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Linear Programming based Model for Design of Looped Water Distribution Networks with Redundancy

Rajesh Gupta**, Yamini Lakshmi, Shweta Rathi
Civil Engineering Department, Visvesvaraya National Institute of Technology, India

Abstract
A new linear programming based two-phased methodology is suggested for design of looped water distribution networks with redundancy. The redundancy is provided against failure of pipes and a network is designed to sustain failure of any one of the link without affecting nodal supplies in a part or full. In the first phase, network is designed under normal pipe working conditions for assumed flow distribution using linear programming. The performance of designed system is checked using node-flow analysis for one pipe-failure conditions and most critical pipe failure condition is obtained in the second phase. The linear programming formulation in the first stage is appended to incorporate constraints for critical pipe failure conditions and solved. This process of successive addition of constraints in first phase continues until network design becomes satisfactory to sustain failure of any single pipe. The methodology is general and successive addition of constraints reduces the size of problem to be handled at a time. The methodology can be used for any type of flow-distribution. However, flow-distribution based on Chiong's model is observed to provide better design. The methodology is illustrated with example networks taken from literature.

Keywords: *Design, Linear programming, Optimization, Redundancy, Water Distribution Network*

****Author for Correspondence*** E-mail: drrajeshgupta123@hotmail.com

INTRODUCTION

Optimization and redundancy are two conflicting aspects in the design of water distribution networks (WDNs). While optimization tries to remove redundancy to minimize total cost, redundancy requires extra capacities and thus increases the cost. A looped WDN gets converted to a branching configuration on optimization if no constraints for minimum pipe flows or minimum pipe size are imposed [1–3]. When these constraints are imposed in optimal design of a WDN, flows gets concentrated in few pipes known as primary pipes and other pipes become secondary or loop forming pipes carrying minimum flows. The provision of minimum size or minimum capacity loop forming links only ensures connectivity of the demand nodes with source in case of failure of primary pipe but cannot guarantee delivery of nodal demands with adequate pressures. Hence, provision of minimum size loop forming links assures topologic redundancy but not the hydraulic redundancy. To incorporate hydraulic redundancy, hydraulic capacities under component failure should be assured. Although, a network consists of several components, the redundancy in the network under pipe failures is important. Further, probability of simultaneous failure of two or more pipes is very low and can be disregarded [4–7]. Thus, a network capable of sustaining failure of any pipe without affecting the nodal supplies in part of full are considered herein as a network with adequate redundancy.

A new linear programming (LP) based model is suggested for optimal design of looped WDNs with redundancy. The redundancy consideration in the design of WDNs requires inclusion of multiple flow patterns associated with failure of each link in addition to those from normal demand patterns. This increases the size of LP problem manifold. Further, to obtain a set of link sizes and their lengths, which satisfy the loop head loss constraints for all loops with multiple flow patterns is difficult as discussed later in this paper. To overcome these problems, a two-stage iterative methodology is suggested in which the network is initially designed for the normal demands by suppressing the loop-head loss constraints. Hydraulic consistency is then checked and most critical pipe failure condition is identified in the second stage using node flow analysis. The pressure constraints for this most critical pipe failure conditions are then added in LP problem framed in first stage. The successive addition of most critical failure conditions requires little number of iterations, but helps in reducing the size of problem as can be seen from the results of illustrative example.

LITERATURE REVIEW

The Linear Programming application to design a single source branched WDN, first suggested by Karmeli, Gadish and Meyers, provides global optimum solution. Each link is assumed to be consisted of all the available pipe sizes with their lengths as unknowns [8]. The objective function consists of minimization of total network cost subjected to the conditions that: (1) the summation of the length of individual pipes in a link should be equal to the length of that link; and (2) the head loss in various paths from source to demand nodes should be less than the available head difference.

Kally suggested *difference linear programming formulation* for the design of Looped WDNs. The method starts with some feasible solution [9]. The network was analyzed to obtain a flow-distribution. To reduce the cost of network, desirability of change to the higher or the lower size than in feasible solution for the full or part length was examined using LP. The LP formulation consists of maximizing the savings in total cost due to the change in the sizes of each link subjected to the constraints of change in pressure heads due to change in sizes and extents of lengths which can be replaced. Morgan and Goulter used Kally's difference linear programming formulation for selection of optimal layout and design of looped WDNs [10].

Alperovits and Shamir suggested *linear programming gradient* method for optimal design of Looped WDNs [11].

In linear programming gradient method, initially assumed flows are successively corrected using the auxiliary information available from LP solution. Several modifications to linear programming gradient method were suggested by different researchers to get better designs. Bhave and Sonak analyzed the philosophy of linear programming gradient method and showed that the method can at best provide a local optimum solution [12]. Sonak , Bhave and Shah suggested replacement-elimination process to identify global optimal tree solution of looped WDNs [13,14]. Bhave suggested two-phased LP methodology for minimum cost design of multi-source looped WDNs [15]. In the first phase, LP model was used for flow-allocation in different links for a multi-source network, and in the second phase, a separate LP model was used for minimum cost design. The primary focus of different methods, discussed so far, was on minimum cost design of looped WDNs with constraints of minimum capacity secondary links.

Xu and Goulter and Bhave and Gupta used fuzzy linear programming model for design of looped WDNs with uncertain nodal demands [16, 17]. The fuzzy linear programming model involved constraints for multiple loadings. Morgan and Goulter also suggested extension of their methodology for multiple demand patterns in which these patterns were considered owing to fire or other loadings, or pipe failures [10]. The main problem with multiple demand patterns is that size of problem increases, especially when pipe failures are considered, as each failure condition provides one flow-pattern. Morgan and Goulter suggested restricting number of path constraints equals to number of links in the network and selecting them in order of pressure deficiencies observed at different nodes for different loadings [10]. Kessler et al. and Ormsbee and Kessler suggested provision of two independent paths through two overlapping spanning trees capable of meeting the consumer demands independently in a LP based formulation [4, 5]. Consideration of branching configuration avoided loop head loss constraints and alternative tree avoided constraints for multiple demands as alternate tree contained all pipes omitted in first tree.

However, simultaneous removal of number of pipes one from each loop resulted in over redundant system [18].

Herein, a LP problem is formulated using appropriate flow-distribution model for normal demands. The constraints for multiple patterns due to failure of each link are added iteratively by identifying the most critical failure condition and improving the design successively. The iterative addition of constraints in LP formulation is observed to reduce the problem size drastically.

DEVELOPMENT OF ALGORITHM

Flow-Distribution Models

A LP model can be formulated and solved for a fixed-flow distribution in a looped WDN. Several flow-distribution models have been suggested to obtain least cost design, or design with flexibility. While Bhave suggested selecting primary and secondary pipes in looped WDN using path concept in which branching configuration consisting of primary pipes are obtained such that each demand node is connected to the source node through the shortest path [19]. Secondary links are assigned some minimum flow or minimum size and flows in primary links are fixed. Xu and Goulter [16] provided weights to different paths for fixing a flow-distribution. Bhave and Gupta [17] considered weights in inversely proportion to the path lengths with the assumption that longer path will carry lesser flows. Chiong suggested a model to obtain more uniform flows in different links for more flexibility in design [20–21].

LP Model Formulation

The optimization problem for a single source gravity network (*X* pipes, *C* Loops and *N* demand nodes can be expressed in standard design form as [22]

Minimize $$C_T = \sum_{x=1}^{X}\sum_{y=1}^{Y} c_y L_{xy} \qquad (1)$$

in which C_T is the total cost; c_y is the unit cost of pipe of size *y*; *Lxy* = length of pipe size *y* in link *x*. Note that the second summation gives the sum of the costs of *Y* pipes in a link, while the first summation gives the sum of the costs of *X* links.

Subjected to
X link-length constraints

$$\sum_{y=1}^{Y} L_{xy} = L_x \text{, for } x = 1, \ldots, X \qquad (2)$$

N path-head loss constraints involving primary pipes

$$\sum_{x \in P_j}\sum_{y=1}^{Y} S_{xy} L_{xy} \le H_0 - H_j^{\min},$$

for all paths P_j, $j = 1, \ldots, N$ (3)

in which S_{xy} = hydraulic slope for pipe size *y* in link *x*; H_0 = HGL at the source node; and $H_j^{\min}$ = minimum required HGL at the end node of path P_j.

C path-head loss constraints involving secondary links

$$\sum_{x \in P_j}\sum_{y=1}^{Y} S_{xy} L_{xy} + \sum_{y=1, x \in SL}^{Y} S_{xy} L_{xy} \le H_0 - H_j^{\min},$$

for all paths involving secondary links *SL*=*C*, (4)

and *XY* non-negativity constraints

$$L_{xy} \ge 0 \text{, for } x = 1, \ldots, X;\ y = 1, \ldots, Y \qquad (5)$$

Thus, the number of path constraints will become N+C, and M demand nodes will have a pair of path constraints. Each pair of path constraints is required to be given a common slack variable so as to indirectly satisfy loop-head loss constraints. For example, consider a single loop network with source node as 1 and demand nodes as 2, 3 and 4 (Figure 1). The pipe 4 is identified as secondary pipe and flow direction in this pipe is decided from 3 to 4. Flow directions in primary pipes are fixed. Herein, 1-3, 1-2 and 1-2-4 are primary paths from source node 1 to demand nodes 2, 3 and 4, respectively. Path 1-3-4 involves secondary link 4. The two paths ending at node 4 are 1-2-4 and 1-3-4 and can be given same slack variable. Thus, path equations in terms of head loss in links can be written as

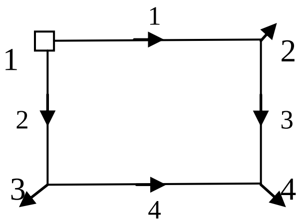

Fig. 1: *A single looped WDN.*

$$h_1 + S_2 \le H_0 - H_2^{\min} \quad (6)$$

$$h_2 + S_3 \le H_0 - H_3^{\min} \quad (7)$$

$$h_1 + h_3 + S_4 \le H_0 - H_4^{\min} \quad (8)$$

$$h_2 + h_4 + S_4 \le H_0 - H_4^{\min} \quad (9)$$

The constraints (8) and (9) in solution to the LP problem will ensure that loop head loss constraints are exactly satisfied and thus ensure hydraulic consistency. However, in case of network designs with multiple patterns, above constrains are required to repeated for each pattern. This causes two types of problems: (1) Obtaining one solution that will satisfy loop-head constraints exactly for every demand pattern; and (2) the size of LP problem increases manifold, especially when each pipe failure condition is considered for redundancy. To resolve first type of problem, pair of constraints were assign different slack variable. This assured the head loss in all paths from source to demand nodes to be less than the available head-difference for the considered flow-distributions with loss of hydraulic consistency. The performance and thus hydraulic consistency of the network so designed is checked through node flow analysis under designed loadings, and if necessary the design is repeated with obtained flow-distribution. To tackle the second type of problem, it is proposed to include the constraints for multiple patterns successively as discussed later.

Node Flow Analysis

The network performance can be checked by node head analysis or node flow analysis (NFA). The NFA has an advantage over node head analysis that it provides deficiency in nodal supplies, which are useful. The NFA uses a relationship that exists between flow and pressure at a node which is termed the node head-flow relationship (NHFR). In describing the NHFR, Gupta and Bhave used available flow, q^{avl}, equals to required flow, q^{req}, if HGL at a node is more than desirable HGL, H^{des}. For an available HGL less than minimum required HGL, H^{min}, q^{avl} is considered as 0; and for HGL values between H^{min} and H^{des}, partial availability of flows between no-flow and the required flow is characterized using a parabolic equation as below [23]. Thus,

$$\begin{aligned} q_j^{avl} &= q_j^{req}, if H_j^{avl} \ge H_j^{des} \\ q_j^{avl} &= q_j^{req}\left(\frac{H_j^{avl} - H_j^{\min}}{H_j^{des} - H_j^{\min}}\right)^{1/1.5}, if H_j^{\min} \le H_j^{avl} \le H_j^{des}, \text{ for } j = 1 = 1, \ldots, J \\ q_j^{avl} &= 0, if H_j^{avl} \le H_j^{des} \end{aligned} \quad (10)$$

A set of three alternative equations (Eq. 10) at each demand node are solved with continuity equations usually represented in NFA by unknown heads as follows:

$$\sum_{x \in j}\left(\frac{KL_x}{C_{HW_x} D_x^{\beta}}\right)\left(H_i^{avl} - H_j^{avl}\right)\left|H_i^{avl} - H_j^{avl}\right|^{(1/\alpha - 1)} - q_j^{avl} = 0 \quad (11)$$

Proposed Methodology

To develop a level-1 redundant WDN, two separate types of redundancies must be established: topologic and hydraulic. While topologic redundancy assures the availability of a continuous physical path from the source to each demand nodes in the event of pipe failure, the hydraulic redundancy will ensure supply of required quantity of water at desired pressures. In a level-1 topological redundant single-source looped network each node must be connected with at least two pipes. Kessler et al. [4] suggested an algorithm to achieve level-1 topological redundancy and can be used. A flow chart depicting the methodology for achieving level-1 hydraulic redundancy is shown in Figure 2. The methodology consists of two stages. In the first stage, an initial design of the system is obtained using LP for link flows obtained by considering one of the flow-distribution models {this initial design is also referred later as design under 0-pipe failure (0-PF) condition}. In the second stage, the performance of network is evaluated using a NFA under multiple single-pipe failure conditions (1-PF). The iterative procedure is terminated if the performance of the network is found satisfactory under both 0-PF and 1-PF conditions. Otherwise, the most critical pipe failure condition is identified and a new additional flow-distribution corresponding to critical pipe failure is passed on to first stage to improve the design.

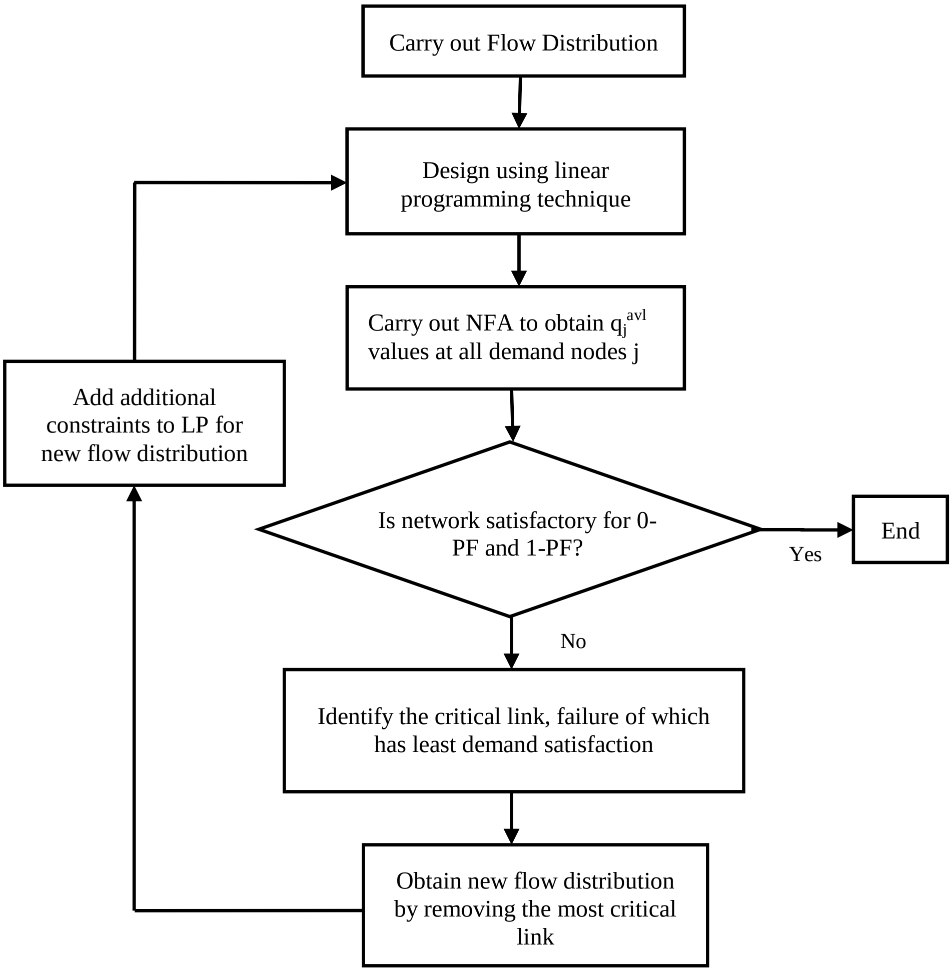

Fig 2: *Flow Chart for Design of WDNs with Redundancy.*

ILLUSTRATIVE EXAMPLE 1

The design methodology is illustrated with a two-loop example network of Alperovits and Shamir [11] as shown in Fig. 3. Source head and nodal demands along with minimum required HGL values are shown in Fig. 3. All pipes in the network are of 1000 m length. The cost data can be obtained from original paper [11]. Herein, it can be observed from the two-loop network that the source node 1 is connected by only one pipe. The network is now designed step by step.

(1) To achieve a topological redundancy, a parallel pipe of same size for pipe 1 is considered between nodes 1 and 2 as no other information of possible connection is available.

(2) The flow-distribution model of Bhave and Gupta is used [17]. The network is analyzed with all links of minimum size and flow-directions as shown in Figure 3 are obtained. There are two paths at each of the nodes 5 and 7. One of the two paths cover loop forming link. Nodal flows are distributed to connected incoming links based on the inverse propositional to path lengths.

(3) Initial flow-distribution for APWC is shown in column (2), Table 1.The LP problem (Eqs.1–5) is solved for APWC, without considering parallel pipe for 1. The network cost is 427458 units and

solution is given in Table 1 in columns (3) and (4).

(4) The NFA for network is carried out for APWC to check hydraulic consistency and also for 1-PFC to check most critical failure condition. The design is found satisfactory under APWC. However, it was observed deficient under all 1-PFCs. The most critical failure condition is failure of pipe 1.

(5) A new flow-distribution is obtained by removing pipe 1 (column 5). Herein, flow-distribution could not change as this link is replaced by parallel pipe, which will now carry the same flow. Constraints for both the patterns are considered simultaneously in LP model. The network is redesigned and design solution is provided in columns (6) and (7). The solution is essentially the same as only parallel pipe is added and cost is increased to 574481.

(6) The NFA is again repeated and most critical failure condition is observed to be of pipe 3. This pipe is now removed and a new flow-distribution (column 8) is obtained. LP problem is appended by adding the constraints for this new flow-distribution and solved. The design solution is provided in columns (9) and (10). The cost is increased to 886440.

The NFA now showed that network is capable of providing required flows and desired pressures at all nodes during failure of any one of the pipe. Hence, the process is stopped. Thus, two pipe failure conditions pipe1 and pipe 3 are required and in all final design is obtained in 3 iterations.

ILLUSTRATIVE EXAMPLE 2

The Hanoi WDN [24] as shown in Figure 4 is considered as an example network 2. Networks details are not provided herein. Readers can refer original paper for the same.

The final design using five flow-distribution models (Path Concept [15], entropy [25], Suribabu and Neelakanthan's [26], Bhave and Gupta's [17] and Chiong's [20]) are presented in Tables 2 and 3.

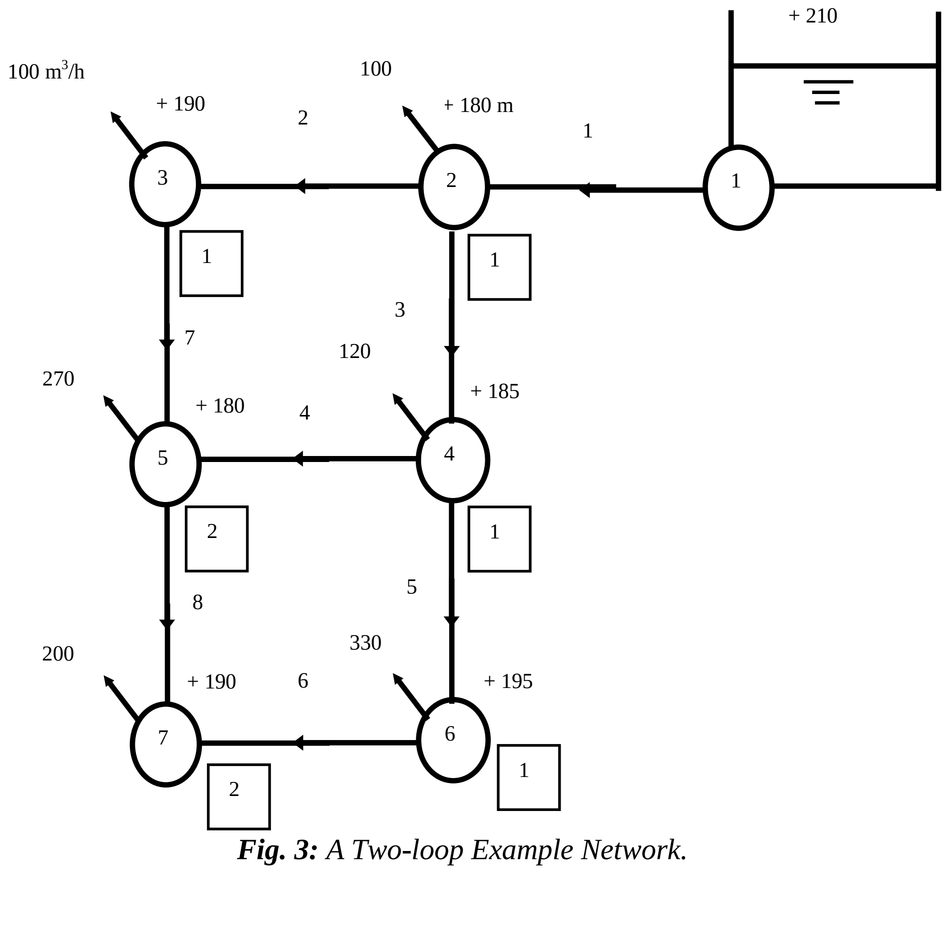

Fig. 3: *A Two-loop Example Network.*

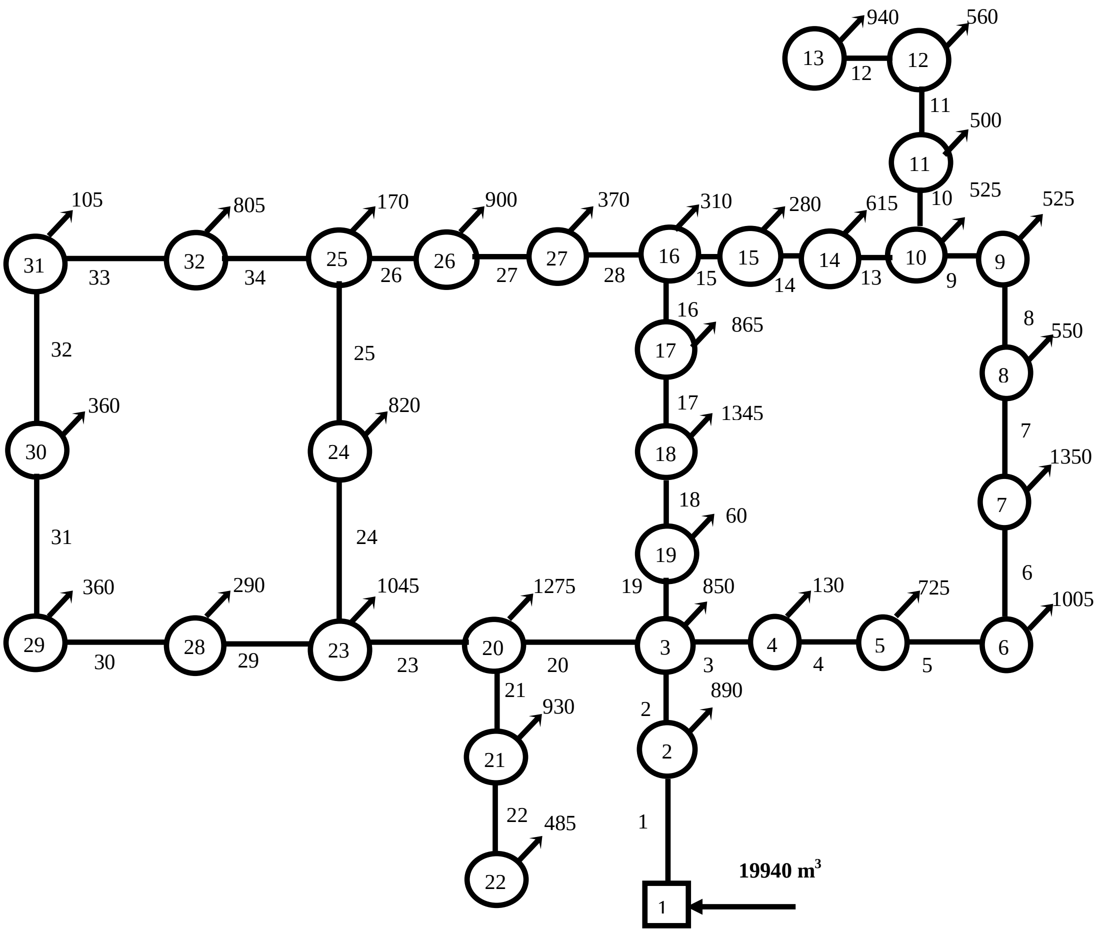

Fig. 4: Example Network 2.

Table 1: Network Design for Illustrative Example.

Pipe No.	Initial Flows APWC	Initial Solution for APWC		Flows under pipe-1 failed	Solution for Pipe-1 FC		Flows under pipe-3 failed	Solution for Pipe-3 FC	
		L	D		L	D		L	D
	(m^3/hr)	(m)	(mm)	(m^3/hr)	(m)	(mm)	(m^3/hr)	(m)	(mm)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1*	1120.00	574.4	457.2	1120.00	574.4	457.2	1120	810.7	457.2
		425.6	508.0		425.6	508.0		189.3	508.0
2	285.00	137.4	203.2	285.00	137.4	203.2	1020	1000.0	457.2
		862.6	254.0		862.6	254.0			
3	735.00	1000.0	406.4	735.00	1000.0	406.4	0	1000.0	406.4
4	185.00	83.7		185.00	83.7		285	162.9	203.2
		916.3	203.2		916.3	203.2		837.1	254.0
5	430.00	1000.0	254.0	430.00	1000.0	254.0	165	359.4	355.6
								640.6	406.4
6	100.00	82.1	355.6	100.00	82.1	355.6	165	31.8	254.0
		917.9			917.9			968.2	304.8
7	185.00	1000.0	152.4	185.00	1000.0	152.4	920	1000.0	457.2
								1000.0	406.4
8	100.00	1000.0	203.2	100.00	1000.0	203.2	365	810.7	457.2
								189.3	508.0
		427458			574481			886440	

** indicate parallel pipe of same size.*

Table 2: *Final Redundancy Based Designs using Different Flow-Distribution Models for Ex.2.*

Pipe No	Network design for flow-distributions using									
	Path Concept		Entropy Model		Suribabu and Neelakantan		Bhave and Gupta Model		Chiong`s Model	
	Length	Diameter	Length	Diameter	Length	Diameter	Length	Diameter	Length	Diameter
	m	mm	m	mm	m	mm	m	mm	m	mm
*1	100.0	1016.0	100.0	1016.0	100.0	1016.0	100.0	1016.0	100.0	1016.0
*2	1350.0	1016.0	1350.0	1016.0	1350.0	1016.0	1350.0	1016.0	1350.0	1016.0
3	900.0	1016.0	900.0	1016.0	900.0	1016.0	900.0	1016.0	900.0	1016.0
4	1150.0	1016.0	1150.0	1016.0	1150.0	1016.0	1150.0	1016.0	1150.0	1016.0
5	613.2	762.0	779.2	762.0	756.6	762.0	429.9	762.0	887.9	762.0
	836.8	1016.0	670.8	1016.0	693.4	1016.0	1020.1	1016.0	562.1	1016.0
6	450.0	762.0	450.0	762.0	450.0	762.0	450.0	762.0	450.0	762.0
7	464.1	762.0	850.0	762.0	850.0	762.0	479.9	762.0	850.0	762.0
	385.9	1016.0					370.1	1016.0		
8	850.0	1016.0	553.8	762.0	611.8	762.0	850.0	1016.0	850.0	762.0
			316.2	1016.0	238.2	1016.0				
9	800.0	1016.0	800.0	1016.0	800.0	1016.0	800.0	1016.0	800.0	762.0
*10	950.0	1016.0	950.0	1016.0	950.0	762.0	950.0	762.0	950.0	762.0
*11	1200.0	762.0	1033.9	609.6	1195.3	609.6	1200.0	762.0	1200.0	609.6
			166.1	762.0	4.7	762.0				
*12	1795.3	609.6	3500.0	609.6	3500.0	609.6	1795.4	609.6	572.8	508.0
	1704.7	762.0					1704.6	762.0	2927.2	609.6
13	800.0	1016.0	800.0	1016.0	800.0	1016.0	800.0	1016.0	205.2	762.0
									594.8	1016.0
14	500.0	1016.0	500.0	1016.0	500.0	1016.0	500.0	1016.0	500.0	1016.0
	550.0	1016.0	550.0	1016.0	550.0	1016.0	550.0	1016.0	550.0	1016.0
15	2730.0	1016.0	2730.0	1016.0	2730.0	1016.0	2730.0	1016.0	2730.0	1016.0
16	1750.0	1016.0	1750.0	1016.0	1750.0	1016.0	1750.0	1016.0	1750.0	1016.0
17	800.0	1016.0	800.0	1016.0	800.0	1016.0	800.0	1016.0	800.0	1016.0
18	400.0	1016.0	400.0	1016.0	400.0	1016.0	400.0	1016.0	400.0	1016.0
19	1375.9	762.0	1092.5	762.0	902.5	762.0	247.1	762.0	3.1	762.0
20	824.1	1016.0	1107.5	1016.0	1297.5	1016.0	1952.9	1016.0	2926.9	1016.0
	204.7	762.0	1218.4	762.0	1500.0	609.6	1500.0	609.6	787.2	609.6
*21	1295.3	1016.0	281.6	1016.0					712.8	762.0
	500.0	762.0	500.0	508.0	500.0	508.0	500.0	508.0	500.0	508.0
*22	2650.0	1016.0	2650.0	1016.0	447.9	762.0	2338.3	762.0	2650.0	1016.0
					2202.1	1016.0	311.7	1016.0		
23	1230.0	1016.0	1230.0	762.0	1230.0	762.0	1230.0	1016.0	1230.0	762.0
24	1300.0	1016.0	1300.0	762.0	1300.0	762.0	1300.0	1016.0	1300.0	1016.0
25	850.0	1016.0	850.0	1016.0	850.0	1016.0	850.0	1016.0	850.0	1016.0
26	300.0	1016.0	300.0	1016.0	300.0	1016.0	300	1016	300.0	1016.0
27	750.0	1016.0	750.0	1016.0	750.0	1016.0	750	1016	750.0	1016.0
28	1500.0	609.6	1500.0	762.0	1500.0	762.0	114.69	508	1500.0	609.6
							1385.31	609.6		
29	1594.7	508.0	2000.0	762.0	2000.0	762.0	2000	508	2000.0	508.0
	405.3	609.6								
30	1600.0	508.0	1600.0	762.0	1600.0	762.0	1600	508	1600.0	609.6
31	150.0	508.0	150.0	762.0	150.0	762.0	150	508	150.0	609.6
32	860.0	508.0	860.0	762.0	47.1	762.0	860	508	860.0	609.6
					812.9	1016.0				
33	56.2	508.0	291.09	762	950.0	1016.0	892.54	508	205.9	609.6
	893.8	609.6	658.91	1016			75.45	609.6	744.1	762.0
34	100.0	1016.0	100.0	1016.0	100.0	1016.0	100.0	1016.0	100.0	1016.0

** indicates parallel pipe of same diameter for that pipe.*

Table 3: *Cost and No. of iterations Example Network 2 for different flow distribution Models.*

Particulars	Final cost of network using flow distribution method				
	Path Concept	**Entropy Model**	**Suribabu And Neelakantan**	**Bhave and Gupta Model**	**Chiong`s Model**
Initial Cost (No redundancy)	**6180648**	6356568	6185928	6316890	6523753
No. of Iterations	8	8	9	8	8
Final Cost (with redundancy)	10612045	1013607	9978251	1014393	**9535194**

For the nodes connected with a single pipe, parallel pipes are considered. There are 7 such pipes (pipes 1, 2, 10, 11, 12, 21 and 22). Looking at the figure, it seems that it might have been more appropriate to join nodes 1 and 22, and nodes 13 and 14 to make it topological redundant. However, such options are not considered herein. Further, parallel pipes for these links are not added since beginning.

These are added only when failure of particular link becomes critical. There are 34 links and therefore simultaneous consideration of all 1-PFC would have required 35 flow-patterns. However, iterative addition of constraints corresponding to most critical failure conditions resulted in at the most 9 demand patterns to be considered simultaneously (Table 3) for most of the models.

The eight most critical conditions were observed to be of failure of pipe 1 and 2, 20, 3, 10, 11, 21, 12, and 22. It can be seen that last five iterations could have been avoided if parallel pipes to them are considered in the first iteration itself with pipes 1 and 2. When this was done, the number of iterations reduced to 3. Thus, critical failure conditions for the network are failure of pipes 1 and 2, 3 and 20. Further, additional iteration was observed in each case to check the hydraulic consistency. While designing with Chiong’s model, the step was repeated on addition of flow pattern corresponds to failure of pipe 3.

In case of Suribabu and Neelakanthan’s model, repetition was found necessary during addition of flow pattern for failure of pipe 20. In case of other models, it was for APWC itself. Thus, the proposed method is simple and reduces computational exhaustiveness associated with LP model involving multiple flow patterns.

It can be observed from Table 3 that flow-distribution using Chiong’s model provided minimum-cost design with redundancy. Flow-distribution using path concept resulted in minimum cost initial design (no redundancy); however, it provided maximum costly design when redundancy is considered.

SUMMARY AND CONCLUSIONS

A two-phase LP based methodology is suggested for minimum cost design of WDNs with redundancy. Redundancy is provided in the network to sustain effect of single pipe failure without affecting consumer services in part or full.

This requires consideration of path head loss constraints for several flow patterns in the formulation of LP model; each corresponds to failure of one of the link. Thus, it not only increases the size of LP model but also sometimes creates problems in getting a solution satisfying the loop head loss constraints with multiple patterns.

It is shown herein that problem can be solved by liberalizing the path constraints, and using NFA to check hydraulic consistency at the end of the iteration. The NFA also identifies the most critical failure conditions, and provides feedback to reformulate LP model for improving the solution until the design becomes satisfactory under failure of any one of the pipes.

The solution for a large example network is obtained in 4 iterations; however, final solution depends on selected flow-distribution model. Chiong’s model is found to provide minimum cost design with redundancy.

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