Spatial Approach for Preliminary Design of Real Water Distribution Network

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ABSTRACT

An economic design of water distribution system components plays an important role in the water-supplying agency due to requirement of large financial investment on construction, operation and maintenance. Due to rapid growth of population and urbanization, inadequacy of source, the old water distribution networks are in detrimental condition to meet the growing demand. This posed a challenging problem to municipal engineers in taking decision on rehabilitation or revamping the existing network within the available fund. The effective construction of a distribution network heavily depends on the design, directly influencing the financial investment required. The time factor plays a critical role in securing initial sanctions for commencing a project. This study proposes a spatial approach for preparation of preliminary estimate for the design of real water distribution network. The pipe network layouts for the study area are prepared using satellite imagery and pipe sizing is done by proposed Heuristic approach. Segment-wise population is estimated. The demand to be met by each pipe network is estimated and projected for future population growth. Heuristic concept is employed to determine the near-optimum size of the network pipes. Spatial approach results in quick and easy determination of population and thus can be used for preparing a preliminary estimate facilitating quick financing. The proposed Heuristic approach gives a practical and nearly economical solution in designing a water distribution network.

Key words: Water distribution system, urbanization, satellite imagery, Heuristic approach

INTRODUCTION

Water distribution systems are the first ever truly planned engineering in our civilization. Evolving over a 1000 years, the distribution system has progressed from simple canals and aqueducts into complex networks consisting of pipelines and its accessories. Thus, a water distribution system has become an integral part of infrastructure, more so for urban living. The design of a water distribution network relies on operational analysis of networks and economical design of newer networks supplemented by strengthening and expansion of existing ones. A proper design of the system ensures that it meets the necessities or demands of the customer both in terms of capacity and the overhaul pressure. The water distribution networks cost more than 50% of the total cost of water supply systems. Hence, optimization of network becomes essential. The pressure loss in pipes is governed by pipe material (roughness), water demand that it caters to length, diameter and gradient of the pipe. The designed network should not exhibit excessive capacity this
leads to long transit times. Synchronously, the pipe should not exhibit a capacity shortage that will increase energy losses to satisfy demand (Suribabu, 2012). Hence, selecting a balanced pipe size for each link is a challenging task for network modelers. Bhave (2003) pointed out that optimization of network becomes essential since the cost of the pipes cost more than 50% of the total cost of water supply systems. This study proposes a heuristic-based approach to determine the near-optimum pipe diameters. Here, the flow velocity is considered as an inherent information in selection of the appropriate size of each link.

Design of water distribution system involves a selection of the pipe sizes and characteristics of various piping components for a given system layout by means of certain design process. The design process may be a Trial and Error process based on engineering judgments or by well defined selection guidelines while respecting certain basic requirement such as meeting the demand at various nodes and satisfying minimum required pressure. The selection of diameter of the link is considered as a vital part in the design of water distribution network, so that, the resulting configuration will be at least cost one. Selection of pipe diameter can be done by; Trial and Error method; Traditional optimization technique; Nature inspired algorithms; Heuristic technique based on performance measures such as reliability, availability, etc., incorporating performance measures as a constraint in optimization model. There is no guarantee that network is designed based on Trial and Error method results least cost design. Use of traditional optimization techniques and nature inspired algorithms (like genetic algorithm, particle swarm ant colony etc.) provide least cost solution with considerable expense computational effort. Heuristic approach provides alternative method to optimize the network reasonable close to optimal solution with limited applications. Incorporation of performance measures either as an objective or constraint for network design and may result better solution in terms of overall performance under pressure deficient conditions. Literature available over the past three decades certainly indicate that how significantly research has been taking place on the development of optimization algorithms and models for the optimal design of water distribution networks due to its computational and engineering complexity (Alperovits and Shamir, 1977; Quindry et al., 1981; Fujiwara and Khang, 1990; Lansy and Mays, 1989; Murphy and Simpson, 1992; Simpson et al., 1994; Savic and Walters, 1997; Cunha and Sousa, 1999; Vairavamoorthy and Ali, 2000; Maier et al., 2003; Suribabu and Neelakantan, 2006a, b; Neelakantan et al., 2008; Suribabu, 2010; Vasan and Simonovic, 2010; Mohan and Babu, 2010; Suribabu, 2012). A Heuristic is an experience-based method that can be used as an aid to solve various NP-hard design problems. Use of experience based and logical means can reduce computation effort and time to arrive close to optimal solution. This study proposes a method based on Heuristic method of optimization which provides a quick, accurate and economical solution. The preliminary estimate for the entire water distribution network is arrived using spatial approach.

OPTIMIZATION MODEL

The primary aim of any distribution network is to minimize the cost function. This in turn is influenced by the number of variables such as pipe diameter and pipe length (shortest possible route), etc. An optimization problem consists of an objective function and constraints. An objective function is the expression defining the objective, the different conditions which have to be satisfied by the objective function are termed as constraints. Optimization can be defined as finding an alternative with the most cost effective or highest achievable performance under the given constraints by maximizing desired factors and minimizing undesired ones.

The network cost was calculated as the sum of the pipe costs in which pipe costs are expressed in terms of cost per unit length. Total network cost was computed as follows:
\[
\text{Cost} = \sum_{i=1}^{N} C(D_i) L_i
\]

Where:
- \( C(D_i) \) = Cost per unit length of the ith link with diameter \( D_i \)
- \( L_i \) = Length of the ith link

For a given layout, lengths are fixed; consequently, diameters are the decision variables. This objective function needs to be minimized, subject to a set of constraints as follows, continuity of flow in each node should be maintained in the network and the quantity of flow entering the node should be equal to that leaving the node. The latter includes the external demand and outward flow through other pipes emerging from the node.

This is expressed in mathematical form as:

\[
\sum_{i \in \text{in}, a} Q_i = \sum_{j \in \text{out}, a} Q_j + ND_n \quad \forall n \in \text{NN}
\]

Where:
- \( Q \) = Pipe flow
- \( ND_n \) = Demand at node \( n \)
- \( \text{in}, n \) = Set of pipes entering to the node \( n \)
- \( \text{out}, n \) = Set of pipes emerging from node \( n \)
- \( \text{NN} \) = Node set

The total head loss around the closed path (loop) should be equal to zero or the head loss along a path between nodes should be equal to the difference in elevation, expressed as:

\[
\sum_{i \in \text{loop}, p} hf_i = \Delta p \in \text{NL}
\]

\( hf_i \) = Head loss due to friction in pipe \( i \)
\( \text{NL} \) = Loop set
\( \Delta H \) = Difference between nodal heads at both ends (\( \Delta H = 0 \) if the path is closed)

The pressure head in all nodes should be greater than the prescribed minimum pressure head, expressed as:

\[
H_n > H_{\text{min}}
\]

Where:
- \( H_n \) = Pressure head at node \( n \)
- \( H_{\text{min}} \) = Minimum required pressure head

The diameter of the pipes should be within what is commercially available.
CASE STUDY-SRIRANGAM TOWN

Srirangam is a sub-urban of Tiruchirapalli city located in Tamil Nadu, India and being a major tourist attraction has witnessed unprecedented growth in the last few decades. This temple town is an island bound by the rivers Kaveri and Kollidam and having elevation of 70 above MSL m. Srirangam thrives on tourism attributed to the location of the famous “Sri Ranganathaswamy Temple”, the largest temple complex in India. Spread across a sweeping area of 631,000 m², it encompasses seven concentric walled sections. The height of the Rajagopuram is 72 m (237 ft). This has led to a spurt in the demand for various resources, including the demand for potable water. In order to meet the escalating demands, it is imperative to modernize the present water distribution network. The water distribution network should be capable of meeting the demands of the present population and also have provisions to account for future demands. Srirangam’s infrastructure, especially its water supply network has not been kept pace with its growth. Hence, Srirangam has been chosen as the study area in order to address the above issues. In this study, the per capita consumption is taken as 200 lpcd since the population of the study area, Srirangam is around 1, 86,000. Arithmetic increase method is used to forecast the population for a design period of 50 years. The rate of increase in population is assumed as 10% for every decade. Peak factor is taken as 2.5 of the daily average demand. The current population of Srirangam is estimated using Spatial Approach with the help of Google Earth. The population was estimated for each street by calculating the number of houses/dwellings and assuming 6 persons per household. The total population arrived was 155,000. Accounting for future expansion, the population arrived is 249,711. The total water supply demand is estimated at 124.855 MLD.

PREPARATION OF NETWORK CONFIGURATION USING SATELLITE IMAGERY

The layout for the distribution network is prepared using “Google Earth”. A Google Earth image depicts the entire layout of the city along with the road networks and elevations. The pipe network is drawn along the existing roads such that they catered to maximum possible area in its vicinity. The layout was created using the “Add Path” option from the menu bar (Go to Add–Path). A new window “Google Earth-New Path” appears. The path is assigned with a unique name and properties (like colour) are changed as required. The part of above procedure is repeated for drawing the entire network. An intersection of two or more pipes is treated as a node. The nodes along with their appropriate unique names are created and their elevations (in meters) on the ground are recorded. The overall layout composed of both the pipe networks and the nodes are shown in Fig. 1.

The length of each pipe and elevation of each node is obtained from Google Earth as these data will be the required input to the EPANET 2.0 (Rossman, 2000). The length of each pipe in the network layout was found using the following commands:

- Go to Tools→Ruler
- A new window “Ruler” appears (Fig. 2)
- The length of the pipe is found between its nodes, using the mouse

The elevation of each node is displayed in Google Earth at the bottom as indicated in the Fig. 3. Thus, the length of each pipe and the elevation of each node in the entire network is found and tabulated.
Fig. 1: Overall view of network in Google Earth

Fig. 2: Dialog box for ruler

For optimization process, entire network layout imported in EPANET. Figure 4 shows the layout of Srirangam newly planned water distribution network for analysis and optimization process in EPANET.

PROPOSED HEURISTIC APPROACH

The proposed approach makes uses Heuristic method of optimization. It consists of two stages: First, pipe size is increased sequentially from a minimum size to what is required based on maximum flow velocity. Second, the reduction of assigned pipe size is done for those links which do not violate the minimum pressure requirement at all the nodes. The entire set of links is checked
for their diameter based on the maximum flow velocity and minimum pressure required. The pipe size is then reduced in order of the selection index which is explained here.

Any of the following two types of the selection index may be followed:

**Selection index 1**: Pipes are tested for its reduction based on their flow velocity. Based on flow velocity, they are ranked in ascending order. A potential pipe for reduction shall be the one with the lowest flow velocity. The pressure is checked in the nodes. If nodes do not exhibit a
Assign diameter of all pipes as 80 mm and perform hydraulic simulation

Increase diameter of pipe having velocity more than 2 m sec⁻¹ to next available size and perform hydraulic simulation

Is pressure head at any one node less than 8 m?

Rank the pipes as per condition of the chosen selection index

Select the pipe for reduction

Reduce its diameter to the next available size and perform hydraulic simulation

Is pressure head at all nodes greater than 8 m?

Retain its earlier size

Whether all the pipes are tested for reduction of size?

Start

Yes

No

End

Fig. 5: Flowchart for the proposed Heuristic approach

Pressure deficit, the pipe size is again reduced. If the nodes exhibit a pressure deficit for the updated size, the earlier size is retained.

Selection index 2: Ranking of the pipes is done based on unit head loss, in ascending order. Among all the pipes in the network, the one with the lowest unit head loss is selected first for reduction. The remaining procedure is followed similarly to that of the previous index.

The details of the algorithm to be implemented are depicted in the flowchart in Fig. 5.

RESULTS AND DISCUSSION

The preliminary model for designing the routes for the network is first created using Google Earth Satellite imageries. Viable paths, mostly along existing roads are taken as networks and nodes are fixed. The pipe networks are marked out and the entire layout is extracted. Water demand is calculated for each area segment. Demand in an area is usually influenced by population

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Table 1: Preliminary estimate for materials

<table>
<thead>
<tr>
<th>Total length (m)</th>
<th>Diameter (mm)</th>
<th>DSR item No.</th>
<th>Material</th>
<th>UcM</th>
<th>Rate (m)</th>
<th>Amount (Rs.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1340.75</td>
<td>80</td>
<td>1052</td>
<td>G.I. pipe</td>
<td>M</td>
<td>426</td>
<td>571162.482</td>
</tr>
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<td>2022.01</td>
<td>100</td>
<td>8644</td>
<td>CPVC pipe</td>
<td>M</td>
<td>1,640</td>
<td>3310986.40</td>
</tr>
<tr>
<td>6584.51</td>
<td>150</td>
<td>8645</td>
<td>CPVC pipe</td>
<td>M</td>
<td>2,870</td>
<td>18323543.70</td>
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<tr>
<td>10406.6</td>
<td>200</td>
<td>7700</td>
<td>G.I. pipe</td>
<td>M</td>
<td>2,120</td>
<td>22092182.80</td>
</tr>
<tr>
<td>3550.22</td>
<td>250</td>
<td>7701</td>
<td>G.I. pipe</td>
<td>M</td>
<td>2,830</td>
<td>10047122.60</td>
</tr>
<tr>
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<td>300</td>
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<td>M</td>
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<td>79084999.60</td>
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<tr>
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<td>350</td>
<td>7703</td>
<td>G.I. pipe</td>
<td>M</td>
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<td>14174775.00</td>
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<tr>
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<tr>
<td>1482.2</td>
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<td>12952945.80</td>
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<tr>
<td>180.25</td>
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<td>M</td>
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<td>10831282.90</td>
</tr>
</tbody>
</table>

Cost of pipe materials 36270767.80

variation, improvement in economic status of the community, increase in pressure in the distribution network, climate or seasonal variation and type of supply, etc. Therefore, the per capita water consumption is assumed in accordance with CPHEEO manual. The nodal demand estimated is the average daily demand. The design of water distribution network should be based on hourly fluctuation. The ratio of maximum demand to average demand is termed as peak factor. The peak factor in the present case is taken as 2.5 as the population of the town fall between 50,000 and 200,000. To forecast the future expected population, various methods such as arithmetic increase, geometric increase and graphical method etc., are employed. Real time data from government censes can depict the average rate of growth of an area. The design period or life of the distribution system is decided based on technological advances, available resources and capacity of the system components. In order to find the maximum water demand, peak factor is assumed appropriately. The extracted layout is used as a background and the entire network is re-modelled in EPANET. Input data such as population, nodal demand and elevation of nodal points are entered. The demand at any point in the area within a pressure zone is allocated to the node nearest to it. The file extracted as satellite imagery is converted from "kmz to .net file" in EPANET. The flow units are kept in Million Liters per Day (MLD) and Hazen-William's formula is used to calculate the head loss. The pipe size in each pipe is arrived using proposed method. The pipes initially are assigned with 80 mm as diameter. The entire iterative nature of exercise of optimization is done manually using EPANET 2.0 software. It is understood from the experience that manually process consumes considerable time. The time can be reduced once computer code is written for algorithm. Table 1 gives the list of pipe sizes selected by the proposed optimization method and preliminary estimation carried out using pipe sizes and its length. The cost of pipe is obtained from Delhi schedule of rates. The pipe material is selected based on its diameter. The total cost of the network is worked out by summing the cost of each diameter of pipe based on its total length.

CONCLUSION

Traditional methods of design of water distribution network such as Trial and Error method, results in uneconomical design. Moreover, they may be incompatible to meet the future demands. Heuristic method of optimization, as established from the study, gives a practical and economical
solution for design of water distribution network. Spatial approach provides an easy means to determine the population and subsequently determine the water supply demand. It negates the need for field work, thereby reducing the initial cost and duration in the preliminary phase of the project.

The preliminary estimate of the project can be estimated easily using spatial approach thereby facilitating quick sanction of funds for the project.

REFERENCES
