Supplemental Material for Rathi et al., "Minimizing the Variance of Flow Series using Genetic Algorithm for Reliability-based design of Looped Water Distribution Networks", *Engineering Optimization*, 2019.

ILLUSTRATIVE NETWORK

The water main System, as shown in Figure S1, has one source and 16 demand nodes. Ormsbee and Kessler (1990) labeled Source Node as S (herein labeled 1) and demand nodes 1 through 16 (herein, labeled 2 through 17). Links are labeled 1–22, the same as done by Ormsbee and Kessler (1990). Interested readers may find the link and the node details from Ormsbee and Kessler (1990). Ormsbee and Kessler (1990) provided designs for three loading conditions: (1) Maximum day demand loading condition (MDD); (2) peak-hour demand loading condition (PHD); and (3) Maximum day demand plus fire loading condition (MDDF). Herein, a comparison is shown in details with PHD and MDDF conditions. Other design data are as follows:

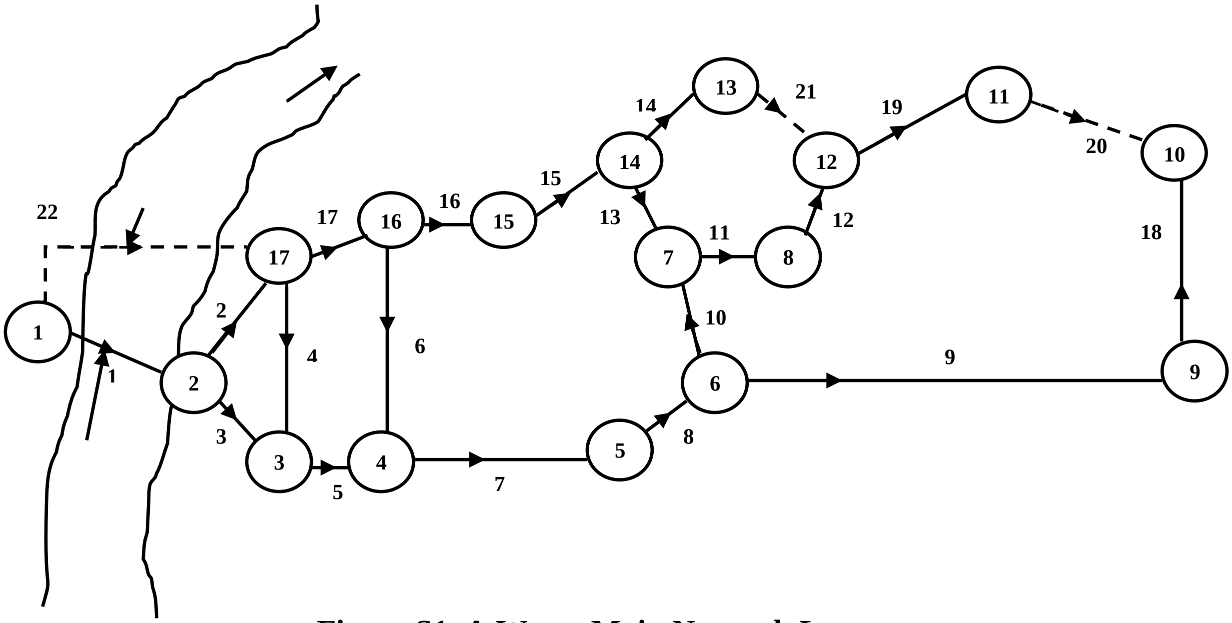

Figure S1. A Water Main Network Layout.

1. The MDD is 1.4 times the average day demand (ADD), and PHD is 2.5 times the ADD.
2. No parallel pipe was considered for Link 1 because of the structural consideration of Key Bridge. Instead, an alternative path from the source to the network is considered through a new pipe 22 which is to be placed under the Roosevelt bridge.
3. The effective pressure at the source node is 662 kPa (96 psi). The minimum required residual pressure at each demand node is 276 kPa (40 psi) for MDD and PHD. The minimum required pressure during the maximum day demand plus fire (MDDF) condition is 138 kPa (20 psi) at each demand node.
4. The available pipe diameters for strengthening and expansion are 254, 304.8, 355.6, 406.4, 457.2, 609.6, and 762 mm having a HW coefficient of 120.
5. A cost function for the pipes is given by: $C = 335.174 \times 10^{-3} D^{1.24}$; where C = unit cost associated with diameter in dollars per meter length; and D = diameter in millimeters.

Initially, Links 20–22 are added as done by Ormsbee and Kessler (1990) so as to achieve topologic redundancy of level-1. The minimum required HGL, H_j^{min}, is considered as the node elevation. The desirable HGL, H_j^{des}, at a node is taken as the node elevation plus the required pressure head of 28.16 m (40 psi) for the MDD and PHD conditions, and 14.08 m (20 psi) for the MDDF condition.

Design for PHD Condition

The network now consists of six loops and 22 pipes. In the first step, the GA is used to obtain a flow-distribution corresponding to a minimum variance considering the all-pipes working condition. Herein, flows in six pipes, one from each loop, are considered as the basic unknowns. The selected pipe numbers are 4, 6, 10, 20, 21 and 22. The GA parameters used in solving the problems are as follows: Population size = 500; Number of generations = 80; Probability of Crossover = 0.95; Probability of mutation = 0.02; Penalty multiplier = 100. The GA provided flow-distribution is given in Col. 2 of Table S1.

Table S1. Flow-Distribution used in LP for PHD loading

Pipe	Pipe flows in m^3/min using Proposed model during absence of			
Number	No-pipe	Pipe-1	Pipe-16	Pipe-9
(1)	(2)	(3)	(4)	(5)
1	12.0439	-	16.3038	16.2347
2	6.0372	-3.6635	6.528	11.7671
3	6.0067	3.6635	9.7758	4.4676
4	5.7275	3.4297	8.8018	3.3650
5	9.5642	4.9230	16.4078	5.6625
6	0.8966	0.4758	1.9172	0.5762
7	9.5908	4.5278	17.454	5.3678
8	6.0708	1.0068	13.933	1.8467
9	3.4175	6.4497	6.6492	-
10	2.6534	5.4428	7.2838	1.8467
11	4.1584	1.1765	2.1933	6.0889
12	4.1584	1.1763	2.1923	6.0889
13	2.9251	8.0393	-3.6715	5.6622
14	3.0641	3.0128	1.7975	4.5501
15	7.4092	12.4722	-0.454	11.6323
16	7.8592	12.9262	-	12.0863
17	9.0558	13.7050	2.2202	12.9657
18	1.9975	5.0297	5.2292	-1.42
19	4.3825	1.3493	1.1498	7.7989
20	3.8725	0.8383	0.6388	7.2879
21	1.6441	1.5928	0.3775	7.2879
22	8.9361	20.9870	4.6832	3.1301

Note: Negative flow values shows flow in opposite to direction shown in Figure 3.

Corresponding flow directions are shown in Figure S1. The LP problem is then formulated using these flows and their associated distribution. A pair of path head loss constraints is now written for demand nodes 3, 4, 7, 10, 12 and 17. The two paths from source node 1 to node 3 are 1-2-3 and 1-17-3. The two paths from source node to node 4 are 1-2-3-4 and 1-17-16-4 and so on. The cost of the network in iteration 1 is $ 2,377,566 as shown in Table S2. The network is found completely satisfactory under the all-pipe working condition but found deficient under the individual failure of pipes 1, 9, 15, 16 and 17 with available flows of 13.0571, 20.226, 16.89, 16.5148, and 18.2128 m^3/min, respectively, against the requirement of 20.98 m^3/min. The available flows are obtained by NFA (Bhave 1981, Gupta et al. 2015) with the use of EPANET considering the methodology suggested by Abdy Sayyed et al. (2015). This showed that failure of pipe 1 is most critical. A flow-distribution is obtained by removing pipe 1 using EPANET as shown in Col. 3 of Table S1. Now, the network is redesigned by adding the path constraints of this new flow-distribution along with those previously considered. The improved solution is given in Table S1 (Iteration 2). The cost of the network becomes $ 3,508,723 in the second iteration (Table S2). The network is now found deficient under failure of pipes 9, 15, 16, 17, and 18, having the failure of pipe 16 as most critical. The same procedure is followed again by obtaining the flow-distribution for failure of pipe 16 (Col. 4, Table S1) and by imposing additional path constraints in the LP model for use in improving the design (Table S2, Iteration 3). After the third iteration, the cost increased to $ 4,331,155 and network is found deficient under failure of pipes 1, 9, 17 and 18. Now, failure of pipe 9 is most critical among all three. The network is redesigned by incorporating additional path constraints for a flow-distribution obtained by EPANET analysis after removing pipe 9. The network cost now becomes $ 4,429,122. Herein, NFA showed that the network is still deficient during failure of pipes 1 and 17. Therefore, the design is repeated with the flow distribution obtained in the analysis. The revised cost becomes $ 4,459,430 and the network is found completely satisfactory during failure of any single pipe. Thus, the total final cost of the network becomes $ 4,459,430. Complete design details are given in Table S2.

Design for MDDF Condition

Under the MDDF loading condition, the network should be able to provide MDD with a normal pressure of 28.16 m, and in addition, it should be able to meet fire demand at nodes 10 and 4 with reduced pressure requirement of 14.08 m. Thus, three loadings (MDD, MDD with fire demand at node 4, and MDD with fire demand at node 10) are required to be considered simultaneously. These three conditions can be directly incorporated. However, instead of considering them simultaneously, these are considered sequentially starting with the MDD and then the most critical fire condition as suggested and done by Gupta et al. (2015). Thus, initially the MDD is considered. The performance of the network during fire demands is obtained using NFA considering the design solution for the MDD condition. The fire demand at Node 10 is found more critical than the fire demand at Node 4, and is considered first. The total cost of the network is $7,102,781. The final solution is provided in Table S3.

Discussion on Results

The solution obtained for different loading conditions are compared with those obtained by Ormsbee and Kessler (1990) and Agrawal et al. (2007), Dongre et al, (2015) and Gupta et al. (2015) are provided in Table S3. These results reflect the outcomes from four different algorithms such as the LP-based algorithm (Ormsbee and Kessler 1990), marginal capacity factor based design algorithm (Agrawal et al. 2007), GA alone (Dongre et al. 2014), and a LP-based model (Gupta et al. 2015). The proposed methodology which makes use of both GA and LP provided solutions which are 4.489%, and 2.061% cheaper than those obtained by Gupta et al. (2015) for PHD and MDDF loadings, respectively, thereby demonstrating the utility and efficiency of the proposed methodology.

Table S2. Design details for PHD loading using proposed methodology

Iteration	Flow-distribution for failure of	Design Solution			Cost in $	Deficient under failure of	Critical pipe
		Pipe	Length (m)	Dia. (mm)			
1	No-pipe	19	296.117	254.0	2,377,566	1, 9, 15, 16, 17	1
		20	914.40	254.0			
		21	355.28	254.0			
		22	2571.97	355.6			
			1085.63	406.4			
2	No-Pipe, Pipe-1	19	111.721	254.0	3,508,723	9, 15, 16 17, 18	16
		20	914.40	254.0			
		21	355.28	254.0			
		22	1414.41	457.2			
			2216.17	609.6			
3	No-Pipe, Pipe-1, Pipe-16	7	904.561	304.8	4,331,155	1,9,17, 18	9
			448.749	355.6			
		8	409.73	406.4			
		19	114.223	254			
		20	914.4	254.0			
		21	335.28	254.0			
		22	1597.77	457.2			
			2059.83	609.6			
4	No-Pipe, Pipe-1, Pipe-16, Pipe-9	7	904.561	304.8	4,429,122	1,17	1
			448.749	355.6			
		8	409.73	406.4			
		19	341.38	254			
		20	608.88	254.0			
			305.52	304.8			
		21	355.28	254.0			
		22	1597.77	457.2			
			2059.83	609.6			
5	Pipe 1, Pipe-16, Pipe-9	5	147.147	304.8	4,459,430*	-	-
		7	1311.59	304.8			
		8	409.73	406.4			
		19	341.38	254			
		20	611.91	254.0			
			302.49	304.8			
		21	355.28	254.0			
		22	1506.21	457.2			
			2151.39	609.6			

* Solution obtained in fourth trial

Table S3. Design solutions by proposed methodology and comparison with others

Link	Solution by Ormsbee and Kessler (1990) – Solu. A		Solution by Agrawal et al. (2007) – Solu. B		Solution by Dongre and Gupta (2014) Methodology– Solu. C		Solution by Gupta et al. (2015) Methodology– Solu. D		Solution by Proposed Methodology –Solu. E	
No.										
	Diameter (mm)	Length (m)	Diameter (mm)	Length (m)	Diameter (mm)	Length (m)	Diameter (mm)	Length (m)	Diameter (mm)	Length (m)
Case 1 : Peak-hour loading condition										
3	406.4	452.40	-	-	-	-	-	-	-	-
5[a]	406.4	440.43	-	-	-	-	-	-	304.8	147.15
-	304.8	138.68	-	-	-	-	-	-	-	-
6	-	-	355.60	486.63	304.8	486.63	254.00	322.14	-	-
7	304.8	1341.12	254.00	1353.31	254.0	1353.31	304.80	1310.60	304.8	1311.60
8	457.2	490.73	355.60	490.73	355.6	490.73	406.40	490.73	406.4	490.73
19	304.8	341.38	254.00	341.38	254.0	341.38	254.00	341.38	254.00	341.38
20[a]	355.6	914.40	304.80	914.40	304.8	914.40	304.80	695.36	304.80	302.49
-	-	-	-	-	-	-	254.00	219.04	254.00	611.91
21	406.4	335.28	254.00	335.28	254.0	335.28	254.00	355.28	254.00	355.28
22[a]	609.6	2993.14	609.60	3657.60	609.6	3657.60	457.20	1038.14	457.20	1506.21
-	457.2	664.46	-	-		-	609.60	2619.46	609.60	2151.39
Case 2 : Maximum day plus fire loading condition										
3	609.6	152.40	-	-	-		-	-	-	-
5	609.6	579.12	457.20	579.12	457.20	579.12	457.20	579.12	457.2	579.12
6[a]	-	-	304.80	484.63	-	-	304.80	80.61	254	343.55
-	-	-	-	-	-	-	254.00	404.02	-	-
7	609.6	1353.31	457.20	1353.31	457.20	1353.31	457.20	1353.31	457.2	1353.31
8	609.6	490.73	609.60	490.73	609.60	490.73	609.60	490.73	609.6	335.84
-	-	-	-	-	-	-	-	-	457.2	154.89
9	609.6	225.86	254.00	1359.41	254.00	1359.41	-	-	-	-
14	609.6	365.76	-	-	-	-	-	-	-	-
15	-	-	-	-	-	-	-	-	406.4	474.38
18[a]	609.6	316.38	355.60	731.52	355.60	731.52	406.40	550.81	406.4	700.28
-	406.40	415.14	-	-	-	-	355.60	180.71	355.6	31.244

19	406.40	341.38	406.40	341.38	406.40	341.38	457.20	341.38	457.2	341.38
20[a]	609.6	914.40	609.60	914.40	609.60	914.40	609.60	519.94	609.6	118.63
-	-	-	-	-	-	-	457.20	394.46	457.2	795.77
21	609.6	335.28	355.60	335.28	355.60	335.28	457.20	355.28	457.2	335.28
22[a]	762.00	2709.06	609.60	3657.60	609.60	3657.60	762.00	782.13	609.60	3657.60
-	609.60	948.54	-	-	-	-	609.60	2875.47	-	-
Note: Network cost: Case 1: Solution A = $5,339,886; Solution B = $4,980,178; Solution C = $4,939,405; solution D=$4,669,069; Solution E = $4,459,430, Case 2: Solution A = $9,283,700; Solution B = $7,458,460; Solution C = $7,263,071 solution D=$7,252,218; Solution E = $7,102,781										