OPTIMIZATION OF POTABLE WATER NETWORK (CASE STUDY)

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ABSTRACT

An approach to the optimal design of pipe networks is presented and applied to a case study. The sequential unconstrained minimization technique to solve the optimal design of network is applied for pipe network optimization and the Newton-Raphson method for the hydraulic analysis of the network. Water distribution system design satisfying all constraints including pipe diameter and nodal pressure is performed. The performance of the proposed approach is tested on an existing network. The case study is for El-Mostakbal City network, an extension to an existing distribution network of Ismailia City, Egypt. The application of the method on the network shows its capability to solve such actual optimization problems.

INTRODUCTION

The pipe distribution network of a water supply can comprise a major part of the capital cost of the project. Numerous arrangements of pipe sizes within the network may exist to satisfy the field requirements. Each arrangement results in a different total cost of the project. Therefore, attempts to obtain optimal solutions have been done through the hydraulic analysis of the network and an optimization technique. The optimal solution always means minimum cost of the network.

Several optimization models have been reported for the optimal design of water distribution systems. Two different optimization techniques are applied to solve these models: the deterministic optimization techniques (including linear, dynamic, and non-linear programming) and the stochastic optimization techniques (such as genetic algorithms and simulated annealing).

In linear programming, two principal approaches have been developed by Alperovits and Shamir (1977) and Quindry et al. (1981). Alperovits and

Shamir's (1977) approach has the ability to consider various components in a distribution network, however, it is severely limited in the size of the system and the number of loads which it can handle. Quindry et al. (1981) improved the method allowing for a larger system to be considered, but difficulties arise when analyzing multiple loads. Fujiwara et al. (1987) presented a modified linear programming gradient for solving looped water distribution networks. The linear programming gradient of Alperovits and Shamir's (1977) is modified in terms of both search direction and step size. Kessler and Shamir (1989) used the linear programming gradient method as an extension of the method proposed by Alperovits and Shamir (1977). Eiger et al. (1994) used the same formulation as Kessler and Shamir (1989), which leads to the determination of lengths of one or more segments in each link with discrete diameters. Sârbu and Borza (1997) proposed a model based on the method of linear programming to treat looped networks which have concentrated outflows or uniform outflow along the length of each pipe.

Non-linear programming is applied to pipe network optimization problems and many researches have been reported, [Lansey and Mays (1989), Fujiwara and Khang (1990), Samani and Naeeni (1996), Djebedjian et al. (2000 a), Djebedjian et al. (2000 b) and Herrick (2001)]. Lansey and Mays (1989) reported on the development of two-step procedure for the design of water distribution under multiple loading conditions. Fujiwara and Khang (1990) used a two-phase decomposition method extending that of Alperovits and Shamir (1977) to non-linear modeling. Samani and Naeeni (1996) proposed a non-linear optimization technique coupled with the Newton-Raphson method to minimize the design total cost. Djebedjian et al. (2000 a), Djebedjian et al. (2000 b) and Herrick (2001) used the sequential unconstrained minimization technique SUMT method of Fiacco and McCormick (1964) as the optimization analysis and the Newton-Raphson method is employed for the hydraulic analysis. Two different procedures; SUMT I [Djebedjian et al. (2000 a)] and SUMT II [Djebedjian et al. (2000 b)]; were applied on a gravity-fed network and the obtained results were compared with other researches. The results were identical with some results and very close to the others.

From the beginning of 1990's, methodologies for the application of genetic algorithms (GAs) to the optimal design of water distribution network have been developed by Simpson et al. (1994); Dandy et al. (1996); Savic and Walters (1997); Montesinos et al. (1999); Lippai et al (1999) and Abdel-Gawad (2001). Simpson et al. (1994) presented a methodology for the application of the GA technique to the optimization of pipe network design. Dandy et al. (1996) proposed an improved genetic algorithm for pipe network optimization. The improved GA used variable power scaling of the fitness function. Savic and Walters (1997) developed a computer model GANET that involves the application of genetic algorithms to the problem of least-cost design of water distribution networks. Montesinos et al. (1999) proposed a modified genetic algorithm for optimal water network design. Lippai et al (1999) demonstrated the use of several commercial optimizers for the optimal design of water network. Abdel-Gawad (2001) presented another improved genetic algorithm with several alternative formulations for selection, crossover and mutation schemes.

Simulated annealing have been developed to obtain the least-cost design of a looped distribution network. Loganathan et al. (1995) applied optimal design approach using simulated annealing to the New York network expansion problem and Cunha and Sousa (1999) applied the same approach to the Hanoi network design problem. The optimal solutions from both applications derived significantly smaller costs than the ones reported previously by other researchers.

In the present investigation, the sequential unconstrained minimization technique (SUMT) to solve the optimal design of network is applied for the pipe network optimization and the Newton-Raphson method for the hydraulic analysis of the network. The explanation of the optimization model formulation is brought from Djebedjian et al. (2000 a). The case study is a real network. It is an extension to an existing distribution network of Ismailia City. The coupled hydraulic modeling and optimization procedure are used to evaluate the design of the extension of the network.

OPTIMIZATION MODEL FORMULATION

The optimization of the network design problem is the identification of the commercial pipe size diameters combination that give the minimum cost under certain conditions such as the specified demands and prescribed range of pressures at given nodes.

The minimization of cost for a network is expressed by the objective function which is assumed to be a function of pipe diameters and lengths, (Savic and Walters, 1997):

$$f(D_1,...,D_N)=\sum_{i=1}^{N} c(D_i,L_i) \qquad (1)$$

where $c(D_i,L_i)$ is the cost of the pipe i with the diameter D_i and the length L_i, and N is the total number of pipes in the network.

The minimization of cost for a network is characterized by the following conservation laws and constraints:

(1) Mass conservation at each junction node:

$$\sum Q_{in} - \sum Q_{out} = Q_e \qquad (2)$$

where Q_{in} and Q_{out} are the flow into and out of the junction, respectively, and Q_e is the demand at the junction node.

(2) Energy conservation in each loop can be written as:

$$\sum h_f = 0 \tag{3}$$

The head loss h_f in the pipe is expressed by the Darcy-Weisbach formula as:

$$h_f = f_i . \frac{L_i \, Q_i^{\,2}}{D_i^{\,5}} \left(\frac{4}{\pi} \right)^2 \frac{1}{2g} \tag{4}$$

where Q_i is the pipe flow. The friction factor f_i is calculated by the expression proposed by Swamee and Jain (1975):

$$f_i = \frac{0.25}{\left[\log \left(\frac{\varepsilon_i}{3.7 D_i} + \frac{5.74}{\mathrm{Re}_i^{0.9}} \right) \right]^2} \tag{5}$$

where ε_i is the pipe roughness height and $\mathrm{Re}_i = 4Q_i / (\pi D_i \nu)$ is the Reynolds number.

(3) Minimum pressure head requirements at each node in the network is given in the form:

$$H_j \geq H_{j,\min} \qquad j = 1,...,M \tag{6}$$

where H_j is the head at node j, $H_{j,\min}$ is the minimum required head at the same node and M is the total number of nodes in the network.

(4) Minimum diameter requirements are defined by:

$$D_i \geq D_{\min} \qquad i = 1,...,N \tag{7}$$

where $D_{\min}$ is the minimum diameter. The diameter of each pipe is chosen from a specified set of commercial pipes.

The SUMT Method

The Sequential Unconstrained Minimization Technique (SUMT) was first suggested by Carroll (1961) and thoroughly investigated by Fiacco and McCormick (1964). The formulation of the constrained minimization problem is in the form:

$$\textit{minimize} \qquad z = f(x) \tag{8}$$

$$\textit{subject to} \quad c_j(x) \geq 0; \quad j = 1, 2, \ldots, m \tag{9}$$

where $c_j(x)$ presents the constraints and m is the number of constraints. Fiacco and McCormick (1964) used the following formulation to generate a sequence of feasible vectors to the original problem for a strictly decreasing sequence of r values tending to zero:

$$\textit{minimize} \qquad L(x,r) = f(x) + r \sum_{j=1}^{m} \frac{1}{c_j(x)} \tag{10}$$

Hence, the generalized objective function for the cost can be introduced as:

$$L(D_i, H_j, r) = f(D_i) + r\left[\sum_{i=1}^{N}\frac{1}{D_i - D_{\min}} + \sum_{j=1}^{M}\frac{1}{H_j - H_{j,\min}}\right] \qquad (11)$$

In the above expression, when the diameters and pressure heads are in the allowable ranges, *r* should be considered equal to zero which means it does not affect the real cost. The objective function given by Eq. (11) is minimized by the SUMT method to obtain the minimum cost.

Computational Analysis

The steps for the coupled hydraulic and optimization analysis of network are as follows:

1) Assumption of the diameters of the pipes.
2) Calculation of the pressure heads at nodes, discharges and head-losses of all pipes using the Newton-Raphson method.
3) Computation of the objective function, Eq. (11).
4) Minimizing the cost objective function using the SUMT method. If the objective function is not minimum, pipes diameters should be changed and the cycle from step (2) is repeated.

CASE STUDY

An actual water network has been selected to apply the developed program set of the hydraulic modeling and optimization to evaluate the design of the network, also, to test the capabilities of the developed model in a real and large network.

The network selected here as a case study is built to serve a new residential city called El-Mostakbal. It is a new extension to City of Ismailia. The network was designed as an extension to the original network of Ismailia City. The layout of the network and the index numbers of the nodes and pipes are shown in Figure 1.

The data for the studied network is shown in Table 1. It includes the index (ID) for each node and pipe. The extension network has 31 nodes and 43 pipes. For the nodes, the elevation and specified demands are given, while for the pipes the start and end nodes and their lengths and diameters are represented. The total demand for the network is 232 L/s. The designer chooses node number 481 from the original network of Ismailia City to connect it with the new extension network. The average pressure head at this node before connection equals 25.5 meters (calculated from the hydraulic model analysis). The connection pipe (Pipe 7000) between the two networks is 600-mm diameter with 8692.7 meter long.

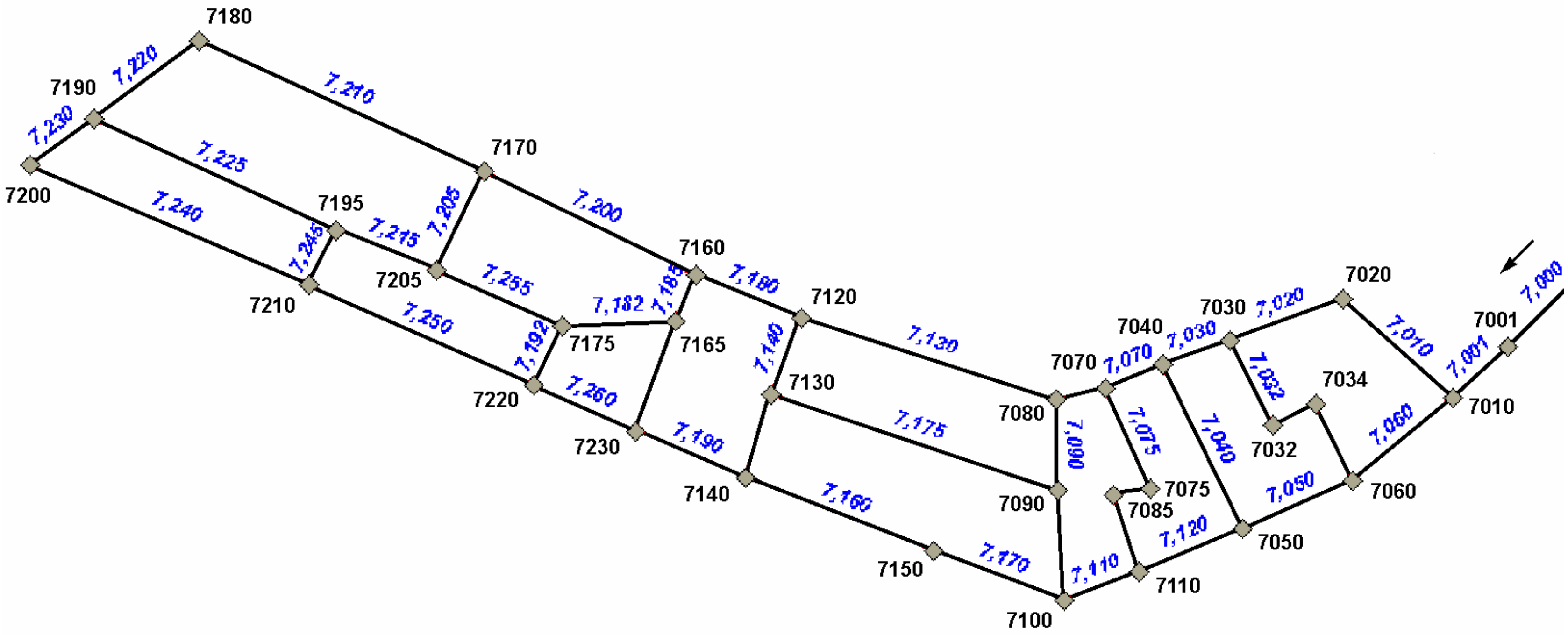

Figure 1. El-Mostakbal network

Table 1. El-Mostakbal network data (original design)

(a) Nodes

Node ID	Elevation (m)	Demand (LPS)
7001	15	15
7010	14	15
7020	14	0
7030	14	12
7032	14	0
7034	14	0
7040	14	12
7050	14	13
7060	14	11
7070	14	0
7075	14	0
7080	14	15
7085	14	0
7090	14	0
7100	14	12
7110	14	0
7120	15	15
7130	15	12
7140	15	18
7150	15	0
7160	15	10
7165	15.5	0
7170	15.5	10
7175	15.5	0
7180	15.5	10
7185	15.5	0
7190	15.5	12
7195	15.5	0
7200	15.5	12
7205	15.5	0
7210	15.5	15
7220	15.5	0
7230	15.5	13
Total Demand = 232 L/s		

(b) Pipes

Pipe ID	Start Node	End Node	Length (m)	Diameter (mm)
7000	481	7001	8692.70	600
7001	7001	7010	100.00	600
7010	7010	7020	328.00	300
7020	7020	7030	80.00	300
7030	7030	7040	152.50	300
7032	7030	7032	149.30	150
7034	7032	7034	67.00	150
7036	7034	7060	184.30	150
7040	7040	7050	341.65	150
7050	7050	7060	100.00	400
7060	7060	7010	288.00	400
7070	7040	7070	70.70	300
7075	7070	7075	172.00	150
7080	7070	7080	127.60	250
7085	7075	7085	109.00	150
7090	7080	7090	164.60	150
7095	7085	7110	104.70	150
7100	7090	7100	98.40	150
7110	7100	7110	123.50	400
7120	7110	7050	155.00	400
7130	7080	7120	309.15	250
7140	7120	7130	163.40	150
7150	7130	7140	134.20	150
7160	7140	7150	198.00	300
7170	7150	7100	225.50	400
7175	7090	7130	357.90	150
7180	7120	7160	92.70	200
7182	7185	7175	156.50	150
7185	7160	7165	84.90	200
7190	7140	7230	100.00	300
7192	7175	7220	101.00	150
7195	7165	7230	226.30	200
7200	7160	7170	230.50	200
7205	7170	7205	145.80	150
7210	7170	7180	370.60	150
7215	7205	7195	109.90	150
7220	7180	7190	184.00	150
7225	7195	7190	257.40	150
7230	7190	7200	120.00	150
7240	7200	7210	181.90	150
7245	7195	7210	114.90	150
7250	7210	7220	262.60	200
7255	7175	7205	185.00	150
7260	7220	7230	217.00	300

COMPUTATIONAL RESULTS AND DISCUSSION

The network is analyzed as a part of the whole network by using the hydraulic model developed here by using the Newton-Raphson method. The results of the analysis for the extended network of the original design are shown in Table 2. It is worthy to note that the analysis has been done at the peak demands, i.e. the demands in Table 2 (a) is greater than that in Table 1 (a) by a factor 1.6.

The results obtained from the hydraulic analysis, Table 2 (a), show that the pressure head distribution at the nodes of the network is very low. The average pressure head is 7.1 meters and the maximum node pressure head is about 13.6 meters. This means that we are going to face a problem of water feeding, since the maximum pressure head at the network is 13.6 meters which is not sufficient to feed the consumer with water.

To solve this drawback, the previous optimization model is applied to the case study. The computer program for the network analysis and optimization was written in Fortran 90. For the studied network, it should be mentioned that for 43 pipes and a set of 13 commercial pipes, the total number of designs is $13^{43} = 7.9 \times 10^{47}$. Therefore, it is very difficult for any mathematical model to test all these possible combinations of design and a very small percentage of combinations can be reached.

The coupled hydraulic model and optimization technique SUMT were applied to the network to optimize the extended network and to choose the most economic and suitable node from the old network to connect the two networks.

The applied constraints of the design of the network come as follows: the minimum acceptable pressure head requirements for all nodes of the network are set as 22 meters. The cost values used in the optimization problem are the real costs that are used in the Suez Canal Authority water sector. There are 13 commercially available diameters for P.V.C. and ductile pipes, Table 3.

The optimization model is applied to the extended network of El-Mostakbal City. The optimal solution is obtained as follows:

1- The node chosen to connect the old network with the extension is a different node than that chosen in the original design. The node chosen to connect the two networks by the optimization program is node number 456. Its average pressure head is 43.89 meters (calculated from the hydraulic model).
2- The connection pipe is 800-mm diameter with length about 2463 meters long.

Table 2. El-Mostakbal network analysis results (original design)

(a) Nodes

Node ID	Demand (LPS)	Pressure (m)
7010	24.0	13.60
7020	0	11.54
7030	19.2	11.04
7032	0	11.22
7034	0	11.30
7040	19.2	10.30
7050	20.8	10.94
7060	17.6	11.53
7070	0	10.03
7075	0	10.13
7080	24.0	8.72
7085	0	10.20
7090	0	8.83
7100	19.2	9.74
7110	0	10.26
7120	24.0	5.81
7130	19.2	5.87
7140	31.28	6.08
7150	0	8.16
7160	16.0	5.03
7165	0	4.59
7170	16.0	3.04
7175	0	4.36
7180	16.0	0.34
7190	19.2	0.33
7195	0	2.12
7200	19.2	0.33
7205	0	3.03
7210	24.0	2.11
7220	0	4.62
7230	20.8	5.04

Average Pressure = 7.1 m
Max. Pressure = 13.6 m
Min. Pressure = 0.33 m

Note: The initial directions for the flow in the pipes, Fig. 1, are proposed. If the actual direction is in the contrary direction, a negative sign in the results is appeared in the flow, Table 2 (b).

(b) Pipes

Pipe ID	Length (m)	Diameter (mm)	Flow (LPS)	Velocity (m/s)
7000	8692.70	600	350.70	1.24
7001	100.00	600	350.70	1.24
7010	328.00	300	-98.80	1.40
7020	80.00	300	98.80	1.40
7030	152.50	300	-86.17	1.22
7032	149.30	150	-6.57	0.37
7034	67.00	150	-6.57	0.37
7036	184.30	150	-6.57	0.37
7040	341.65	150	-8.32	0.47
7050	100.00	400	202.72	1.61
7060	288.00	400	226.88	1.81
7070	70.70	300	-75.29	1.07
7075	172.00	150	-4.46	0.25
7080	127.60	250	-79.75	1.62
7085	109.00	150	-4.46	0.25
7090	164.60	150	-4.82	0.27
7095	104.70	150	-4.46	0.25
7100	98.40	150	-19.65	1.11
7110	123.50	400	169.14	1.35
7120	155.00	400	-173.60	1.38
7130	309.15	250	60.56	1.23
7140	163.40	150	-3.27	0.19
7150	134.20	150	-7.64	0.43
7160	198.00	300	-130.28	1.84
7170	225.50	400	-130.28	1.04
7175	357.90	150	-14.84	0.84
7180	92.70	200	-39.84	1.27
7182	156.50	150	7.37	0.42
7185	84.90	200	-10.76	0.34
7190	100.00	300	-91.36	1.29
7192	101.00	150	9.80	0.55
7195	226.30	200	-18.13	0.58
7200	230.50	200	-34.60	1.10
7205	145.80	150	-1.32	0.07
7210	370.60	150	-17.28	0.98
7215	109.90	150	18.49	1.05
7220	184.00	150	-1.28	0.07
7225	257.40	150	-16.87	0.95
7230	120.00	150	1.05	0.06
7240	181.90	150	20.25	1.15
7245	114.90	150	1.62	0.09
7250	262.60	200	-42.63	1.36
7255	185.00	150	17.18	0.97
7260	217.00	300	52.43	0.74

Table 3. Commercially available pipe sizes and cost per meter

Diameter (inches)	Diameter (mm)	Unit Cost (L.E./m)	
		P.V.C.	Ductile
1	25	6.25	
2	50	14.50	
4	100	28.52	
6	150	57	188
8	200	105	255
10	250	147	333
12	300	202	419
16	400	310	570
20	500		735
24	600		1110
30	800		1485
40	1000		2505
48	1200		3220

The optimization procedure gives an optimal solution for the extended network. All pipes are selected from ductile unless the required diameter is not available then P.V.C. pipes are used, Table 3. Based on the today prices used in the Suez Canal Society utility, Table 4 gives a comparison between the total costs of the original and optimized designs. The original design of the extended network costs *L.E.* 11,868,999, while the optimal solution of the network calculated from the optimization procedure costs *L.E.* 6,770,787 only. It should be noticed that the length of the first pipe; No. 7000; is different in Table 4 in the original and optimized designs as it is mentioned before. Due to the utilization of a new junction for the extending network, a saving of *L.E.* 5,990,565 in the cost is achieved. On the other hand, the total cost of pipes without including pipe 7000 is *L.E.* 2,220,879 for the original design and *L.E.* 3,113,232 for the optimized design. Increasing the diameters of many pipes decreases the losses and consequently increases the pressure heads at the nodes.

The output results from the hydraulic analysis of the case study network are shown in Table 5. The pressure head distribution in the extended network after optimization is higher than that of the original design. Figure 2 shows a comparison between the pressure head distribution of the extended network before and after the optimization. The pressure heads at all nodes of the optimized network are greater than 22 meters which is the minimum acceptable pressure head requirements.

Table 4. Comparison between the total costs of the original and optimized designs

Original Design					Optimized Desgin				
Pipe ID	Length (m)	Diameter (mm)	Cost (L.E./m)	Total Cost (L.E.)	Pipe ID	Length (m)	Diameter (mm)	Cost (L.E./m)	Total Cost (L.E.)
7000	8692.00	600	1110.0	9,648,120.00	7000	2463.00	800	1485.0	3,657,555.00
7001	100.00	600	1110.0	111,000.00	7001	100.00	800	1485.0	148,500.00
7010	328.00	300	419.0	137,432.00	7010	328.00	400	570.0	186,960.00
7020	80.00	300	419.0	33,520.00	7020	80.00	400	570.0	45,600.00
7030	152.50	300	419.0	63,897.50	7030	152.50	400	570.0	86,925.00
7032	149.30	150	188.0	28,068.40	7032	149.30	150	188.0	28,068.40
7034	67.00	150	188.0	12,596.00	7034	67.00	150	188.0	12,596.00
7036	184.30	150	188.0	34,648.40	7036	184.30	150	188.0	34,648.40
7040	341.65	150	188.0	64,230.20	7040	341.65	150	188.0	64,230.20
7050	100.00	400	570.0	57,000.00	7050	100.00	600	1110.0	111,000.00
7060	288.00	400	570.0	164,160.00	7060	288.00	600	1110.0	319,680.00
7070	70.70	300	419.0	29,623.30	7070	70.70	400	570.0	40,299.00
7075	172.00	150	188.0	32,336.00	7075	172.00	150	188.0	32,336.00
7080	127.60	250	333.0	42,490.80	7080	127.60	300	419.0	53,464.40
7085	109.00	150	188.0	20,492.00	7085	109.00	150	188.0	20,492.00
7090	164.60	150	188.0	30,944.80	7090	164.60	200	255.0	41,973.00
7095	104.70	150	188.0	19,683.60	7095	104.70	150	188.0	19,683.60
7100	98.40	150	188.0	18,499.20	7100	98.40	200	255.0	25,092.00
7110	123.50	400	570.0	70,395.00	7110	123.50	600	1110.0	137,085.00
7120	155.00	400	570.0	88,350.00	7120	155.00	600	1110.0	172,050.00
7130	309.15	250	333.0	102,946.95	7130	309.15	300	419.0	129,533.85
7140	163.40	150	188.0	30,719.20	7140	163.40	200	255.0	41,667.00
7150	134.20	150	188.0	25,229.60	7150	134.20	200	255.0	34,221.00
7160	198.00	300	419.0	82,962.00	7160	198.00	400	570.0	112,860.00
7170	225.50	400	570.0	128,535.00	7170	225.50	600	1110.0	250,305.00
7175	357.90	150	188.0	67,285.20	7175	357.90	150	188.0	67,285.20
7180	92.70	200	255.0	23,638.50	7180	92.70	250	333.0	30,869.10
7182	156.50	150	188.0	29,422.00	7182	156.50	100	28.5	4,463.38
7185	84.90	200	255.0	21,649.50	7185	84.90	250	333.0	28,271.70
7190	100.00	300	419.0	41,900.00	7190	100.00	400	570.0	57,000.00
7192	101.00	150	188.0	18,988.00	7192	101.00	150	188.0	18,988.00
7195	226.30	200	255.0	57,706.50	7195	226.30	250	333.0	75,357.90
7200	230.50	200	255.0	58,777.50	7200	230.50	250	333.0	76,756.50
7205	145.80	150	188.0	27,410.40	7205	145.80	150	188.0	27,410.40
7210	370.60	150	188.0	69,672.80	7210	370.60	200	255.0	94,503.00
7215	109.90	150	188.0	20,661.20	7215	109.90	150	188.0	20,661.20
7220	184.00	150	188.0	34,592.00	7220	184.00	200	255.0	46,920.00
7225	257.40	150	188.0	48,391.20	7225	257.40	150	188.0	48,391.20
7230	120.00	150	188.0	22,560.00	7230	120.00	200	255.0	30,600.00
7240	181.90	150	188.0	34,197.20	7240	181.90	200	255.0	46,384.50
7245	114.90	150	188.0	21,601.20	7245	114.90	150	188.0	21,601.20
7250	262.60	200	255.0	66,963.00	7250	262.60	300	419.0	110,029.40
7255	185.00	150	188.0	34,780.00	7255	185.00	150	188.0	34,780.00
7260	217.00	300	419.0	90,923.00	7260	217.00	400	570.0	123,690.00
Total Cost = 11,868,999.15 L.E.					**Total Cost = 6,770,787.53 L.E.**				

Table 5. Results of hydraulic analysis of optimized network

(a) Nodes

Node ID	Demand (LPS)	Pressure (m)
7010	24.0	35.63
7020	0	33.54
7030	19.2	33.03
7040	19.2	32.28
7070	0	32.01
7080	24.0	30.67
7060	17.6	33.52
7050	20.8	32.92
7110	0	32.23
7100	19.2	31.70
7032	0	33.22
7034	0	33.30
7090	0	30.78
7085	0	32.17
7075	0	32.11
7120	24.0	27.73
7130	19.2	27.77
7140	34.09	27.97
7150	0	30.10
7160	16.0	26.93
7165	0	26.49
7230	20.8	26.93
7220	0	26.51
7175	0	26.25
7205	0	24.92
7170	16.0	24.93
7195	0	24.01
7210	24.0	24.00
7180	16.0	22.23
7190	19.2	22.22
7200	19.2	22.23
Average Pressure =		**29.04 m**
Max. Pressure =		**35.63 m**
Min. Pressure =		**22.22 m**

(b) Pipes

Pipe ID	Length (m)	Diameter (mm)	Flow (LPS)	Velocity (m/s)
7000	2463.00	800	386.45	0.77
7001	100.00	800	386.45	0.77
7010	328.00	300	-99.56	1.41
7020	80.00	300	99.56	1.41
7030	152.50	300	-86.94	1.23
7032	149.30	150	-6.58	0.37
7034	67.00	150	-6.58	0.37
7036	184.30	150	-6.58	0.37
7040	341.65	150	-8.34	0.47
7050	100.00	400	204.74	1.63
7060	288.00	400	228.93	1.82
7070	70.70	300	-76.09	1.08
7075	172.00	150	-4.40	0.25
7080	127.60	250	-80.48	1.64
7085	109.00	150	-4.40	0.25
7090	164.60	150	-4.74	0.27
7095	104.70	150	-4.40	0.25
7100	98.40	150	-19.75	1.12
7110	123.50	400	171.21	1.36
7120	155.00	400	-175.60	1.40
7130	309.15	250	61.22	1.25
7140	163.40	150	-2.99	0.17
7150	134.20	150	-7.18	0.41
7160	198.00	300	-132.26	1.87
7170	225.50	400	-132.26	1.05
7175	357.90	150	-15.01	0.85
7180	92.70	200	-40.21	1.28
7182	156.50	150	7.45	0.42
7185	84.90	200	-10.44	0.33
7190	100.00	300	-90.99	1.29
7192	101.00	150	9.71	0.55
7195	226.30	200	-17.89	0.57
7200	230.50	200	-34.65	1.10
7205	145.80	150	-1.37	0.08
7210	370.60	150	-17.29	0.98
7215	109.90	150	18.52	1.05
7220	184.00	150	-1.29	0.07
7225	257.40	150	-16.87	0.95
7230	120.00	150	1.05	0.06
7240	181.90	150	20.25	1.15
7245	114.90	150	1.66	0.09
7250	262.60	200	-42.59	1.36
7255	185.00	150	17.16	0.97
7260	217.00	300	52.30	0.74

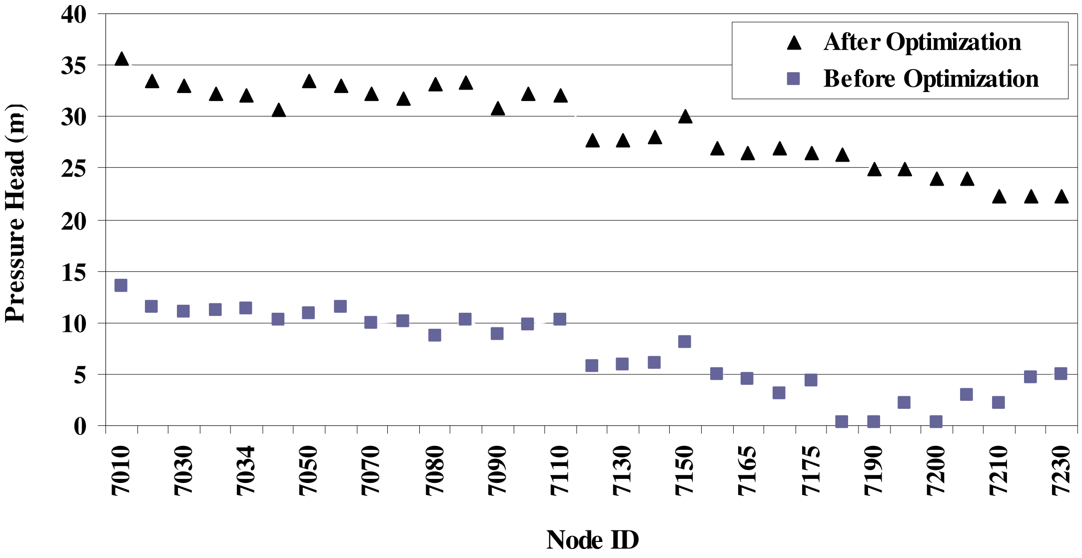

Figure 2. Comparison of pressure head distribution between the optimized network and the original design

CONCLUSIONS

The optimal design for water distribution networks is important, as it often comprises major part of the whole investment in such a system. In this paper, the Newton-Raphson method for the hydraulic analysis of the network and the sequential unconstrained minimization technique (SUMT) of Fiacco and McCormick (1964) are used to solve the optimal design of network.

The studied network is for El-Mostakbal City, which is a new extension to City of Ismailia. The network is fed from the network of Ismailia City. The application of the method on the network shows its capability to solve such actual optimization problems.

A drawback in the original network is the water feeding due to the low pressure heads at the nodes. For the optimized network, the modification of the starting node and the utilization of optimization technique results in minimizing the cost and increasing the pressure heads at all nodes of the network to be greater than the minimum acceptable pressure head requirements.

NOMENCLATURE

$c(D_i, L_i)$	cost of the pipe i
$c_j(x)$	constraints
D_i	diameter of pipe i, (m)
$D_{\min}$	minimum diameter, (m)

H_j	head at node j, (m)
$H_{j,\min}$	minimum required head at the node j, (m)
h_f	head loss, (m)
L	objective function
L_i	length of pipe i, (m)
M	total number of nodes in the network
m	number of constraints
N	total number of pipes in the network
Q_e	demand at the junction node, (m^3/s)
Q_i	flow in pipe i, (m^3/s)
Q_{in}	flow into of the junction node, (m^3/s)
Q_{out}	flow out of the junction node, (m^3/s)
Re_i	Reynolds number
r	scale factor, Eq. (10)
ε_i	roughness height of pipe i, (m)
ν	kinematic viscosity, (m^2/s)

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