ASSESSMENT OF VARIATIONS IN NODAL DEMAND SATISFACTION OF WATER DISTRIBUTION NETWORKS

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Abstract

Nodal demand satisfaction is one of the means to assess the performance of a Water Distribution Network (WDN). In most of the developing countries, the public water supply systems are not capable of meeting consumer demands. In such situations it is more appropriate to observe deviations in nodal demand satisfaction. Through this paper a new parameter named Uniformity Coefficient is suggested to quantify these variations and a methodology is developed to estimate UC values for a network. Further, Demand Driven Analysis of WDN does not give a clear picture of rate of supply, which leads to erroneous performance evaluation of WDNs. A modification of the nodal discharges based on source head available and desirable and minimum source head required for each node is presented in this paper. A program was developed in 'C' language using EPANET- Toolkit. Simulation studies were conducted on different networks using this program.

Keywords: Water Distribution Networks; Pressure dependant outflow; Node supply ratio; Uniformity coefficient

1. INTRODUCTION

The objective of a protected water supply system is to supply safe and clean water in adequate quantity, conveniently and as economically as possible. Water Distribution Network is one of the components of Water Supply System, which need to be designed and operated more carefully to have a safe and satisfactory supply of water to the consumers. WDN usually accounts for 40 – 70% of the capital cost of water supply project.

In many of the developing countries, drinking water supplies are inadequate to meet the consumers' needs. Reasons for this may be rapid growth of population, lack of sufficient quantity of water in the source, lack of funds, improper planning, inadequate fund allocation etc. Because of these reasons many of the water supply systems are designed and operated as intermittent systems, in spite of its disadvantages. Main objective in design and operation of water supply system should be to supply adequate quantity of water at desired pressure, at required time to consumers. The pressure head available is not same at all nodes. Outlets are uncontrolled and discharge through the outlet will be more or less than the designed discharge based on head available at that node. In case of intermittent supply, the duration of supply is fixed and during the same period some nodes where the pressure is more, discharge more quantity of water and other nodes may discharge less water.

Even when there is inadequate quantity of water at source, a similar situation arises where some nodes draw more water than their proportionate share and other nodes get less quantity. Water supply authorities presume that they were able to satisfy certain percent (say 50%) of water demand of a particular area. Whereas in actual situation some people in that area may get 100% of their requirement and some people may get much less than 50%. This is a most common situation in water supply systems of developing countries. To have a control over these variations, one of the design guidelines incorporated in design manuals was to see that the variation in head among various nodes within a distribution area should lie within a certain range or divide the area into smaller zones to satisfy this criterion. For Indian systems CPHEEO (1999) recommends that this pressure variation should be less than 3m-5m. Pressure variations of this magnitude may also lead to considerable variations in nodal demand satisfaction, as the head available is also less (5-10m).

Reliability is one of the aspects that is gaining importance in design and operation of any system. Different people have defined reliability of water supply systems in different ways and they have also tried to estimate it using different procedures. In situations, where there is no shortage of supply, Reliability was considered as probability of a node being connected to the network. In this approach the assumption was that once a node is connected to the network it gets required quantity of water with sufficient pressure. Shamir and Howard (1986) defined reliability as the probability that a given reliability factor will be achieved which was defined in terms of capacity lost during failure. Su et. al. (1987) defined reliability as probability of satisfying nodal demands and pressure heads for various pipe failures. They evaluated reliability using minimum cut-set method and probability of failure of a minimum cut-set was considered as product of failure probabilities of pipes of this minimum cut-set. Bao and Mays (1990) defined nodal reliability as the probability that available pressure head at a given node is greater than or equal to the required minimum pressure head, assuming demand is satisfied once pressure available is more than minimum required. Awumah et. al., (1991) proposed a measure of redundancy in water distribution network based on entropy. The assumption was that each node must be supplied by multiple links and flow should be drawn uniformly from all links. Another definition of Reliability (Khomsi et al, 1996) was probability of having supply to a node with adequate pressure. They have evaluated Reliability of a water distribution network considering probability of failure of pipes and fluctuations in demand. Tanyimboh and Templeman (2000) and Tanyimboh et. al.(2001) defined Reliability of a drinking water supply system as the time averaged value of the flow supplied to the flow required (demand). Tanyimboh and Templeman (2000) tried to establish a relationship between reliability and entropy, which could be used as a surrogate measure of reliability.

In strict sense, the reliability of a water supply system should take into account all possible factors like variations in demand, availability of water at source, failure of components such as pumps, treatment units, valves, pipes etc. and the effect of these factors on performance of water supply system in terms of quantity, pressure, quality etc. Depending on the situation one or more of these factors may become prominent. In case of intermittent supplies, where water is supplied for fixed duration, and when there is shortage of water, people tend to collect water as long as there is supply and hence variations in demand will not be important while assessing intermittent system of supply.

Most of the earlier research in water distribution network analysis was using demand driven approach. Where, each nodal demand is assumed to be satisfied independent of the head available at that node. Later there were modifications suggested for the Demand Driven Analysis (DDA). Gupta and Bhave (1996) proposed a head driven analysis technique. They made a comparison of different methods for predicting performance of deficient networks, in which they studied various head discharge relationships. They have identified that parabolic head-discharge relationship was the best. Ozger and Mays developed a semi-pressure driven approach, which uses DDA results as a starting point and proceeds in an iterative manner. They concluded that with DDA system deficiency is more serious than it is in reality and more piping in a network does not always improve system performance. If the pressure at a node using the modification is more than that using DDA, they have considered the value of availability factor to be one. Tanyimboh and Tabesh (1997) developed a methodology for calculating network reliability by relating the discharge with source head instead of node head. Tanyimboh et. al. (2001) proposed a means of modifying the nodal and system discharges based on source head and compared the reliability values calculated with those given in literature but in their analysis they have assumed discharge as equal to demand when head available is more than desired.

2. PROPOSED APPROACH

In the present work reliability is defined as supply ratio or demand satisfaction, which is calculated as the ratio of total water supplied and total demand. The variations in demand with time are insignificant in intermittent system. Hence the ratio of total supply at the node to total demand of the node is taken as Supply Ratio (SR). The program developed here can also predict supply ratios at different times. Since head available at different nodes is different, the discharges will be different. So in this paper node supply ratios (ratio of demand and supply of a node) are calculated for each node and from these SR for the entire system is calculated.

Demand Driven Analysis (DDA) of water distribution networks has been in practice since a long time. In DDA the demand is assumed to be satisfied irrespective of the head available at nodes. Most of the outlets in water distribution system are free flowing which means discharge will be proportional to head. Many modifications were proposed to correct the discharges calculated in DDA based on head available at node or at source. In these modifications their emphasis was mainly on nodes having lesser head with the assumption that discharge at other nodes is greater than demand and hence their level of satisfaction is more than one. In case of deficit supplies and intermittent system of supply where a limited quantity of water is supplied to the entire area, public tendency is to collect water as long as there is supply. In such situation, certain nodes get higher quantity of water while nodes with lesser head may get much less quantity than their proportionate share. This is a most common situation in many water supply systems of most of the developing countries. To have a more realistic estimation of demand satisfaction, discharges should be corrected at all nodes. Tanyimboh et.al (2001) used Eq. (1) to modify the discharges at nodes. Same relation is used in this study also to correct discharges based on source head. They assumed $Q_j = Q_{jreq}$ when H_{sj} is greater than H_{sjdes} In this paper Q_j is assumed to increase with H_{sj} beyond Q_{jreq} also. An iterative procedure is developed where nodal discharges (Q_j) are corrected based on source head.

$$Q_{jnew} = \left((H_s - H_{sjmin})/(H_{sjdes} - H_{sjmin}) \right)^{1/n} Q_{jold} \qquad (1)$$

In this study n value is taken as 2.

With the given nodal demands, network is analysed using EPANET and node heads are obtained. Using these, head loss between source and node (HL_j) is calculated as given in (2).

$$HL_j = H_s - H_j \qquad (2)$$

H_{sjdes} i.e. desirable source head to get required discharge at node is calculated taking into account, elevation of outlet at node j (which is taken as sum of elevation of node (el_j) and height of outlet at node (H_{jmin})), head required at node j to have required discharge (H_{jdes}) and head loss between source and node

$$H_{sjdes} = el_j + H_{jmin} + HL_j + H_{jdes} \qquad (3)$$

Minimum head at source required to have the flow just started is indicated as H_{sjmin}. To calculate this, demand at each node is set to zero (only one node at a time) and head loss in that situation (HL_{j1}) is noted. H_{sjmin1} is calculated using (4).

$$H_{sjmin1} = el_j + H_{jmin} + HL_{j1} \qquad (4)$$

Nodes are sorted in ascending order of H_{sjmin1} values. Then the demands at the nodes are set to zero one by one and HL_{j2} i.e. head loss between source and demand node in this situation is calculated. One important thing to be noted is, while calculating H_{sjminf}, discharges at all nodes above the particular node in the sorted list are set to zero. The idea is, all nodes whose minimum required head is more than H_s will not get any discharge. H_{sjminf} is calculated as given in (5)

$$H_{sjminf} = el_j + HL_{j2} + H_{jmin} \qquad (5)$$

Discharge is modified based on source head, H_{sjdes} and H_{sjminf}, which are calculated in (3) and (5). These modified discharges are taken as nodal demands and the process of calculating H_{sjdes}, H_{sjminf}, and Q modified is continued till the variation in head at a particular node during successive iterations is negligible. These final discharges are used in calculating node supply ratios.

The above procedure is repeated at each time step. While calculating supply ratio mean of discharge at the beginning and end of time steps is taken as supply. Node supply ratio is taken as weighted mean of node supply ratio values at different time steps or ratio of sum of supplies at all time steps and sum of demands at all time steps at that node. Flow chart of the procedure is presented in Fig. 1

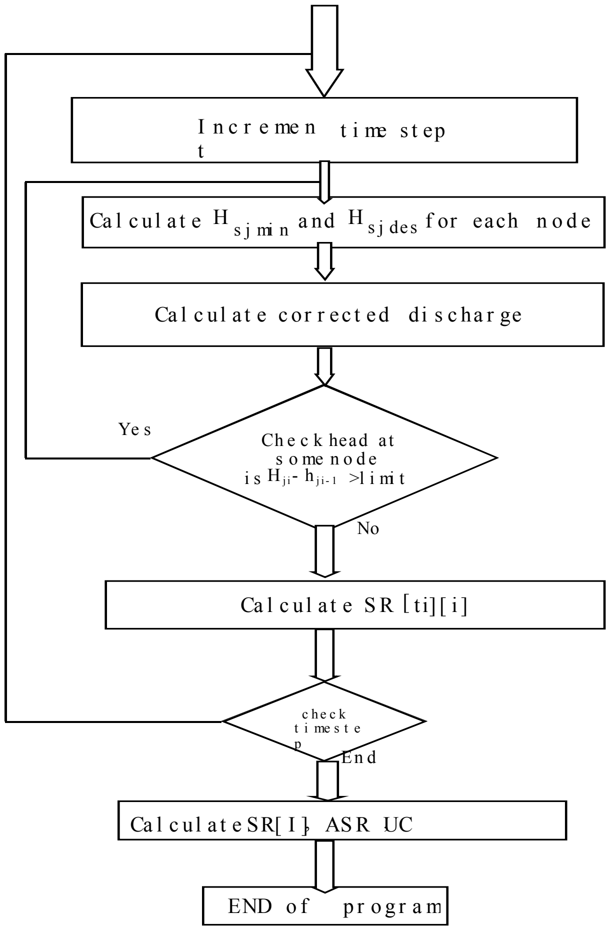

Fig. 1 flow chart of procedure

To quantify the variations in node supply ratios, a new parameter Uniformity Coefficient (UC) is introduced. This is calculated using node supply ratios as given below.

Average supply ratio for the system (ASR) is calculated as mean of node supply ratios. Deviation in supply ratio of each node is taken as modulus of difference between ASR and supply ratio of that node. Average deviation (ADEV) is calculated from these deviations. Using Average deviation and average supply ratio Uniformity Coefficient is calculated from (6).

$$U.C. = 1- (ADEV/ASR) \tag{6}$$

When all the nodes have equal demand satisfaction, the value of UC would be one. A program is developed in 'C' language using EPANET- Toolkit. The objective in design and operation of water supply systems should be to maintain the value of Uniformity Coefficient as one or Supply Ratio of each and every node should be more than one.

3. RESULTS AND DISCUSSIONS

The network analysed in the present study is taken from Kansal (1995) which is shown in Fig. 2. When the same network is tested on EPANET, it is observed that pressures were varying in the range of 25.25 m – 8.07 m of water head. By reducing all the demands proportionately and running the program the variations in Supply Ratios (SRs) are observed, which are ranging from 1 – 0.69 and Uniformity Coefficient was 0.916.

Diameters of pipes of the network are changed as the pressure variations at different nodes are very high and simulations are run with different conditions to study the effect of various parameters on UC. Changed diameters for network are presented in (Fig. 2). Trial runs are made with different values of peak factor, Roughness coefficient (HWC) and elevation and size of service reservoir. It is observed that UC does not change much with these parameters. As shown in (Fig. 3) for peak factor varying from 0.4 to 1.5 UC has changed from 0.909 to 0.882 i.e for nearly three fold increase of peak factor, variation in UC is only 3%. However, Average supply ratio decreased uniformly from 2.513 to 0.671. This is expected as demand increases for a particular quantity of water in the service reservoir, Supply Ratio decreases. For all values of peak factor, product of peak factor and ASR remained around one.

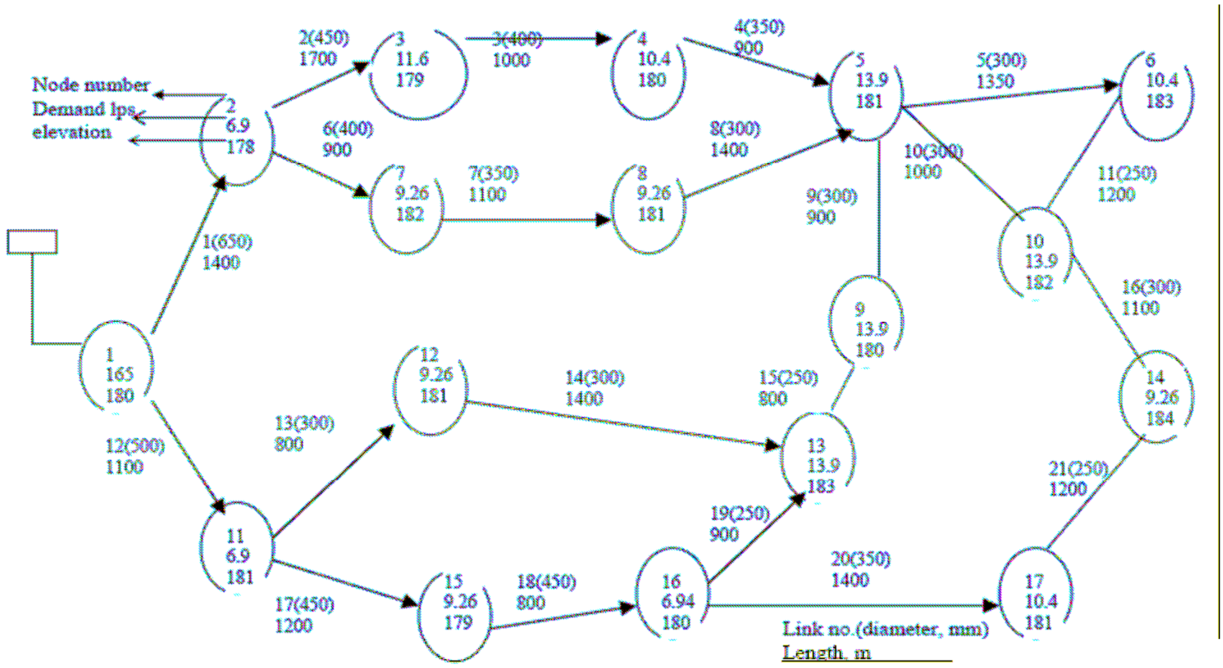

Fig. 2 Line Diagram of Network Given in Kansal (1995)

Simulations with different values of Hazen William Coefficient indicate that there is no considerable variation in UC and ASR for HWC values ranging from 80 to 150. The results are presented in Fig.4. The pattern of variation in ASR is not clear but the magnitude of variations is mere 2%.

As shown in (Fig. 5) from the results of simulations with different elevations of service reservoir, it is observed that UC and ASR values increase initially and then stabilize. This indicates that certain height of service reservoir is required to maintain a level of supply and beyond that increasing the height may not serve any purpose. This type of simulations may be useful in arriving at reasonable height of service reservoir for a given water distribution network. It is observed that UC does not change with size (diameter) of service reservoir however as the diameter is increased Quantity of water available is increasing and hence the Average Supply Ratio is increasing. Variation of UC and ASR with size of reservoir is presented in (Fig. 6).

In EPANET, if the elevation of a particular node is changed, pressure at that node only is changed and there will not be any effect in pressure or discharge at other nodes. This may not be correct in real situation. This program shows the effect of change in elevation of a node on supply ratios of the surrounding nodes.

Effect of node elevation on Supply Ratio of the node and also on SRs of surrounding nodes is also studied. SR of a node is decreasing with increasing node elevation except for a short range in between where the trend is reverse. Similar trend is observed for node 7, node 13 and other nodes also. Effect of change in elevations of node 7 and node 13 are presented in (Figs. 7 and 8) respectively. The reverse trend started at node elevation of 180m, which is the elevation of most other nodes. The reason for the reverse trend is not understood at the moment. It is also clear from the graphs that when SR of a node is decreasing SRs of the surrounding nodes is increasing and vice versa. But the effect may be insignificant.

From the results of simulations it is observed that decrease or increase of demand at certain nodes leads to variations in UC. For example, change in UC due to change of discharge at certain nodes to zero or doubling the discharge at certain nodes is presented in table 1. It is observed that, by making demand at certain nodes to zero that are very close to or very far off from the reservoir, UC can be improved considerably. So separating certain nodes from the network i.e. by having separate pipes to supply these nodes or by having staggered supply hours may be considered as an alternative to improve UC. Similarly change in diameter of pipes and addition or removal of a pipe also effect UC. However, mere increase in diameter does not ensure increase in UC. For instance, with increase in diameter of pipe 1 UC values increased initially and then decreased as shown in (Fig. 9). This decrease in UC might be due to increased pressure variations because of diversion of majority of flow in one path. In case of pipe 9, increasing the diameter from 250 mm to 750 mm could increase UC by 0.3% only. The data is presented in Fig.10. This may be because this is a link away from the reservoir. Another reason may be, pipes connecting that link are smaller and increasing diameters of a series of pipes may show change in UC.

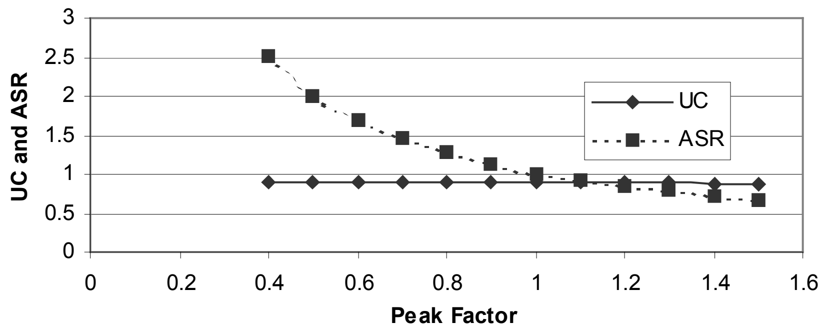

Fig.3 Variation of UC w ith Peak factor

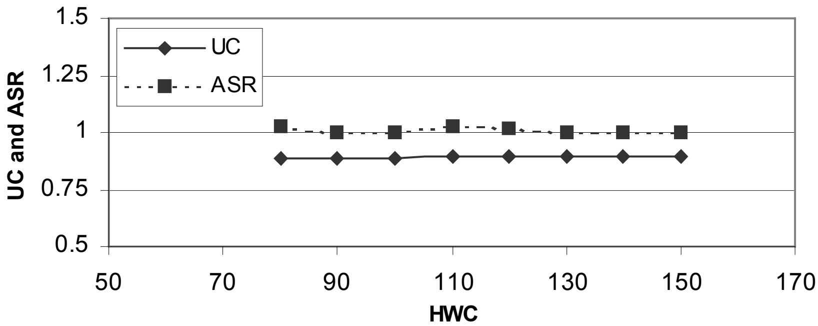

Fig.4 Variation of UC w ith Roghness coefficient (HWC)

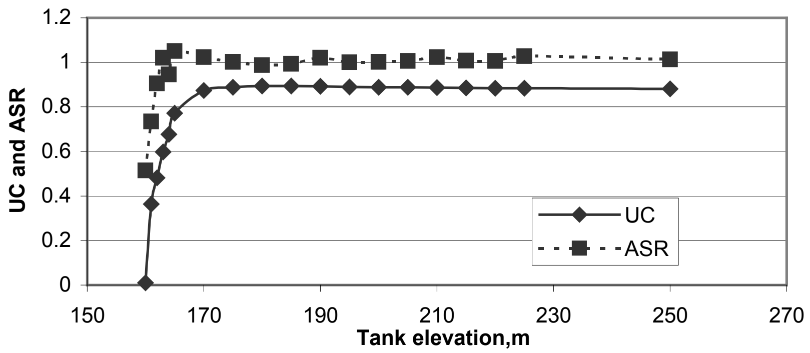

Fig.5 Variaon of UC with Tank Elevation

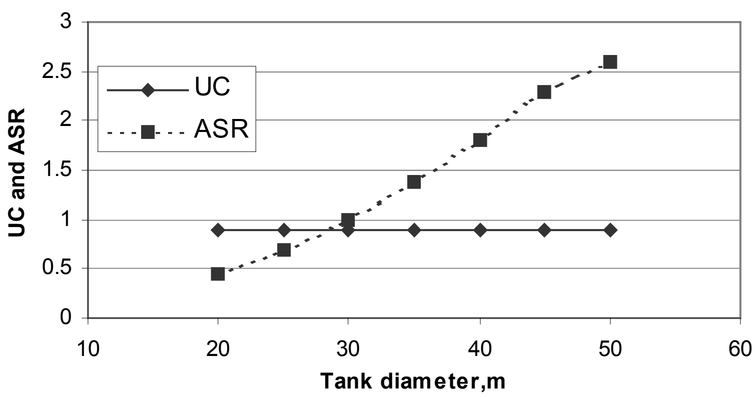

Fig.6 Variation of UC with tank diameter

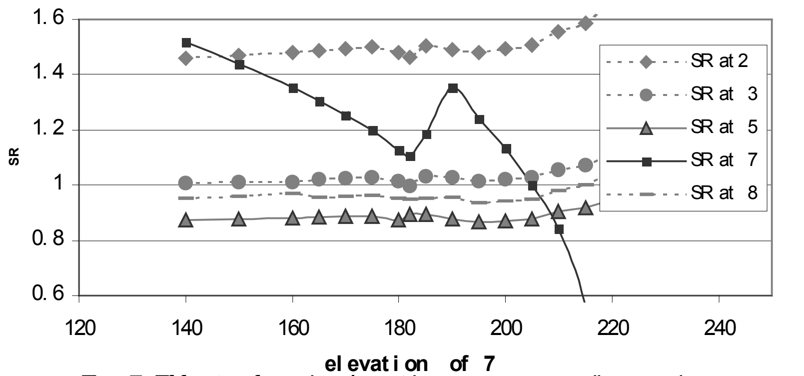

Fig.7 Effect of node elevation on surrounding nodes

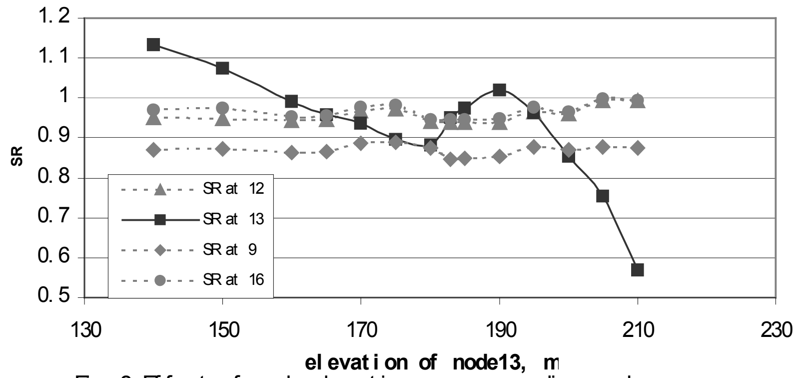

Fig.8 Effect of node elevation on surrounding nodes

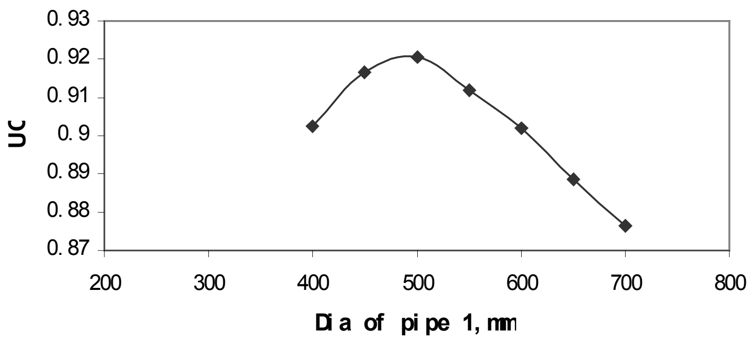

Fig.9 Change in UC with Diameter of pipe

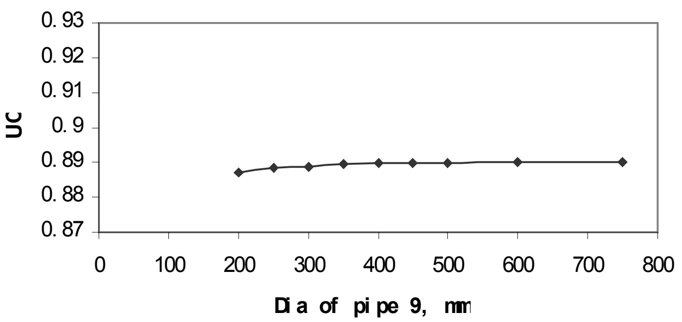

Fig.10 Change in UC with Diameter of pipe

4. CONCLUSIONS

From the results it may be concluded that for given node elevations and demands UC mainly depends on layout of the network and diameters of pipes. Mere increase in diameter may not help in improving the uniformity of supply. This program is to be linked with some optimization tool to develop a network that is optimum in terms of uniform distribution of supply and cost. UC may be included as one of the criteria in the design of Water Distribution Networks. This may be used as a tool to study the effect of different field problems, like pipe failures or variations in demand etc. on uniform supply.

Notation

Q_j = Discharge at node J
Q_{jreq} = Required discharge (demand) at node J
Q_{jnew} = Corrected discharge at node J
Q_{jold} = Discharge at node J in previous iteration
H_s = Head at source or reservoir
H_{sjmin} = Minimum source head required to have supply at node J
H_{sjdes} = Source head required to have desired discharge at node J
HL_j = Head loss between source and node J
el_j = Elevation of outlet at node J
H_{jmin} = Minimum head required at node J to have supply
H_{jdes} = Head required at node J to have desired discharge
H_{sjminf} = Minimum source head below which flow at node J and other nodes with higher H_{jmin} will be zero
SR = Supply ratio (demand / supply)
UC = Uniformity Coefficient

REFERENCES

Awumah, K, Goulter, I.C. and Bhatt, S.K. (1991). "Entropy based redundancy measures in water distribution networks" *J. Hydr. Engrg. ASCE,* Vol.117, PP.595-614.

Bao, Y. and Mays, L. W. (1990). "Model for water distribution system Reliability" *J. Hydr. Engrg. ASCE,* Vol.116, PP.1129- 1137.

CPHEEO (1999)."Manual on water supply and treatment" Ministry of urban development, Govt. of India.

Gupta, R. and Bhave, P.R. (1996) " Comparison of methods for predicting deficient-network performance" *J. Water Resour. Plng. and Mgmt. ASCE*, Vol.122, PP.214-217.

Kansal, M.L., Arun Kumar, and Sharma, P.B. (1995). " Reliability analysis of water distribution systems under uncertainty" *Reliability Engrg. and Sys. Safety*, Vol. 50, PP. 51-59.

Khomsi, D., Walters, G.A., Thorley, A.R.D., and Ouzar, D. (1996) " Reliability tester for water distribution networks" *J. Comp. In Civil Engrg.*, *ASCE*, Vol.10, PP.10 – 19.

Ozger, S.S., and Mays, L.W.(2003). " A semi-pressure driven approach to reliability assessment of water distribution networks", *http://www.public.asu.edu/lwmays/ozger-mays.pdf.*

Shamir, U. and Howard, C.D. (1981) "Water supply reliability theory" *J. Amer. Water Works Asso.* Vol.73, PP.379 – 384.

Su Yu-chun, Mays, L.W., Duan, N., and Lansey, K.E. (1987) "Reliability based optimization model for water distribution systems" *J. Hydr. Engrg. ASCE*, Vol.122, PP. 301 – 311.

Tanyimboh, T.T. and Tabesh, M. (1997) " The basis of source head method of calculating distribution network reliability" *Water pipeline systems,* PP.211 –220.

Tanyimboh, T.T., Tabesh, M. and Burrows (2001) "Appraisal of source head methods for calculating reliability of water distribution networks" *J. Water Resour. Plng. and Mgmt. ASCE*, Vol. 127, PP. 206-213.

Tanyimboh, T.T. and Templeman, A.B. (2000) " A Quantified assessment of the relationship between the reliability and entropy of water distribution systems" *Engrg. Optimization* Vol.33, PP.179 –199.