the decision to repair or replace the pipes in the state of failure. The objective function of the model is to maximize the total weighted long-run availability of the whole system. The concept of hydraulic reliability is employed to determine the weight of pipes in the maintenance program.

Bhave P R and R Gupta (2004) attempted to design a network using a fuzzy linear programming model modified by including loop head loss constraints in the form of path head loss constraints to avoid iterative procedure. But reliability of excess pressures in the network is not incorporated in the model.

Vamvakeridou et al. (2007) used GA with Fuzzy membership function for floating-on-the-system tank simulation for the optimization of water distribution networks. Tank capacity and minimum normal operational level were taken as decision variables.

Afshar M.H.(2009) proposed a compact genetic algorithm to reduce the storage and computational requirements of population based genetic algorithms.

3. Formulation of the Problem

Definition of the problem

Minimization of the total cost of the network and maximization of reliability are considered as two objectives and hence the problem is a two-objective problem. In such a situation one gets several solutions with different costs and having different reliabilities. Our aim would be to obtain a Pareto-optimal front, consisting of several Pareto-optimal solutions.

Objective function and Constraints

Minimize C_T

Subjected to $(TH)_i \geq (TH_{min})_i$ $i=1,2,3\ldots\ldots N$ …. (1)

$V_{min} \leq V_j \leq V_{max}$ $j=1,2,3\ldots\ldots M$ …. (2)

$NRP \geq NRP_{min}$ …. (3)

$\sum Q_k = 0$ $k=1,2,3\ldots\ldots P$ …. (4)

$\sum h_x = 0$ $x=1,2,3\ldots\ldots R$ …. (5)

$D_j \geq 0$ ….. (6)

Where

i= index used to represent demand node in the network; j= index used to represent the link in the network; k=index used to represent any node in the network; x=index used to represent any link in the loop of network; N= Number of demand nodes in the network; M= Number of links in the network; P= Number of links joined at the node M= Number of links in the loop;C_T = total cost of the network

$C_T = \sum L_j * D_j * C(D_j)$

L_j = Length of the link 'j'

D_j = Diameter of the link 'j'

$C(D_j)$ = Unit cost for the diameter of the link 'j'

(or)

$C_T = \sum c_j * L_j$

c_j^* = Unit cost according to continuous function (Rs/m)

$= 1.2654 * D_j^{1.327}$

TH = Total Head at the demand node in m; TH_{min} = Minimum HGL required at the demand node ; V_{min} = Minimum Velocity of flow in the link in m/s

V_{max} = Maximum Velocity of flow in the link in m/s V= Actual Velocity of flow in the link in m/s; NRP= Network Reliability Parameter; NRP_{min} = minimum Network Reliability Parameter

Equations (4) and (5) are used to determine hydraulic balance of the network and they are basically continuity and energy equations respectively.The continuity equation is applied at each node with Q_k the flow rate (in and out of the node).

The energy equation is applied to each loop in the network with h_x the head loss in each pipe. The head loss is the sum of minor losses and losses due to friction i.e. major losses. The friction head loss can be computed by various formulae, in the present study, the Hazen-Williams head loss equation is used.

$$h_L = (4.727\ L\ Q^{1.852}) / (\ C^{1.852}\ D^{4.871})$$

h_L = Head loss in the pipe in ft ; C = Hazen-Williams roughness coefficient

d = pipe diameter (ft); L = pipe length (ft); Q = flow rate (cfs)

4. Methodology

The approach proposed in the present study is explained in the following steps. In the present study, the combination of genetic algorithms tool box in Matlab for optimal design and EPANET tool box for analyzing the network are used. The coding for this is developed in the Matlab editor file.

1. Select a standard benchmark network for verifying the proposed methodology with the other researchers who have already applied on that network.

2. Prepare an input file according to the format specified in the EPANET tool kit for the selected benchmark network.

3. In the optimization procedure of using the GA tool box in Matlab, initially generate randomly diameters of equal number of links in the network within the given range of diameters and then they will be assigned to all the links in the network. The diameters are the decision variables on which the cost of the network directly depends and the reliability depends indirectly.

5. For the assigned diameters, analyse the network using EPANET tool kit functions.

6. A report file which is specified in the ENopen function of EPANET tool kit will be generated for each generation of analysis based on the input file supplied and will be stored in the default directory of the computer.

7. Using EPANET tool kit functions obtain the information from the report file generated by EPANET such as total heads, pressure heads, demands at all demand nodes and velocities in all the links of the network.

8. Compare the obtained total heads at the demand nodes with minimum required ones, and velocities with the maximum permissible velocities. If the obtained values are violating the specified conditions, assign penalties in the form of cost which will be added to the objective function.

9. Compare the obtained pressure heads with minimum ones and compute the residual pressure heads. Link the residual heads with satisfaction level of the consumers, through membership function using fuzzy logic. Thus, find the satisfaction index at each demand node.

10. Find the product of nodal demand and satisfaction index at each demand node.

11. Add all products in step 10 and divide by the total network demand to get the network reliability parameter.

12. In the present study, maximization of network reliability parameter is another objective in addition to the minimization o the total cost of the work. Here, this objective is considered as a constraint to the main objective function hence some penalty in the form of cost is added to the objective function, if it violates by certain amount of network reliability.

13. Compute the total cost of the network including penalty cost.

14. The optimization algorithm repeats the steps from 4 to 13 till it gets the optimal cost of the network by assigning different values of diameters randomly at each generation.

15. Convert the optimal diameters obtained into commercially available pipe sizes and then with these diameters analyse the network again and obtain all the parameters required.

16. At the optimal cost, verify the total heads obtained with the minimum required ones, if they are satisfied, the algorithms stops and then note down the details from the report file and work space in the Matlab otherwise the steps from 4 to 14 till satisfying the constraints and obtaining the optimal cost.

17. Repeat the steps from 4 to 16 for getting number of optimal solutions while selecting the next solution increase the sizes of several pipes around nodes with residual pressures near zero. Similarly, for a low-lying area where residual pressures are high , several pipe sizes should be reduced. This will help in improving reliability and keeping the solution near the Pareto-optimal front. This will reduce the total number of solutions required to be generated to obtain the Pareto-optimal front and then show the solution on a graph of network reliability parameter versus network cost.

18. Get a Pareto-optimal front.

19. All solutions lying on the Pareto-optimal front are Pareto-optimal solutions, and the decision maker can choose the proper one depending upon the available funds.

5. Details of Network used in the Present Study

The network shown in Fig 1 was first used by Alperovits and Shamir(1977) for optimal design using LP. Subsequently the same network has been used by several researchers for optimal as well as reliability study. Some of them are Quidry et al (1979), Goulter et al.(1986), Fujiwara et al.(1987), Kessler and Shamir (1989), Savic and Walters (1997), Abebe and Solomatine(1998), Cunha and Sousa (1999), Eusuff and Lansey (2003), T.Devi Prassad et al (2008), Shie-Yui Liong et al.(2004), Keedwell and Khu(2005), Samani and Mottaghi (2006),Suribabu et al.(2006), M Van Dijk et al (2008), M.H.Afshar(2009).

The two loop gravity network consists of 8 links, 6 demand nodes and 1 reservoir. The nodal information for this network is given in table 5.1. Node 1 is a source node with HGL of 210 m and a demand of -1120 m^3/hr. All the links in the network has a length of 1000m and Hazen-Williams coefficient (C_{HW}) is taken as 130. The minimum required HGL values at demand nodes are given in table 1. Table 2 shows the cost of pipes which can be used in the network.

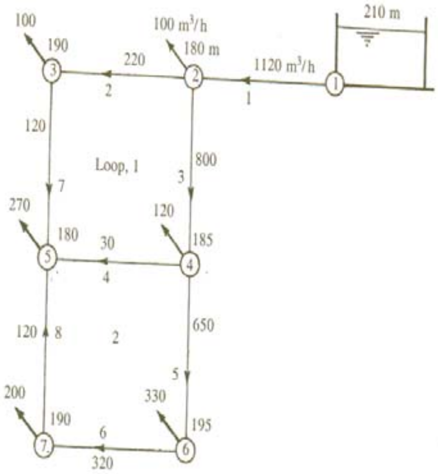

Figure 1: Two Loop Gravity Network

Table 1 Node details for two loop network

Node	Elevation (m)	Min.HGL (m)	Demand (m^3/hr)
2	150	180	100
3	160	190	100
4	155	185	120
5	150	180	270
6	165	195	330
7	160	190	200

Table 2 Cost Data for pipes

Diameter ((in inches)	Diameter (in mm)	Cost (Units)
1	25.4	2
2	50.8	5
3	76.2	8
4	101.6	11
6	152.4	16
8	203.2	23
10	254.0	32
12	304.8	50
14	355.6	60
16	406.4	90
18	457.2	130
20	508.0	170
22	558.8	300
24	609.6	550

RESULTS

The details of the ranges of residual pressures and their satisfaction levels considered in the present study are presented below in figures 2 to 4 based on fuzzy logic.

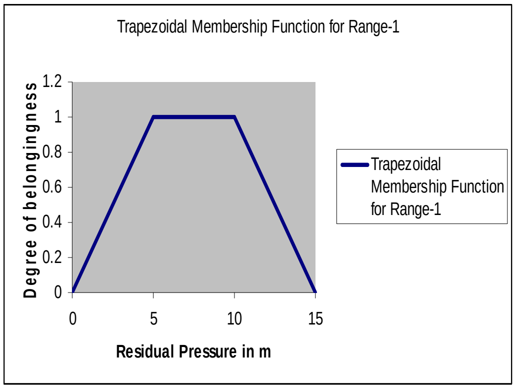

Figure 2 Trapezoidal Membership Function for Range-1

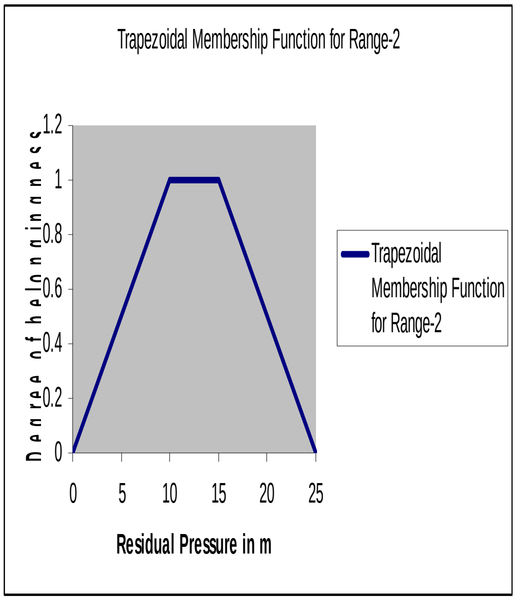

Figure 3 Trapezoidal Membership Function for Range-2

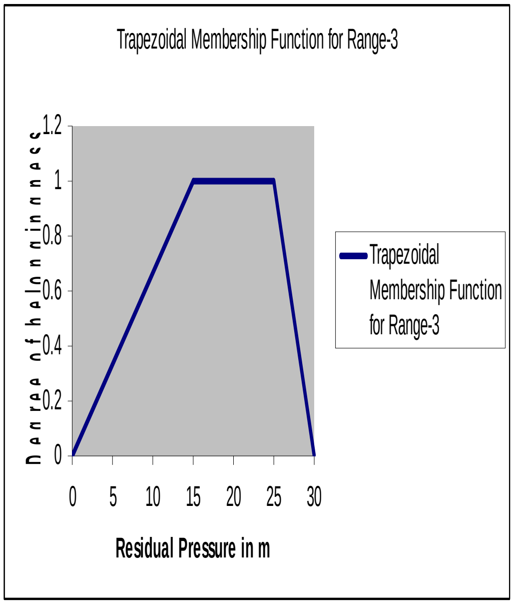

Figure 4: Trapezoidal Membership Function for Range-3

The network reliability parameters obtained based on fuzzy logic are presented in figure 5 for different ranges.

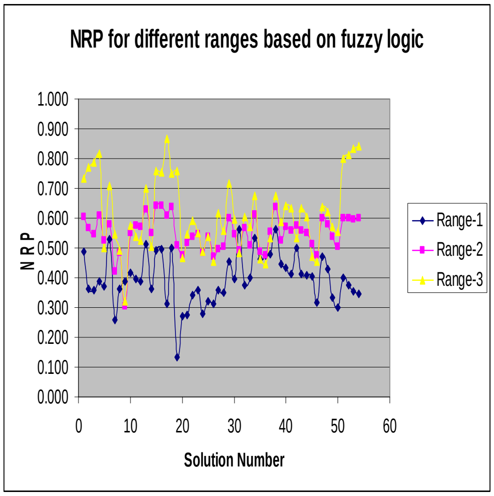

Figure 5: Trapezoidal Membership Function for Range-3

So based on the above results, it is concluded that the range-3 is the best one for getting maximum reliability based on fuzzy logic.

The optimal solutions obtained by different researchers for the two loop network including the present study are given below in the table 3.

Table 3 Optimal solutions for two loop network obtained by different researchers

Reference	D_1	D_2	D_3	D_4	D_5	D_6	D_7	D_8	C_T (10^3)	FEN* (10^3)
Savic and Walters (1997) (GA1)	457.2	254	406.4	101.6	406.4	254	254	25.4	419	65
Savic and Walters (1997) (GA2)	508	254	406.4	25.4	355.6	254	254	25.4	420	65
Abebe and Solomatine(1998)	457.2	254	406.4	101.6	406.4	254	254	25.4	419	1.373
Cunha and Sousa	457.2	254	406.4	101.6	406.4	254	254	25.4	419	25

(1999)										
Wu et al(2001)	457.2	254	406.4	101.6	406.4	254	254	25.4	419	7.467
Eusuff and Lansey (2003)	457.2	254	406.4	101.6	406.4	254	254	25.4	419	11.323
T.Devi Prassad et al (2003)	450	250	400	100	400	250	250	25	419	-
Shie-Yui Liong et al.(2004)	457.2	254	406.4	101.6	406.4	254	254	25.4	419	1.091
M Van Dijk et al (2008)	457.2	254	406.4	101.6	406.4	254	254	25.4	419	100
M.H.Afshar(2009)	457.2	254	406.4	101.6	406.4	254	254	25.4	419	3
Present Study	457.2	254	406.4	101.6	406.4	254	254	25.4	419	0.8

(*FEN-Function Evaluation Number)

Now the comparison is made with the other researchers who had applied already their methodology to this network. The comparison made is shown in the table 4 and in the figures 6 to 8 .

Table 4. Comparison with previous researchers

Para Meter	Authors*	Abebe et al	Savic et al	Present Study
TC in Units (10^3)	419	424	420	543
NRP	0.26	0.46	0.25	0.67
CRR (10^4)	158	930	168	80
CURUL	198	116	209	100

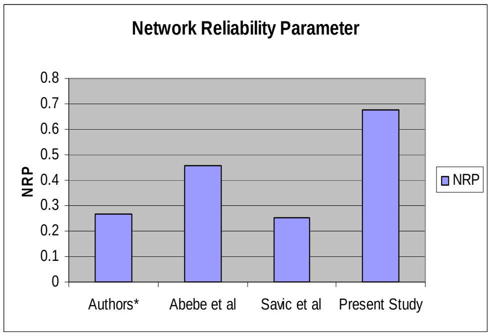

Figure 6: Comparison of NRP with the previous researchers

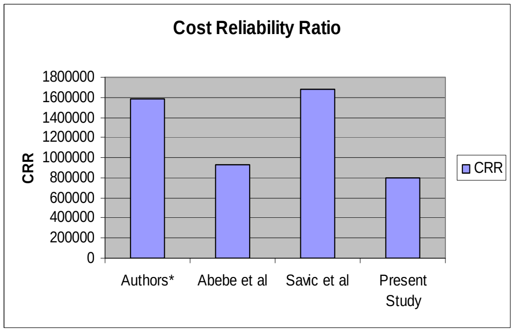

Figure 7: Comparison of CRR with the previous researchers

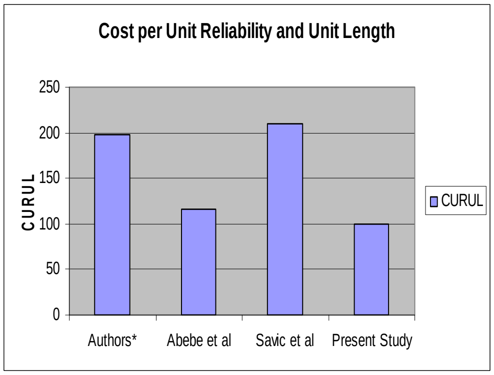

Figure 8: Comparison of CRR with the previous researchers

* Savic and Walters (1997) (GA2), Cunha and Sousa (1999), Wu et al(2001), Eusuff and Lansey (2003), T.Devi Prassad et al (2003), Shie-Yui Liong et al.(2004), M Van Dijk et al (2008), M.H.Afshar(2009)

CONCLUSIONS

Based on the above results, the following conclusions are drawn.

- Three different ranges of residual pressures which are excess of the minimum pressure requirements at the demand nodes are considered in the present study for fixing the best range of residual pressures such that the reliability of the network is maximum.
- Range-3 values are giving highest NRP values in almost all the optimal solutions obtained for two loop network. Hence it is concluded that range-3 is

the best range based on fuzzy logic for incorporating in the optimal design of water distribution networks for maximum reliability.

- Based on the NRP, CRR and CURUL values obtained in the present study developed for two loop networks are showing better than the values obtained by other researchers.

REFERENCES

[1] Afshar M.H.(2009). "Application of a Compact Genetic Algorithm to pipe network optimization problems" Sceitia Iranica, Transaction A: Civil Engineering, Sharif University of Technology, Vol.16, No.3, 264-271.

[2] Aklog D and Y.Hosoi (2003). "Reliability based optimal design of water distribution networks" Water Science and Technology: Water Supply, Vol.3, No. 1-2, 11-18.

[3] Bhave P R and R Gupta (2004). " Optimal Design of water distribution networks for fuzzy demands" Journal of Civil Engineering and Environmental systems, Taylors & Francis, vol.21,No.4, 229-245.

[4] Edgar Reehuis (2010). "Multiobjective Robust Optimization of Water Distribution Networks" A Masters thesis submitted to Leiden Institute of Advanced Computer Science (LIACS), Leiden University, Niels Bohrweg 1, 2333 CA Leiden ,The Netherlands.

[5] Huynh T. Luong and Nagen N. Nagarur (2005). "Optimal Maintenance Policy and Fund Allocation in Water Distribution Networks" *Journal of Water Resources Planning and Management*, *ASCE, Vol.131, No.4*, 299-306.

[6] Muzaffar M. Eusuff and Kevin E. Lansey (2003). "Optimization of Water Distribution Network Design Using the Shuffled Frog Leaping Algorithm" *Journal of Water Resources Planning and Management*, *ASCE, Vol.129, No.3*, 210-225.

[7] Saud A.Taher and John W.Labadie (1996). "Optimal design of water distribution networks with GIS" *Journal of Water Resources Planning and Management*, *ASCE, Vol.122,No.4*, 301-311.

[8] Vamvakeridou-Lyroudia L. S, D. A. Savic, and G. A. Walters (2007). "Fuzzy Hierarchical decision support system for water distribution network optimization" Journal of Civil Engineering and Environmental systems, Taylors & Francis, vol.23,No.3, 237-261.

[9] Wu Z Y and Simpson A. R. (2001). "Competent Genetic-Evolutionary Optimization Of Water Distribution Systems" *Journal of Computing in Civil Engineering*, *ASCE, Vol.15, No.2*, 89-101.