Water supply pipe dimensioning using hydraulic power dissipation

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Abstract. Proper sizing of the pipe component of water distribution networks play an important role in the overall design of the any water supply system. Several approaches have been applied for the design of networks from an economical point of view. Traditional optimization techniques and population based stochastic algorithms are widely used to optimize the networks. But the use of these approaches is mostly found to be limited to the research level due to difficulties in understanding by the practicing engineers, design engineers and consulting firms. More over due to non-availability of commercial software related to the optimal design of water distribution system,it forces the practicing engineers to adopt either trial and error or experience-based design. This paper presents a simple approach based on power dissipation in each pipeline as a parameter to design the network economically, but not to the level of global minimum cost.

1. Introduction

Water distribution system is a hydraulic infrastructure that consists of various components such as pipes, tanks, reservoirs, pumps, and valves etc.[24]. Consumer satisfaction in terms of quantity and quality is an important responsibility of a service provider. Effective water supply is of paramount importance in designing a new water distribution network or in expanding the existing one. It is also essential to investigate and establish a reliable network ensuring adequate pressure head at consumer nodes. Determination of flow and pressure in network pipes has been of great value and interest for those involved with design, construction and maintenance of public water distribution systems. Analysis and design of pipe networkare considered a relatively complex problem, particularly if the network consists of wide ranges of pipes as it frequently occurs in water distribution systems of large metropolitan areas. In the absence of significant fluid acceleration, the behaviour of a network can be visualized as sequence of steady state conditions, which forms a simple practice but is a vital component for assessing the adequacy of a network [15]. Use of optimization techniques in deciding the size of pipes in the network from a set of commercially available diameters have been attempted for more than three decades due to its computational and engineering complexity [1-5,8,11,12,18-21]. Software and programs developed based on demand driven analysis are widely coupled with optimization algorithm to explore pipe diameters that satisfy the hydraulic-head requirements at least cost. [13] and [10] developed a rule based search approach for economical pipe sizing. [7] developed an iterative model in which a network is designed by setting all the pipes to minimum acceptable pipe diameters followed by aniterative process progressing in such a way that the additional cost is as low as possible while the diameter of pipe is increased. [19] presented a new approach in which flow velocity in a pipe is considered as implicit information for pipe sizing. As there is a growing interest in developing a methodology based on heuristics search instead of experimenting with various new populations based algorithms, the present work aims to dimension the pipes using hydraulic power dissipation of energy in the pipeline. The head loss in the pipe is not onlyattributed to the roughness of the pipe, but also due to water demand, pipe length, gradient and diameter. The network configuration initially set by either smaller size or larger size is progressively improved to reach economical configuration using power dissipated in the pipeline to overcome the friction loss. The proposed methodology is illustrated using some well-known bench mark networks.

2. Hydraulic simulation

This study presents the use of EPANET software in the design of the water distribution networks which performs extended period simulation of hydraulic and water quality behaviour within pressurized pipe networks [3]. A network usually consists of pipes, nodes (pipe junctions), pumps, valves and storage tanks or reservoirs. EPANET tracks the flow of water in each pipe, the pressure at each node and the height of water in each tank throughout the network [14]. This software is used to calculate the power dissipation in each link after updating from initial network configuration. The results in each simulation run are used to verify the pressures at all junctions and the flow at all pipes.

3. Method of approaches

This paper presents two methods to dimension the pipes in the network. Both the approaches consider hydraulic power dissipation as the main parameter for sizing the pipe from its initial configuration. In the decreasing diameter method, maximum size is assigned to all pipes of the network as initial configuration, whereas in the case of increasing diameter approach, minimum size is assigned to compose the initial configuration for optimization.

3.1 Decreasing diameter method

1. The pipe system is plotted using EPANET software [13].
2. The corresponding length of the pipes, Hazen William's roughness coefficients, the base demand for various nodes and head available at the tankare given as input.
3. Initially the diameter of all pipes is set to the maximum available commercial size.
4. A hydraulic analysis is then performed and the pressure head at various nodes and the flow and head loss at various links are noted.
5. The power loss (ρgQh_f) due to friction is calculated and tabulated.
6. According to the decreasing diameter approach, the link with minimum power loss is found out and its diameter is decreased subsequently to a lower diameter.
7. Hydraulic analysis is performed again and the pressure head, flow and friction losses are tabulated.
8. Again, the link with minimum power loss is found and its diameter is reduced.
9. Steps 5 and 6 are repeated till the pressure head reaches a value close to the minimum required pressure head.
10. After completing the above steps, the size of each pipe is reduced to next size and violation of pressure is verified, if no violation of pressure is found, then the new diameter is assigned and this process is repeated for all the pipes in the network for further reduction of cost.

3.2 Increasing diameter method

1. The pipe network is plotted using EPANET software.
2. The corresponding length of the pipes, Hazen William's roughness coefficients, the base demand for various nodes and head available at the tankare given as input and the flow is measured.
3. Initially the diameter of all the pipes is set to a minimum available commercial size.
4. Hydraulic analysis is performed and the pressure head at various nodes and the flow and friction loss at various links are noted.
5. Power loss due to friction is calculated and tabulated.

6. According to the increasing diameter approach, the link with maximum power loss is found and its diameter is increased subsequently to a higher diameter.
7. Steps 5 and step 6 are repeated till the pressure head in all the nodes reaches minimum service pressure.
8. After completing the above steps, the size of each pipe is reduced to next size and violation of pressure is verified, if no violation of pressure is found, then the new diameter is assigned and this process is repeated for all the pipes in the network for further reduction of cost.

4. Benchmark networks

4.1 Hanoi network

The Hanoi water distribution network is taken from the literature for illustration of the recommended method. It is arranged in 3 loops with thirty-twonodes and thirty-four pipes. It has only one fixed head source at an elevation of 100 m and no pumping provisions. The required minimum head at all the nodes is set as 30 m. Commercially obtainable pipe diameters of 12, 16, 20, 24, 30 and 40 inches are taken. Figure 1, shows the layout of network. Table 1a, provides the complete data for the design of the network. The Hazen William roughness factor of each pipe is considered as 130. Table 1b, provides the cost details for the network.The results of proposed methods are presented in Table 1c, and for comparison purpose, two results available in the literature are also taken.

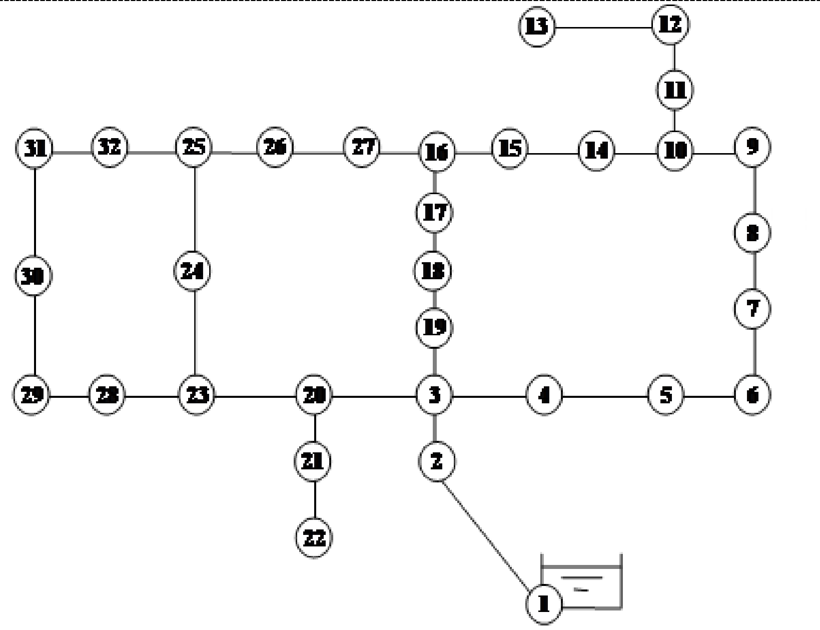

Figure 1. Layout of Hanoi network

Table 1a. Pipe length and nodal demand details

Node no.	Demand (cu.m/h)	Link index	Arc	Length (m)
1	-19940	1	(1,2)	100
2	890	2	(2,3)	1350
3	850	3	(3,4)	900
4	130	4	(4,5)	1150
5	725	5	(5,6)	1450
6	1005	6	(6,7)	450
7	1350	7	(7,8)	850
8	550	8	(8,9)	850
9	525	9	(9,10)	800
10	525	10	(10,11)	950
11	500	11	(11,12)	1200
12	560	12	(12,13)	3500
13	940	13	(10,14)	800
14	615	14	(14,15)	500
15	280	15	(15,16)	550
16	310	16	(16,17)	2730
17	865	17	(17,18)	1750
18	1345	18	(18,19)	800
19	60	19	(19,3)	400
20	1275	20	(3,20)	2200
21	930	21	(20,21)	1500
22	485	22	(21,22)	500
23	1045	23	(20,23)	2650
24	820	24	(23,24)	1230
25	170	25	(24,25)	1300
26	900	26	(25,26)	850
27	370	27	(26,27)	300
28	290	28	(27,16)	750
29	360	29	(23,28)	1500
30	360	30	(28,29)	2000
31	105	31	(29,30)	1600
32	805	32	(30,31)	150
		33	(31,32)	860
		34	(32,25)	950

Table 1b Cost data for Hanoi network

Diameter (mm)	Cost per m length ($/m)
304.8 (12 in)	45.73
406.4 (16 in)	70.43
508 (20 in)	98.38
609.6 (24 in)	129.333
762 (30 in)	180.8
1016 (40 in)	278.3

Table 1c. Optimal results for Hanoi network

Node/ Pipe no.	Increasing diameter approach		Decreasing diameter approach		Differential evolution algorithm (suribabu, 2010)		Heuristic based approach (suribabu, 2012)	
	Diameter (mm)	Pressure (m)	Diameter (mm)	Pressure (m)	Diameter (mm)	Pressure (m)	Diameter (mm)	Pressure (m)
1	1016	100	1016	100	1016	100	1016	100
2	1016	97.14	1016	97.14	1016	97.14	1016	97.14
3	1016	61.67	1016	61.67	1016	61.67	1016	61.67
4	1016	57.94	1016	57.94	1016	56.92	1016	57.59
5	1016	53.34	1016	53.34	1016	51.02	1016	52.54
6	762	48.61	762	48.61	1016	44.81	1016	47.31
7	1016	44.32	762	44.33	1016	43.35	1016	46.11
8	762	43.18	1016	39.71	1016	41.61	1016	44.78
9	762	39.72	762	38.86	1016	40.23	1016	43.74
10	762	37.36	762	36.50	762	39.20	762	43.02
11	609.6	35.8	609.6	34.94	609.6	37.64	762	41.46
12	762	32.37	762	31.51	609.6	34.21	508	40.3
13	304.8	30.95	304.8	30.09	508	30.01	304.8	30.08
14	304.8	35.48	304.8	34.64	406.4	35.52	304.8	31.93
15	406.4	39.04	304.8	38.22	304.8	33.72	304.8	32.00
16	609.6	41.63	609.6	48.78	304.8	31.30	508	34.73
17	762	52.98	1016	57.38	406.4	33.41	609.6	43.42
18	1016	57.99	1016	58.40	609.6	49.93	609.6	50.78
19	762	59.18	762	59.46	508	55.09	762	60.05
20	1016	52.46	1016	51.43	1016	50.61	1016	51.21
21	508	43.11	508	42.48	508	41.26	508	41.86
22	304.8	37.95	304.8	37.32	304.8	36.10	304.8	36.70
23	1016	47.89	1016	46.76	1016	44.52	1016	45.63
24	762	44.75	762	42.95	762	38.93	762	40.70
25	609.6	39.96	762	40.82	762	35.34	762	37.66
26	304.8	33.21	406.4	36.81	508	31.70	406.4	30.55
27	304.8	36.25	304.8	37.54	304.8	30.76	304.8	30.54
28	406.4	38.48	304.8	37.83	304.8	38.94	304.8	40.10
29	406.4	33.1	406.4	32.83	406.4	30.13	406.4	39.49
30	406.4	31.45	406.4	31.60	304.8	30.42	304.8	31.81
31	304.8	31.81	304.8	32.02	304.8	30.70	304.8	32.98
32	304.8	36.05	304.8	36.78	406.4	33.18	304.8	35.50
33	304.8		304.8		406.4		406.4	
34	508		508		609.6		609.6	
Cost	$ 6.477 million		$ 6.717 million		$6.0801 million		$6.2323 million	

4.2 GoYang network

GoYang network consists of thirty pipes, twenty-two demand nodes.A single fixed pump of 4.52 kW is connected to thereservoir with a constant head of 71 m. The Hazen-Williams roughness coefficient for each new pipe is taken as 100. The minimum pressure head for each node is set as 15 m. Figure 2, shows the layout of network. Table 2a, provides the complete data for the design of the network. Table 2b, provides the cost details for the network. The results of proposed methods are presented in Table 2c, and for comparison purpose, two results available in the literature are also taken.

Table 2a. Pipe length and nodal demand details

Node no.	Demand (L/s)	Link index	Length (m)
1	0	1	165
2	1.77	2	124
3	0.82	3	118
4	0.68	4	81
5	0.87	5	134
6	0.78	6	135
7	0.73	7	202
8	0.56	8	135
9	0.49	9	170
10	0.35	10	113
11	0.49	11	335
12	0.43	12	115
13	0.43	13	345
14	0.73	14	114
15	5.16	15	103
16	1.25	16	261
17	0.92	17	72
18	0.64	18	373
19	1.37	19	98
20	1.44	20	110
21	0.37	21	98
22	9.25	22	246
		23	174
		24	102
		25	92
		26	100
		27	130
		28	90
		29	185
		30	90

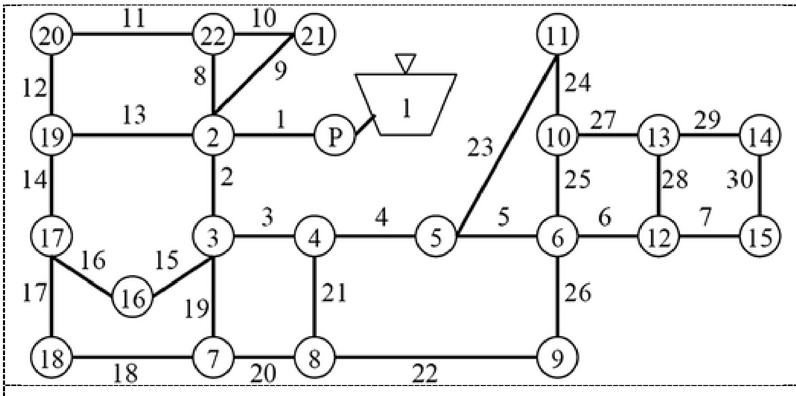

Figure 2. Layout of GoYang network

Table 2b. Cost data for GoYang network

Diameter (mm)	Cost ($/mm)
80	37.89
100	38.933
125	40.563
150	42.554
200	47.624
250	54.125
300	62.109
350	71.524

4.3 New York Tunnel network

This network includes twenty-one pipes arranged in two loops, nineteen demand nodes and one reservoir with a fixed head of 300 ft. (1 ft.=0.3048 m). In order to meet the projected increased demands, all the existing pipes are considered for replication. The Hazen-Williams roughness coefficient for both new and current pipes is 100. The minimum pressure headto be maintained at all nodes is fixed at 255 ft. except for node 16 and 17, where the minimum pressure head that has to be maintained is fixed at 260 ft. and 272.8 ft. respectively.Figure 3, shows the layout of network. Table 3a provides the complete data for the design of the network. Table 3b provides the cost details for the network. The results of proposed methods are presented in Table 3c and for comparison purpose; two results available in the literature are also taken.

Table 2c. Optimal results for GoYang network

Node / Pipe no.	Increasing diameter approach		Decreasing diameter approach		Heuristic based algorithm (Menon,2016)		Harmony search algorithm (Geem,2006)	
	Diameter (mm)	Pressure (m)	Diameter (mm)	Pressure (m)	Diameter (mm)	Pressure (m)	Diameter (mm)	Pressure (m)
1	250	15.62	250	15.62	200	15.62	150	15.61
2	150	29.79	150	29.79	150	28.93	150	24.91
3	100	31.26	100	31.26	100	30.4	125	26.32
4	80	27.78	80	27.78	100	26.89	150	24.11
5	80	23.6	80	23.6	80	24.54	100	22.78
6	80	21.32	80	21.32	80	21.9	100	20.67
7	80	29.76	80	29.76	100	28.92	80	25.34
8	100	28.05	100	28.05	80	27.26	80	24.41
9	80	21.42	80	21.42	80	21.64	80	20.01
10	80	15.91	80	15.91	80	16.55	80	15.43
11	80	15.65	80	15.65	80	16.39	80	15.06
12	80	17.93	80	17.93	80	18.54	80	18.16
13	80	17.23	80	17.23	80	17.84	80	17.38
14	80	15.11	80	15.11	80	15.72	80	15.72
15	80	15.25	80	15.25	80	15.86	80	15.42
16	80	30.69	80	30.69	80	29.83	80	25.88
17	80	28.92	80	28.92	80	28.07	80	24.29
18	80	28.56	80	28.56	80	27.72	80	23.99
19	80	29.54	80	29.54	80	28.69	80	24.89
20	80	29.13	80	29.13	80	28.29	80	24.43
21	80	21.72	80	21.72	80	20.87	80	16.89
22	80	22.02	80	22.02	80	21.16	80	17.21
23	80		80		80		80	
24	80		80		80		80	
25	80		80		80		80	
26	80		80		80		80	
27	80		80		80		80	
28	80		80		80		80	
29	80		80		80		80	
30	80		80		80		80	
Cost	$ 178,193.9		$ 178,193.9		$ 177,275.6		$ 176,994.6	

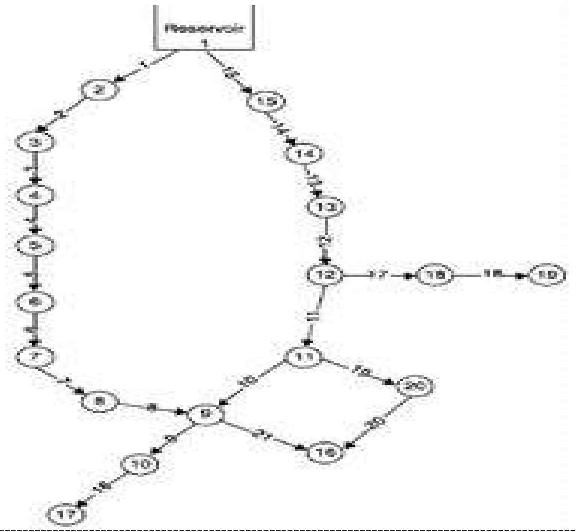

Figure 3. Layout of NYT network

Table 3a. Pipe length and nodal demand details

Node no.	Demand (CFS)	Link index	Length (ft.)
2	92.4	1	11600
3	92.4	2	19800
4	88.2	3	7300
5	88.2	4	8300
6	88.2	5	8600
7	88.2	6	19100
8	88.2	7	9600
9	170	8	12500
10	1	9	9600
11	170	10	11200
12	117.1	11	14500
13	117.1	12	12200
14	92.4	13	24100
15	92.4	14	21100
16	170	15	15500
17	57.5	16	26400
18	117.1	17	31200
19	117.1	18	24000
20	170	19	14400
		20	38400
		21	26400

Table 3b. Cost data for NYT network

Diameter (in.)	Cost ($/ft.)
36	93.59
48	133.70
60	176.32
72	221.05
84	261.61
96	315.80
108	365.46
120	416.46
132	468.71
144	522.11
156	576.59
168	632.09
180	688.54
192	745.91
204	804.14

Table 3c. Optimal results for NYT network

Node/ Pipe no.	Increasing diameter approach		Decreasing diameter approach		Differential evolution algorithm (Suribabu, 2010)		Ant colony optimization algorithm (Maier et al.,2003)	
	Diameter (mm)	Pressure (m)	Diameter (mm)	Pressure (m)	Diameter (mm)	Pressure (m)	Diameter (mm)	Pressure (m)
1	0	300	0	300.00	0	300.00	0	300.00
2	0	294.42	0	295.96	0	294.21	0	294.21
3	0	286.69	0	290.61	0	286.15	0	286.15
4	0	284.44	0	289.13	0	283.79	0	283.79
5	0	282.46	0	287.92	0	281.70	0	281.70
6	0	280.94	0	287.08	0	280.07	0	280.07
7	0	278.57	0	285.96	144	277.51	144	277.51
8	48	275.1	0	284.71	0	276.67	0	276.67
9	84	272.86	0	284.20	0	273.78	0	273.78
10	0	272.84	0	284.17	0	273.74	0	273.74
11	0	272.96	0	284.50	0	273.87	0	273.87
12	0	274.32	0	286.64	0	275.14	0	275.14
13	0	277.4	168	290.72	0	278.10	0	278.10
14	0	285.12	204	294.86	0	285.56	0	285.56
15	0	293.13	204	297.65	0	293.33	0	293.33
16	204	260.82	0	261.09	96	260.08	96	260.08
17	96	272.8	120	276.91	96	273.68	96	273.68
18	96	260.36	60	280.39	84	261.18	84	261.18
19	84	256.58	96	254.00	72	255.05	72	255.05
20	0	264.05	0	277.49	0	260.73	0	260.73
21	72		36		72		72	
Cost	$ 52.59 million		$ 68.90 million		$ 38.64 million		$ 38.64 million	

5. Evaluating the performance of pipe networks using resilience indices

The process of optimization usually involves bringing down the cost by reducing the pipe sizes or by completely eliminating some pipes which tends to render the system with inadequate capacity to respond to pipe failures or user demands which exceed projected values. Hence it is of utmost importance to include reliability considerations in all stages of planning, design and implementation of water distribution systems. A water distribution system is efficient and reliable enough only when it supplies water to all the nodes and meets the demand and pressure under satisfactory conditions. However, sometimes there is a possibility of a pipe failure because of which the entire flow changes resulting in high energy losses. This problem can be overcome by assigning more power than that required at each node and this loss in energy is met up by the surplus energy available in the system. So, assessment of pipe networks in this manner enables us to understand the concept of resilience which clearly indicates how quickly and easily a pipe network revives itself from failure conditions. The formulae proposed to find Resilience Index (RI) [20] and Modified Resilience Index (MRI) [6] are as follows:

$$RI = \frac{\sum_{j=1}^{N} q_i \left(h_{avl,j} - h_{min,j}\right)}{\left(\sum_{i=1}^{R} Q_r h_{res,i} + \sum_{b=1}^{B} \frac{P_b}{\nu}\right) - \sum_{j=1}^{N} q_j h_{min,j}} \tag{1}$$

$$MRI = \frac{\sum_{j=1}^{N} q_i \left(h_{avl,j} - h_{min,j}\right)}{\sum_{j=1}^{N} q_j h_{min,j}} \tag{2}$$

where q_i is the demand at node i, $h_{avl,j}$ is the available pressure head at node j, $h_{min,j}$ is the minimum pressure head at node j, Q_r is the flow from reservoir i, $h_{res,i}$ is the sum of reservoir elevation and its water level of reservoir i, P_b is the capacity of pump b and ν is the specific weight of the liquid.

Table 4. Performance measure values for Hanoi network

Analysis	Increasing Diameter	Decreasing Diameter	Differential evolution Suribabu (2010)	Heuristic-based approach Suribabu (2012)
Resilience Index(RI)	0.235	0.231	0.192	0.216
Modified Index (MRI)	0.549	0.539	0.447	0.504

Table 5. Performance measure values for GoYang network

Analysis	Increasing Diameter	Decreasing Diameter	Heuristic based algorithm Menon (2016)	Harmony search algorithm Geem (2006)
Resilience Index (RI)	0.489	0.489	0.465	0.432
Modified Index (MRI)	0.530	0.530	0.471	0.463

Table 6. Performance measure values for NYT network

Analysis	Increasing Diameter	Decreasing Diameter	Differential evolution Suribabu (2010)	Ant Colony Optimization algorithm Maier et al. (2003)
Resilience Index (RI)	0.421	0.617	0.42	0.42
Modified Index (MRI)	0.072	0.106	0.07	0.07

6. Results and discussion

To increase the reliability and resilience of a network it is advisable to maintain a higher pressure than what is required (i.e. the minimum pressure that has to be maintained at every node). But, maintaining a higher pressure at a node invariably leads to increasing the diameter of the pipe which consequently increases the cost and the design ceases to be economical. Hence, it is necessary to strike a balance between cost and reliability. Higher resilience values usually lead to higher costs but then the networkis hydraulically efficient when compared to a network with lower resilience index. In the case of Hanoi network, the highest pressure maintained is 97.14m for a pipe of diameter 1016mm at node 2 in all the cases. It is seen that the pressure head decreases at every successive node when water flows through larger number of pipes owing to friction loss in every pipe. The friction loss is greater in pipes of smaller diameter. The lowest pressure is seen at node 13 in all the cases. While it would have been safer to assign a larger diameter to pipe 10, 11, 12, 21 and22 which connects node 13 and 22 respectively to enable maintenance of higher pressure since there is only one pipe which supplies water to that point and any leakage or breakage of pipe en-route would affect that consumer point severely, we have resorted to lower diameter according to the various procedures followed.It is observed that pipes which are in quick succession with the reservoir namely pipes 1,2,3, 19 and 20 are of larger diameters when compared to pipes which are relatively far from the reservoir namely pipes 26 to 34 and consequently higher pressure is maintained at nodes connected by pipes 1,2,3, 19 and 20and lower pressure is maintained at nodes connected by pipes 26 to 34.Since the direction of flow changes according to the shortest route possible to reach a node, consecutive nodes are supplied water from two opposing directions which makes the pipe in between them unnecessary and hence lower diameter may be assigned to them for a more economic cost. The difference in cost between the first two solutions found by increasing and decreasing diameter approaches and the solutions obtained by differential evolution method and heuristic based approach results is due to drastic variation in diameter of pipes 16 to 19. The increasing diameter approach provides least cost solution compared with decreasing diameter approach.In the case of GoYang network, it is seen that both the approaches provide the same result which invariably leads to higher diameters for pipes in quick succession to the reservoir namely pipes 1, 2 and 3 and the least possible diameter 80 mm for other pipes which results in sufficient pressure being maintained at all the nodes higher than the required pressure head of 15m.Focussing on the New-York City Tunnel network, the primary objective is to revamp it by taking into account population growth and the consequent increase in water demand. If the current network is no longer able to meet increased demand, it leads to pressure violations at consumer nodes. Hence, the network must be improved by replicating some of the pipes, i.e., putting new pipes in parallel with the existing ones, at a minimum cost. This process consists of the following steps: 1) Determine the pipes that need to be duplicated and 2) For the selected pipes fix a diameter within the available diameter set. It was found that age and increased demands left the existing gravity flow tunnels in New-York City inefficient in meeting the pressure requirements at nodes namely 16, 17, 18, 19 and 20. The network consist of 21 pipes that may be duplicated with one of the 15 available commercial diameter pipe sizes or can be deemed to exist on their own without the need to be duplicated. All the proposed techniques indicate that pipes 17, 18, 19 and 21 require duplication, with the addition of pipes 8, 9 and

16(increasing diameter approach) and pipes 13, 14 and 15(decreasing diameter approach) in our viewpoint.The power dissipation based approaches follow shortest path route to assign diameter to the pipe. It is evident from the study that shortest path alone does not make a network to have a configuration that will lead to an economical design. Since commercial diameter pipe sizes are used to configure the network, assigning higher size than that required for certain links are inevitable in such an optimization method which ultimately deviates from shortest path configuration in order to achieve economical design. While assessing the designed networks from performance point of view, the network having higher cost provides better performance measures than least cost design.

7. Conclusion

The present study proposes a simple method based on power dissipation in the pipe to dimension the water distribution network without the use of an optimization technique. The hydraulic energy available from the source is dissipated while water travels along the pipe to overcome major and minor losses. Sizing the pipe based on power consumed in each pipe uses the shortest path from the source to demand nodes. Though it is the correct way to size the pipe as any commodity needs to be transported along shortest path and it will invariably lead to economical results, in the pipeline dimensioning this idea will not hold good for all the cases as commercial pipe sizes are used, which may be of a greater size than that actually required from the economical point of view.Hence this aspect of the proposed sizing method always leads to higher cost than network design by optimization techniques. But, this method has advantages of its simplicity and also does not use any operation research techniques.Prominent observation of the proposed approaches is that the increasing diameter approach usually provided more economic results (lower cost) than decreasing diameter approach in most of the cases. After carefully studying the reliability characteristics of the various water distribution networks, it was noted thatnetworks with low resilience values were relatively cheaper and exhibited satisfactory hydraulic operational performance. If there should be an occurrence of multiple sources in a water distribution network, the total surplus power available at the demand nodes is not precisely gauged by the resilience index. In such a case, utilization of the modified resilience index is favourable since it considers only the surplus powerat the demand nodes and not the surplus power available for internal dissipation. Hence, it is consequently beneficial to use the modified resilience index as a pointer of the capacity of the network to deal with increased demands or pipe failures. The concerns detailed in this research need to be further advanced and expanded by researchers and engineers who are committed to produce both economic and efficient networks.

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