OPTIMIZATION OF LARGE WATER DISTRIBUTION NETWORK DESIGN USING GENETIC ALGORITHMS

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ABSTRACT

The paper describes the application of genetic algorithms (GAs) to the design optimization of a real water distribution system. The GA is a search technique based on evolution process that imitates nature's ongoing search for better solutions. The GA optimization technique to solve the optimal design of network is applied for pipe network optimization and the Newton method for the hydraulic analysis of the network. In this study, the GA model is adapted to optimize pipe diameters. Water distribution system design satisfying the constraints of nodal pressure is performed. The performance of the proposed approach is tested on an existing network. The case study is for Suez City network, Egypt. The application of the method on the network shows its capability to solve such actual optimization problems.

Keywords: Optimization, Genetic Algorithm, Large Water Distribution Networks

INTRODUCTION

Pipe network optimization involves the design of new pipe network and rehabilitation of existing network. A water distribution system must sustain two hydraulic requirements: water demand and pressure head at the supply locations. There are three types of optimization models including least cost design, maximum benefit design, and cost-benefit tradeoff design, Wu et al. [1]:

(a) Least cost optimization searches for the optimal solution by minimizing the cost while satisfying the design constraints. The least cost optimization, however, produces the minimum pipe sizes that reduce the supply capacity and reliability.

(b) Maximum benefit design optimization maximizes the return on every dollar spent by searching for the maximum benefit design solution within an available budget while still meeting hydraulic constraints.
Both the least cost and the maximum benefit optimization models identify the optimal or near-optimal solutions at the minimum cost and the maximum benefit (often corresponding to the maximum cost) respectively, using a single objective design model.

(c) Cost-benefit tradeoff optimization is achieved using a multi-objective design model to minimize the cost and maximize the benefit while satisfying the constraints.

Traditionally, most of the work on the design of water distribution networks has focused on developing optimization procedures for the least cost pipe-sizing problem.

Numerous optimization techniques are used in water distribution systems. These include the deterministic optimization techniques such as linear programming (for separable objective functions and linear constraints), and non-linear programming (when the objective function and the constraints are not all in the linear form), and the stochastic optimization techniques such as genetic algorithms and simulated annealing. The review of application of these techniques in the water distribution systems can be found in Djebedjian et al. [2]. Genetic Algorithms (GAs) have been applied extensively to optimize water distribution systems for hydraulic criteria. The main advantages of GAs are that they use a population of evolving solutions and identify several solutions from which the decision maker can select, rather than a single optimum. The main disadvantage lies in the high computational intensity.

The literature review shows that the use of optimization is widespread in simple water distribution systems. Large scale water networks design has some important features as the over increasing of population, and the topography. Some papers focus on the details of a particular master planning study or actual water distribution systems.

Schaake and Lai [3] used the New York Tunnel system consisting of 21 pipes, 19 nodes and 1 reservoir. Walski et al. [4] set up the hypothetical Anytown water distribution system (USA) (40 pipes and 22 nodes) as a realistic benchmark to compare and test network optimization software, and has features and problems typical of those found in many real systems. Fujiwara and Khang [5] used the water distribution trunk network in Hanoi consisting of one reservoir, 31 demand nodes and 34 pipes. Halhal et al. [6] studied the optimization of a town in Morocco. The network consisted of 115 nodes, 158 existing pipes to be rehabilitated, and nine new pipelines to be designed (or sized) for the system. Murphy et al. [7] applied the GA optimization model to the Jamestown System expansion plan composed of about 350 pipes and 4 major regulating valves separating the transmission system from the distribution network and isolating the distribution network into 2 pressure zones.

Savic et al. [8] studied the genetic algorithm optimization of an actual water distribution network with a single reservoir which feeds 535 demand nodes through a network of 632 pipes. Walski et al. [9] used the Comprehensive Planning Study (i.e. "master plan") of the water distribution system for the Pennsylvania American Water Company's Wilkes-Barre/Scranton system to illustrate the issues that drive modeling efforts in a master planning study. These issues include the ability to simulate a very wide range of demand loadings and make accurate assessment of the costs and benefits of alternatives.

Rayan et al. [10] applied the sequential unconstrained minimization technique to optimize El-Mostakbal City network, an extension to an existing distribution network of Ismailia City, Egypt. The extension network has 31 nodes and 43 pipes. Letha and

Sheeja [11] used a simple method based on cost-head loss ratio and applied it on an actual field problem: a zone in Thiruvananthapuram City of Kerala State.

Farmani et al. [12] constructed a large realistic water distribution system (EXNET) which is a challenging benchmark problem for multi-objective optimization of water systems. The problem was posed as a multi-objective optimization problem with total cost and the number of demand nodes with head deficiency as optimization criteria. The design variables were the addition of new pipes and sizing of new tanks and operation of water system.

Keedwell and Khu [13] considered an industrial network of a single reservoir-fed system and there are 1106 nodes and 1277 pipes. They applied a hybrid genetic algorithm and the results showed that the proposed method consistently outperforms the conventional non-heuristic-based GA approach in terms of producing more economically designed water distribution networks.

Shau et al. [14] selected the Ruey-Fang water supply system in Taipei County to illustrate the practical application of the GA. There are 26 pipelines, 20 nodes, and 2 water intake points. One of intake is water treatment plant; the other is the Kung-Liao system support.

Lippai [15] illustrated the City of Colorado Springs (USA) current and future water system and presented the “design-by-optimization” approach to reduce costs and streamline design procedures. Significant savings were realized from the designs for some service areas. Design-by-optimization allowed the Colorado Springs Utility to meet specific design criteria at near minimum cost without compromising the integrity or reliability of the distribution system.

Wu et al. [1] studied a water distribution system supplying about 18.3 million gallon of water for a peak day demand. The hydraulic network model contains 2018 pipes, 1371 nodes, 3 pumps, 1 reservoir, 9 elevated storage tanks and 20 wells. They performed optimization runs for optimizing improvement solutions for four scenarios: satisfying full demand growth; determining sustainable demand growth; maximizing water production; and prioritizing phase-in capital improvement.

From the previous review, it can be concluded that the application of the GA optimization model to large scale network systems demonstrates the capability of the GA to incorporate real design concerns of water system planners, to handle large-scale systems of multiple pressure zones, and potentially identify significant cost savings.

In the present investigation, a micro-genetic algorithm is applied for pipe network optimization. The Newton method is utilized for the hydraulic analysis of the network. The approach is applied to Suez City water distribution network to demonstrate its efficiency and effectiveness.

OPTIMIZATION MODEL FORMULATION

The water distribution network optimization aims to find the optimal pipe diameters in the network for a given layout and demand requirements. The optimal pipe sizes are selected in the final network satisfying the conservations of mass and energy, and the constraints (e.g. hydraulic and design constraints).

The objective function is the total cost C_T of the given network:

$$C_T = \sum_{i=1}^{i=N} c_i\left(D_i\right).L_i \tag{1}$$

where N is the total number of pipes, $c_i\left(D_i\right)$ the cost of pipe i with diameter D_i per unit length and L_i is the length of pipe i.

The minimization of cost for a network is characterized by the conservation of mass and the conservation of energy. The conservation of mass states that the discharge into each node must be equal to that leaving the node, except for storage nodes (tanks and reservoirs). For a total number of nodes M in the network, this constraint can be written as:

$$\sum_{j=1}^{M} Q_j = 0 \tag{2}$$

where Q_j represents the discharges into or out of the node j (sign included).

The conservation of energy states that the total head loss around any loop must equal to zero or the energy delivered by a pump E_p if there is any:

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

where h_f is the head loss due to friction in a pipe. This embeds the fact that the head loss in any pipe, which is a function of its diameter, length and hydraulic properties, must be equal to the difference in the nodal heads.

Different forms for the head loss formula have been developed for practical pipe flow calculations. In this study, the head loss h_f in the pipe is expressed by the Hazen-Williams formula:

$$h_f = \frac{10.6744}{C_i^{1.852}} \frac{L_i \;\; Q_i^{1.852}}{D_i^{4.8704}} \tag{4}$$

where Q_i is the pipe flow (m^3/s), C_i is the Hazen-Williams coefficient, D_i is pipe diameter (m), and L_i is pipe length (m).

The objective function is to be minimized under the constraints. These constraints are the design and hydraulic constraints. The design constraints (the pipe diameter bounds (maximum and minimum)) and the hydraulic constraints (the pressure head bounds at each node) are given respectively as:

$$D_{\min} \le D_i \le D_{\max} \qquad i = 1,\ldots,N \tag{5}$$

$$H_{j,\min} \le H_j \le H_{j,\max} \qquad j = 1,\ldots,M \tag{6}$$

where H_j is the pressure head at node *j*, and $H_{j,\min}$ and $H_{j,\max}$ are the minimum and maximum allowable pressure heads at node *j*.

OPTIMIZATION TECHNIQUE

In optimization techniques, external penalty functions have been used to convert a constrained optimization problem into an unconstrained problem. Therefore, for the network optimization, the objective function is given as:

$$Z = C_T + C_P \tag{7}$$

where C_P is the penalty cost.

The design constraints in pipe network optimization that will be used in the penalty function are the minimum allowable hydraulic pressures at given nodes as the diameter of each pipe is chosen from a specified set of commercial pipes. Applying the new adaptive penalty function mentioned in Djebedjian et al. [2], the penalty cost is written as:

$$C_P = \frac{C_T}{M} \cdot \sum_{j=1}^{M} \left(H_{j,\min} - H_j \right) \tag{8}$$

and the objective function is calculated from:

$$Z = \begin{cases} C_T & \text{if } \ H_{j,\min} - H_j \le 0 \\ C_T \left[1 + \dfrac{1}{M} \displaystyle\sum_{j=1}^{M} \left(H_{j,\min} - H_j \right) \right] & \text{else} \end{cases} \tag{9}$$

The penalty cost is applied at the nodes where the pressure head at node is less than the minimum allowable pressure head at the same node.

GENETIC ALGORITHMS

Genetic algorithms are search techniques based on the concepts of natural evolution and thus their principles are directly analogous to natural behavior, Gen and Cheng [17]. The brief idea of GA is to select population of initial solution points scattered randomly in the optimized space, then converge to better solutions by applying in iterative manner the following three processes (reproduction/selection, crossover and mutation) until a desired criteria for stopping is achieved.

The micro-Genetic Algorithm (μGA), Krishnakumar [18], is a "small population" GA. In contrast to the Simple Genetic Algorithm, which requires a large number of individuals in each population (i.e., 30 - 200); the μGA uses a small population size.

A brief description of the steps in using GA for pipe network optimization is as follows, Simpson et al. [19]:

1. ***Generation of initial population.*** The GA randomly generates an initial population of coded strings representing pipe network solutions of population size N_G. Each of the N_G strings represents a possible combination of pipe sizes.
2. ***Computation of network cost.*** For each N_G string in the population, the GA decodes each substring into the corresponding pipe size and computes the total material cost. The GA determines the costs of each trial pipe network design in the current population.
3. ***Hydraulic analysis of each network.*** A steady state hydraulic network solver computes the heads and discharges under the specified demand patterns for each of the network designs in the population. The actual nodal pressures are compared with the minimum allowable pressure heads, and any pressure deficits are noted. In this study, the Newton technique is used.
4. ***Computation of penalty cost.*** The GA assigns a penalty cost for each demand pattern if a pipe network design does not satisfy the minimum pressure constraints. The pressure violation at the node, at which the pressure deficit is maximum, is used as the basis for computation of the penalty cost. The maximum pressure deficit is multiplied by a penalty factor, which is a measure of the cost of a deficit of one unit of pressure head.
5. ***Computation of total network cost.*** The total cost of each network in the current population is taken as the sum of the network cost (Step 2) plus the penalty cost (Step 4).
6. ***Computation of the fitness.*** The fitness of the coded string is taken as some function of the total network cost. For each proposed pipe network in the current population, it can be computed as the inverse or the negative value of the total network cost from Step 5.
7. ***Generation of a new population using the selection operator.*** The GA generates new members of the next generation by a selection scheme.

8. ***The crossover operator.*** Crossover occurs with some specified probability of crossover for each pair of parent strings selected in Step 7.

9. ***The mutation operator*****.** Mutation occurs with some specified probability of mutation for each bit in the strings which have undergone crossover.

10. ***Production of successive generations.*** The use of the three operators described above produces a new generation of pipe network designs using Steps 2 to 9. The GA repeats the process to generate successive generations. The last cost strings (e.g., the best 20) are stored and updated as cheaper cost alternatives are generated.

A computer program was developed based on the GA, and written in FORTRAN. The GA approach and the adaptive penalty function were employed to reduce the number of iterations involved. The Newton method and the system of *H*-equations, [16], are used for hydraulic analysis simulation. The efficacy of the method is verified using the water distribution network of Suez City (Egypt). Applying the present method arrived at an optimal design of the network.

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 water distribution system network. The selected water supply system is that of Suez City (Egypt) which lies at the southernmost point of entry to the Suez Canal and is the northernmost city on the Gulf of Suez. The layout of the network and the index numbers of the nodes are shown in Figure 1. Figure 2 shows the circled portion of the network in more detail. The network has 341 nodes and 389 pipes, three pumps, and three reservoirs. The total population of the zone was 417,610 inhabitants (according to the 1996 census) and the total water demand is 1848.87 L/s (159,742 m^3/day). The Suez water distribution system contains approximately 117 km of pipe.

The data for the studied network is shown in Tables 1 and 2 (in the Appendix). It includes the index (ID) for each node and pipe. Table 1 shows the index (ID) for each node, the elevation, and specified demands. Table 2 gives the original design pipes data including the index for each pipe, the start and end nodes, the length and diameter. The Suez City water distribution system ranges in diameter from 300 mm to 1400 mm.

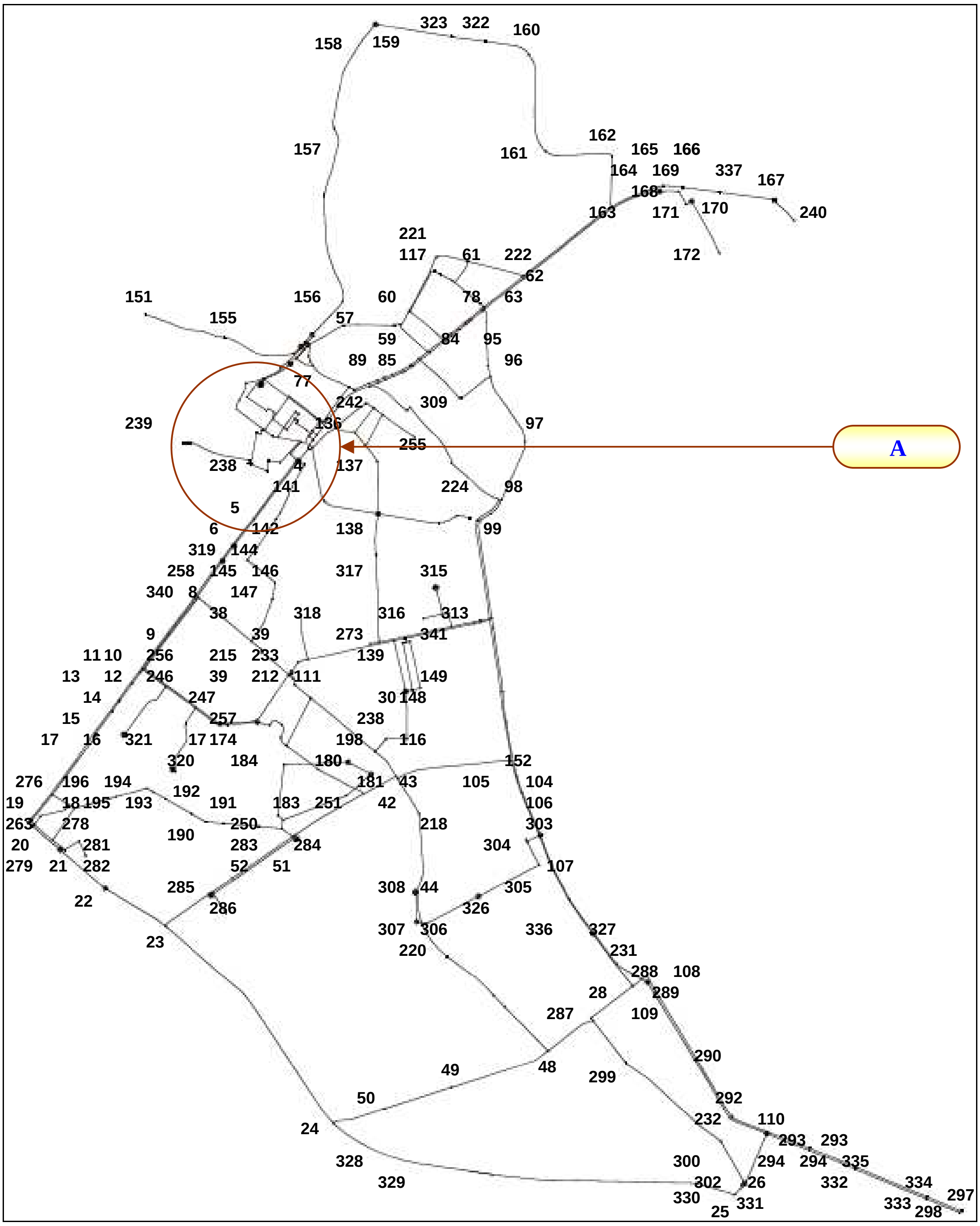

Figure 1. Suez City network. The circled area is shown in more detail in Figure 2

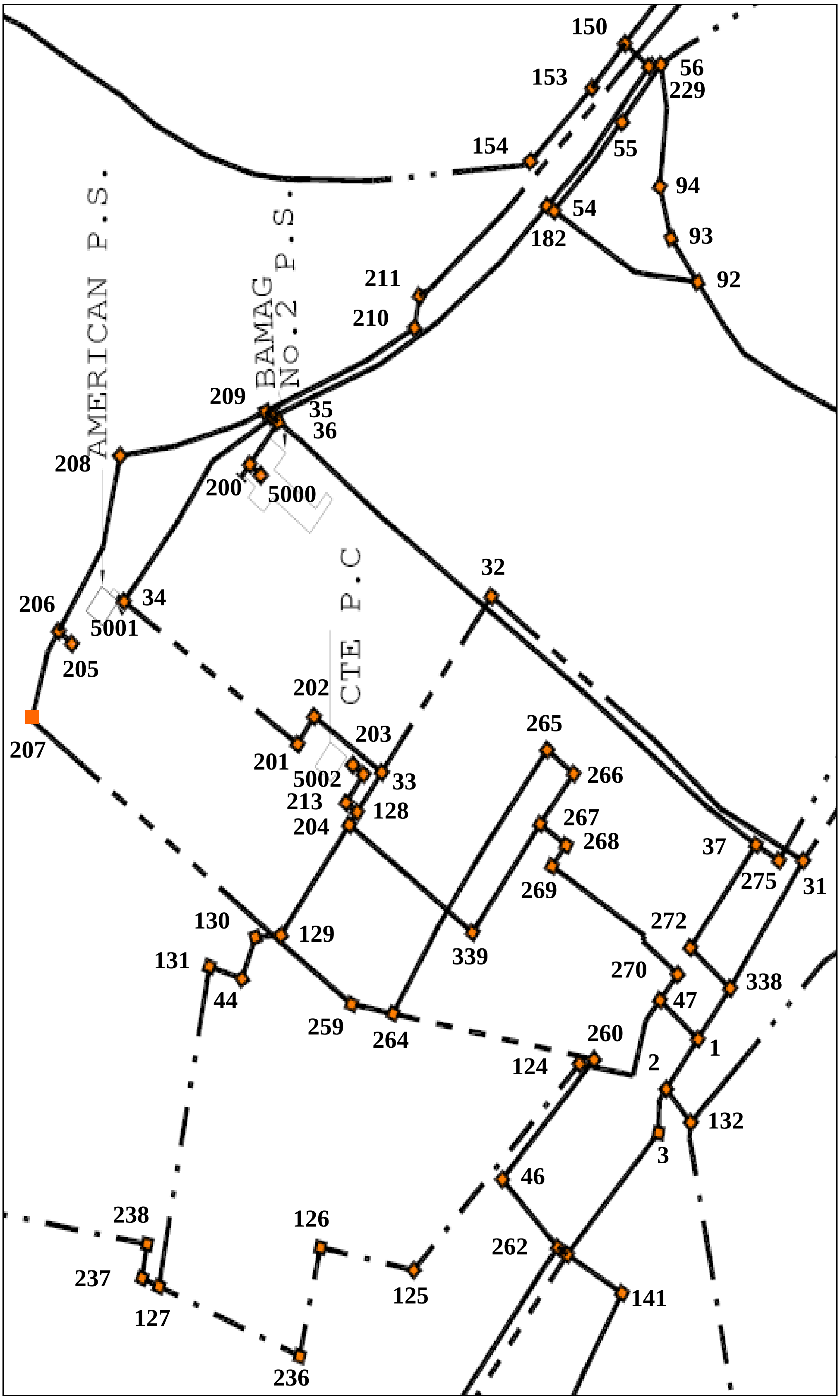

Figure 2. Suez City network. Increased detail near the pumps locations

RESULTS AND DISCUSSION

The hydraulic analysis (Nodes pressure heads), Table 3, of the existing original water distribution system of Suez City demonstrates that the pressure head ranges between a minimum of 27.8 m to a maximum of 53.8 m with an average pressure head for all nodes of 46.85 m. This means that the pressure heads are sufficient for the prescribed demands.

The available data of demands at the nodes have been observed when the Master Plan of Suez City was prepared [20]. Instead of making an optimization for the new demands after the population growth using the usual water consumption per capita approach, the optimization has been done for the original demands but with the constraint of pressure heads less than the observed minimum one. As the minimum pressure head of the original network is in the acceptable usual standard (H_{min} = 25 – 30 m) therefore, two optimization runs have been performed with a minimum pressure head constraint of H_{min} = 27 m and 25 m.

Table 4 gives the cost per meter for commercially available pipe sizes used in the optimization of Suez network. The pipes with diameters greater than 600 mm are in ductile iron otherwise are in u.P.V.C. (Unplasticised Polyvinyl Chloride). It should be mentioned that the cost of original network is calculated using the costs given in Table 4 and not related to the actual past costs of the network. Also, for optimization the diameters 1.2 m and 1.4 m are not included as they are very large. The total number of possible combinations of design for a set of 9 commercial pipes and 389 pipes is 9^{389} which is very difficult to test them; this shows the importance of optimization. The Hazen-Williams coefficients used in the hydraulic analysis are C = 111 for ductile iron and C = 145 for uP.V.C.

Optimization was conducted with a micro-GA which included elitism. The suitable values for GA parameters for the best performance of the code are given in Table 5.

The results of optimization for the pressure heads at the nodes for H_{min} = 27 m and 25 m are shown in Tables 6 and 7, respectively. The minimum pressure head observed for each optimization case approached from the minimum pressure constraint and the average pressure heads at all nodes for the two optimization cases were decreased gradually from that of the original case.

Figure 3 shows the comparison between the pressure heads at the nodes for the original network and the optimization case of H_{min} = 25 m. For the original network, some nodes have high pressure heads which by optimization these heads have been decreased. A similar comparison for H_{min} = 27 m shows the same trend but with less differences.

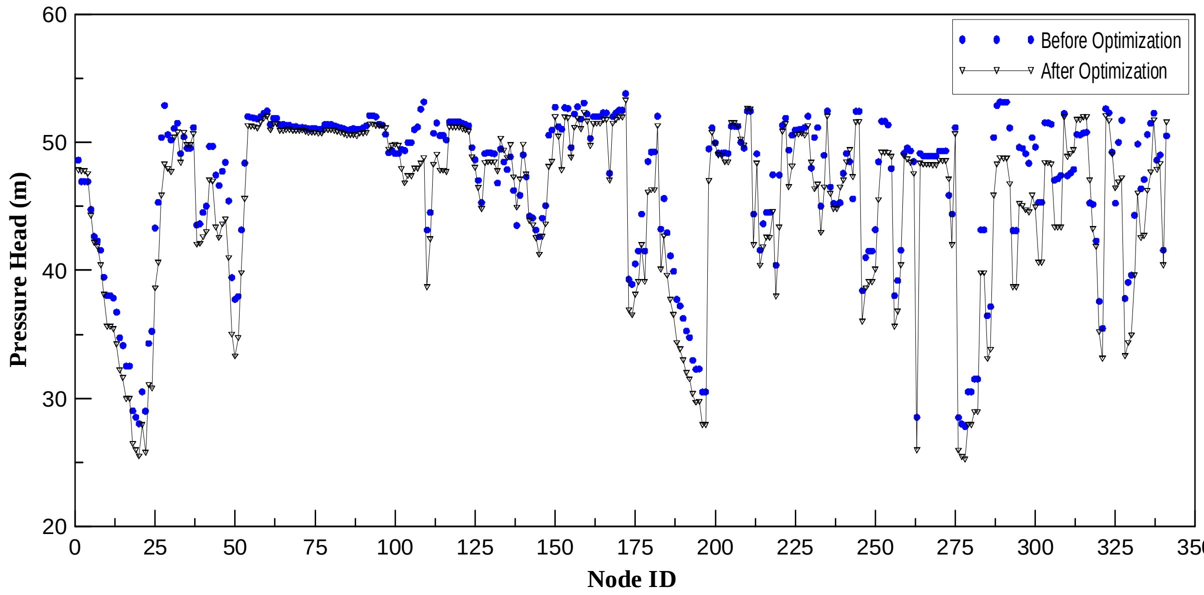

Figure 3. Comparison between nodal pressure heads before and after optimization for H_{min} = 25 m

Table 8 gives the original network diameters and cost for each pipe. Similarly, Tables 9 and 10 illustrates the results of the optimized diameters and cost for each pipe in the network for the cases H_{min} = 27 m and 25 m, respectively. The total cost of pipes has been decreased from 116,164,195 L.E. for the original network to 107,508,725 L.E. for the optimized case H_{min} = 27 m and to 87,838,050 L.E. for H_{min} = 25 m. These results are shown in Figure 4. It is worthy to note that for the original network (before optimization) and according to the hydraulic analysis results, Table 3, the minimum pressure head is 27.8 m. The new optimized costs are 92.55% and 75.62% of the original network cost for minimum pressure heads of 27 m and 25 m, respectively.

Figures 5 and 6 depict the evolution of the solution as the program develops a single run for minimum pressure constraint of 27 m and 25 m, respectively. For H_{min} = 27 m, the number of evaluations is less than that of H_{min} = 25 m. As mentioned before the total search space for this network is 9^{389} different possible network designs. According to the evaluation numbers in Figures 5 and 6, the genetic algorithm reaches the optimal solution in a very small percentage of all possible designs. The calculations have been performed using Pentium 4 (1.7 GHz) PC with an average of 18 hours for 100 generations.

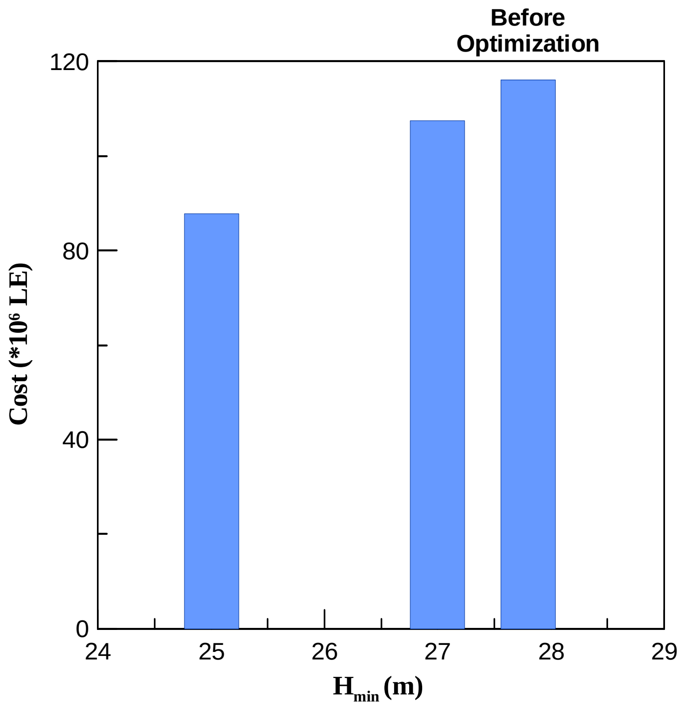

Figure 4. Comparison between costs before and after optimization for H_{min} = 25 m and H_{min} = 27 m

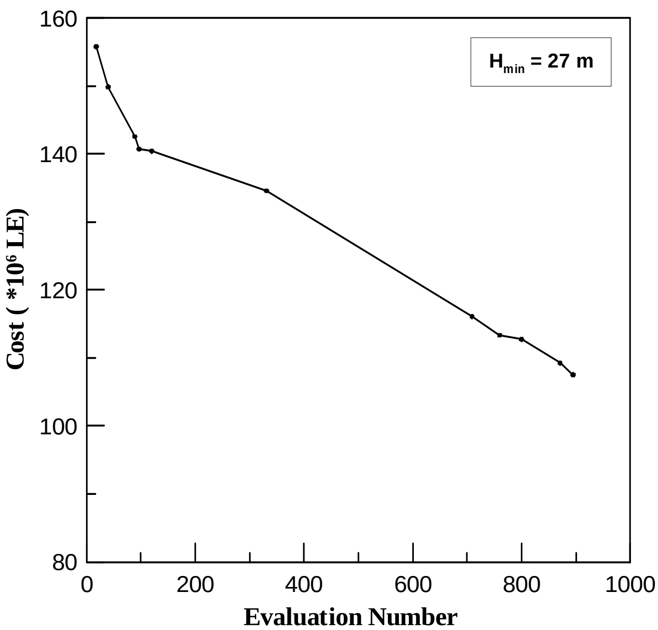

Figure 5. Cost evolution for H_{min} = 27 m

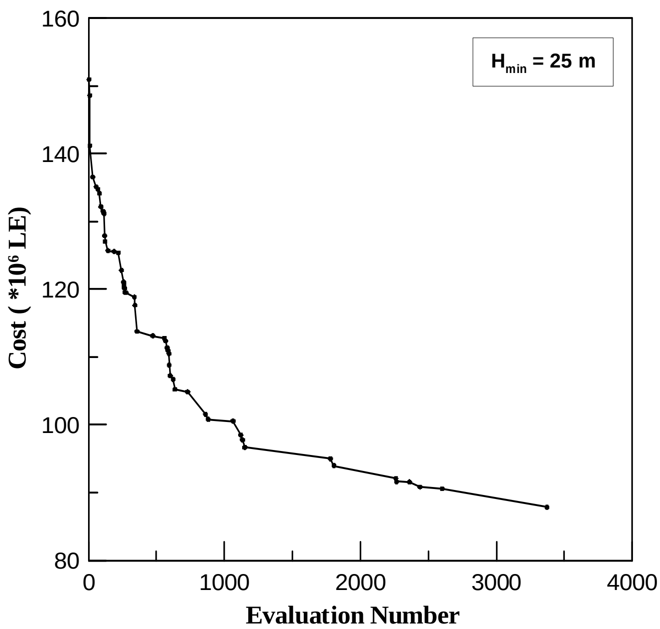

Figure 6. Cost evolution for H_{min} = 25 m

According to Eq. (1) and noting that the cost of pipe increases with the pipe diameter, Table 4, the total cost of pipes is mainly dependent on the length of pipes. The comparison between the used lengths of pipes for each diameter for the original network and the optimized cases of H_{min} = 27 m and H_{min} = 25 m is shown in Fig. 7. It should be mentioned that in the original network, the pipe diameters of 350 m and 450 m have not been used. As these diameters are commercially available, they were used in the optimization study. Also, the pipe diameters of 1200 mm and 1400 mm have not been used in the optimization as they are considered very large diameters. From Fig. 7, it is interesting to observe that in the two optimized cases, there is a concentration of the pipe lengths for medium diameter sizes while for the original (not optimized) case the long pipe lengths exist for small and large diameters. The differences in pipe lengths for each diameter resulted in decreasing the total cost of pipes for the optimized case.

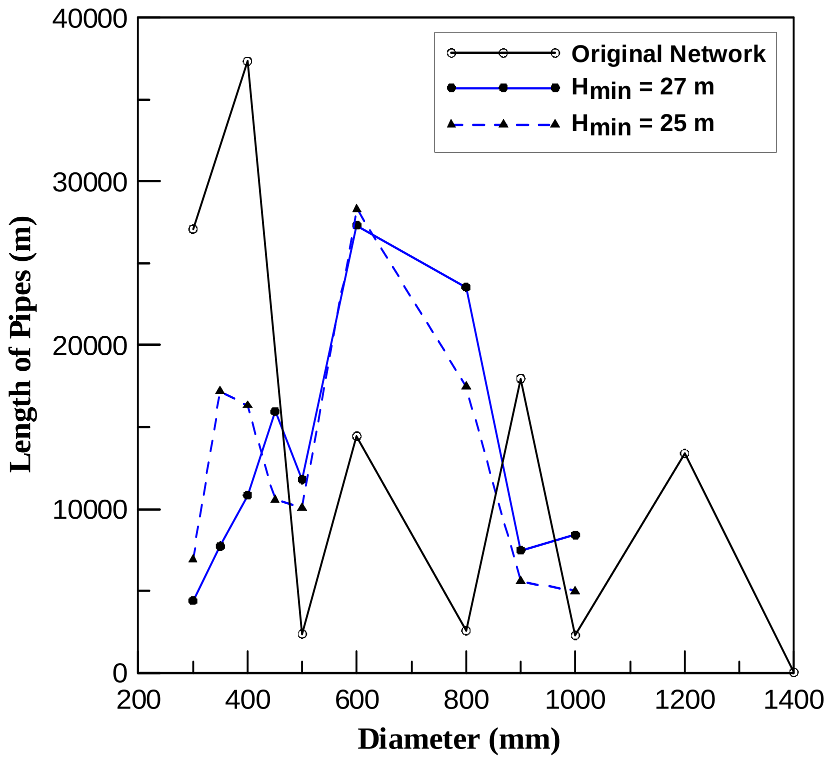

Figure 7. Length of pipes for each pipe size for original network and optimized network with H_{min} = 27 m and 25 m

CONCLUSION

The optimization of a large water distribution system is a complex problem. The utilization of genetic algorithms with the Newton method and the H-equations hydraulic analysis have been presented in the present paper. A numerical code for optimal design and cost evaluation of a water distribution network was developed. The Suez City water supply system in Egypt is selected to illustrate the practical application of the genetic algorithms. There are 389 pipes, 341 nodes, 3 pumps, and

3 reservoirs. The results show that a saving of around 7% and 24% of the original network cost for minimum pressure heads of 27 m and 25 m, respectively. Therefore, the approach shows attractive ability to handle the large-scale pipe network optimization problem efficiently.

NOMENCLATURE

C_i	Hazen-Williams coefficient of pipe *i*
C_P	penalty cost
C_T	total cost
$c_i\left(D_i\right)$	cost of pipe *i* with diameter D_i per unit length
D_i	diameter of pipe *i*, (m)
$D_{\max}$	maximum diameter, (m)
$D_{\min}$	minimum diameter, (m)
E_p	energy supplied by a pump, (m)
H_j	pressure head at node *j*, (m)
$H_{j,\max}$	maximum allowable pressure head at node *j*, (m)
$H_{j,\min}$	minimum required pressure head at node *j*, (m)
h_f	head loss due to friction in a pipe, (m)
L_i	length of pipe *i*, (m)
M	total number of nodes in the network
N	total number of pipes
Q_i	flow in pipe *i*, (m^3/s)
Q_j	discharges into or out of the node *j*, (m^3/s)
Z	objective function

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Table 1. Suez City network original design nodes data

Node ID	Z (m)	Q (LPS)	Node ID	Z (m)	Q (LPS)	Node ID	Z (m)	Q (LPS)	Node ID	Z (m)	Q (LPS)
1	7.0	0	51	15.5	0	101	3.3	0	151	4.3	10.49
2	7.0	0	52	10.3	0	102	3.0	0	152	2.6	5.27
3	7.0	0	53	5.1	17.53	103	3.1	0.62	153	3.0	0
4	7.0	0	54	3.7	0	104	2.5	0.02	154	3.0	46.77
5	9.0	13.71	55	3.7	0	105	2.5	0	155	6.0	10.94
6	11.0	3.31	56	3.7	0	106	1.5	6.11	156	3.5	0
7	11.3	5.68	57	3.5	8.68	107	1.4	0	157	2.7	0
8	12.0	0	58	3.0	0	108	0.5	0	158	3.5	0
9	14.1	0	59	2.7	6.91	109	0.0	0.14	159	2.0	0
10	15.5	25.61	60	2.5	3.98	110	10.0	13.77	160	2.6	10.11
11	15.5	0	61	3.5	5.88	111	9.0	0	161	4.5	9.86
12	15.7	6.59	62	3.0	5.07	112	2.8	0	162	2.8	1.12
13	16.8	0	63	3.0	0.73	113	2.0	0.62	163	2.8	10.44
14	18.8	0	64	3.5	3.15	114	3.3	0	164	2.8	0
15	19.4	6.37	65	3.5	0	115	3.3	0	165	2.5	7.77
16	21.0	0	66	3.6	0	116	3.3	8.85	166	2.5	0
17	21.0	24.33	67	3.6	0	117	3.3	4.23	167	7.2	0
18	24.5	2.64	68	3.7	0	118	3.3	0	168	2.8	2.26
19	25.0	0	69	3.7	0	119	3.3	0	169	2.5	0
20	25.5	0	70	3.8	0	120	3.3	0	170	2.3	0
21	23.0	0	71	3.8	3.84	121	3.4	0	171	2.3	4.14
22	24.5	0	72	3.9	0	122	3.5	0	172	1.0	0.29
23	19.2	1.89	73	4.0	0	123	3.6	0	173	14.2	0
24	18.2	2.12	74	4.0	0	124	6.0	0	174	14.6	0
25	10.0	14.49	75	4.0	0	125	6.9	1.98	175	13.0	18.04
26	8.0	46.30	76	4.1	3.46	126	8.5	0	176	12.0	6.16
27	3.0	0	77	4.1	3.15	127	10.2	0	177	9.0	0
28	0.5	0	78	3.5	11.99	128	6.7	0	178	12.0	0
29	3.3	1.04	79	3.5	0	129	6.6	0	179	5.0	0
30	3.3	3.10	80	3.5	0	130	6.6	0	180	3.7	17.92
31	4.5	0	81	3.6	0	131	6.6	6.19	181	3.7	9.14
32	4.3	0	82	3.7	9.29	132	7.0	12.48	182	3.7	0
33	6.7	0	83	3.8	0	133	4.1	12.29	183	10.0	15.58
34	5.5	0	84	3.9	0	134	5.0	0	184	7.4	10.29
35	6.3	0	85	4.0	10.36	135	5.6	2.99	185	10.5	0
36	6.3	0	86	4.0	0	136	4.6	0	186	12.3	7.79
37	4.5	0	87	4.0	4.44	137	7.1	7.40	187	13.5	40.30
38	10.0	29.72	88	4.1	0	138	9.0	11.33	188	15.7	0
39	9.9	0	89	4.1	0	139	6.1	43.85	189	16.2	45.27
40	9.0	0	90	4.1	0	140	3.3	0.32	190	17.2	0
41	8.5	3.85	91	4.1	0	141	6.6	8.15	191	18.2	0
42	3.8	0	92	3.5	18.61	142	9.5	0	192	18.7	0
43	3.8	7.84	93	3.5	0	143	9.6	17.43	193	20.5	0
44	6.0	6.84	94	3.6	0	144	10.5	1.33	194	21.2	0
45	6.8	0	95	3.0	12.65	145	11.0	0	195	21.2	0
46	5.7	0	96	3.0	6.13	146	9.5	6.42	196	23.0	20.60
47	5.0	0	97	3.0	15.40	147	8.5	8.78	197	23.0	0
48	8.0	0	98	4.0	1.64	148	2.9	0	198	4.0	0
49	14.0	0	99	3.7	5.43	149	2.5	10.74	199	3.8	8.05
50	15.7	0	100	3.3	8.73	150	3.0	0	200	6.3	0

Table 1. (Continued)

Node ID	Z (m)	Q (LPS)	Node ID	Z (m)	Q (LPS)	Node ID	Z (m)	Q (LPS)
201	6.7	4.81	251	4.5	9.45	301	8.0	0
202	6.7	0	252	1.8	0	302	8.0	0
203	6.7	0	253	1.8	0	303	1.0	2.91
204	6.7	0	254	1.8	161.55	304	1.0	4.52
205	4.5	0	255	5.5	5.66	305	1.1	3.69
206	4.5	0	256	15.5	25.16	306	6.0	0
207	4.5	20.00	257	14.2	14.83	307	6.0	0
208	5.8	0	258	12.0	0	308	6.0	0
209	6.3	0	259	6.5	0	309	2.3	6.38
210	3.4	0	260	6.0	0	310	5.0	10.59
211	3.4	0	261	6.2	0	311	4.8	4.36
212	9.0	0	262	7.0	13.88	312	4.5	2.11
213	6.7	0	263	25.0	0	313	1.4	9.45
214	12.0	27.13	264	6.5	0	314	1.4	0
215	9.9	21.03	265	6.7	0	315	1.2	19.98
216	9.0	0	266	6.7	0	316	1.2	6.36
217	9.0	0	267	6.7	0	317	6.7	45.00
218	6.0	22.13	268	6.7	0	318	8.2	24.37
219	13.0	0	269	6.7	19.07	319	11.3	0
220	6.0	0	270	6.3	0	320	15.7	23.16
221	3.6	0	271	6.3	0	321	18.0	11.69
222	3.0	0	272	6.3	0	322	2.2	24.52
223	5.0	0	273	6.1	0	323	2.6	0
224	4.0	2.73	274	9.0	0	324	5.5	17.55
225	4.0	2.99	275	4.5	12.58	325	7.8	9.37
226	4.0	0	276	25.0	0	326	2.5	45.45
227	4.1	0	277	25.5	0	327	1.7	55.09
228	4.3	12.28	278	25.7	0	328	15.6	0
229	3.7	0	279	23.0	0	329	14.3	1.56
230	5.0	0.55	280	23.0	0	330	13.7	17.15
231	2.5	21.94	281	22.0	0	331	9.0	17.22
232	2.0	0	282	22.0	5.71	332	2.5	48.88
233	8.5	0	283	10.3	0	333	6.0	0.27
234	4.5	16.58	284	10.3	0	334	6.0	0.06
235	2.5	0	285	17.0	0	335	2.5	0.12
236	9.0	0	286	16.3	0	336	1.2	4.40
237	10.2	20.20	287	3.0	0	337	2.5	8.77
238	10.2	0	288	0.5	0	338	7.0	0
239	8.5	66.11	289	0.0	9.23	339	6.7	0
240	7.2	0	290	0.0	0.08	340	12.0	0
241	6.6	0	291	0.0	0.06	341	1.6	0
242	5.0	0	292	2.0	0			
243	7.3	22.29	293	10.0	0			
244	3.4	0	294	10.0	0			
245	3.4	0	295	3.5	0.02			
246	15.1	0.26	296	3.5	0.05			
247	12.5	0	297	4.0	0.07			
248	12.0	0	298	4.0	0.27			
249	12.0	0	299	3.0	0			
250	10.0	8.07	300	3.7	0			

Total Demand = 1848.87 L/s

Table 2. Suez City network original design pipes data

Pipe ID	Start Node	End Node	L (m)	D (mm)	Pipe ID	Start Node	End Node	L (m)	D (mm)	Pipe ID	Start Node	End Node	L (m)	D (mm)
1	1	2	57	300	51	37	272	117	1000	101	67	66	28	600
2	2	3	42	1200	52	272	338	56	1000	102	68	67	39	600
3	3	4	148	1200	53	338	1	57	1200	103	69	68	78	600
4	4	5	681	1200	54	8	214	13	1200	104	70	69	91	600
5	5	6	311	1200	55	214	38	637	1200	105	71	70	73	600
6	6	7	176	1200	56	38	39	122	1200	106	72	71	175	600
7	7	8	404	1200	57	39	215	25	1200	107	73	72	206	600
8	8	258	21	1200	58	215	40	336	1200	108	74	73	95	600
9	258	9	420	1200	59	40	216	46	1200	109	75	74	29	600
10	9	10	395	1200	60	216	217	59	1200	110	76	75	157	600
11	10	11	12	1200	61	217	41	192	1200	111	227	76	75	600
12	11	12	35	1200	62	41	198	780	1200	112	77	227	88	600
13	12	13	125	1200	63	198	42	304	1200	113	89	227	23	400
14	13	14	197	1200	64	42	43	24	900	114	78	222	453	400
15	14	15	124	1200	65	152	43	1083	500	115	79	78	13	400
16	15	16	258	1200	66	43	218	389	900	116	80	79	21	400
17	16	17	15	1200	67	218	44	741	900	117	81	80	135	400
18	17	18	687	1200	68	44	220	308	900	118	82	81	52	400
19	19	18	300	1200	69	220	45	373	900	119	83	82	169	400
20	20	19	60	1200	70	45	46	570	900	120	199	83	94	400
21	20	21	343	1200	71	46	47	148	900	121	84	199	182	400
22	21	22	551	1200	72	47	48	574	900	122	85	84	105	400
23	328	329	1105	600	73	48	287	511	600	123	86	85	99	400
24	22	23	659	1200	74	49	48	966	900	124	87	86	190	400
25	329	330	557	600	75	50	49	651	900	125	88	87	78	400
26	23	24	2435	900	76	24	50	503	900	126	89	88	67	400
27	330	331	1332	600	77	23	51	773	800	127	90	89	80	400
28	24	328	726	600	78	51	52	677	800	128	91	90	154	400
29	331	25	369	600	79	283	52	20	800	129	228	91	49	400
30	301	25	110	600	80	53	283	750	800	130	92	228	399	400
31	26	301	29	600	81	42	53	344	800	131	92	93	49	400
32	300	26	450	900	82	35	182	358	600	132	54	92	172	400
33	299	300	1147	900	83	182	54	8	400	133	93	94	48	400
34	28	27	488	900	84	54	55	109	400	134	94	56	112	400
35	287	299	504	900	85	229	182	168	600	135	64	95	531	400
36	327	28	610	900	86	55	56	67	400	136	95	96	104	400
37	27	287	32	900	87	150	229	33	600	137	96	97	695	400
38	29	152	1332	900	88	56	57	367	400	138	97	98	586	400
39	152	327	1792	900	89	57	58	475	400	139	98	99	169	400
40	223	29	946	900	90	58	59	54	400	140	99	230	113	400
41	224	223	285	900	91	59	84	364	400	141	230	100	931	400
42	31	77	545	900	92	59	60	150	400	142	101	100	91	400
43	32	31	415	900	93	60	221	565	400	143	102	101	600	400
44	33	32	199	1200	94	221	61	303	400	144	103	102	285	400
45	202	33	89	1000	95	61	62	535	400	145	104	103	514	400
46	201	202	30	1000	96	222	62	93	400	146	105	104	46	400
47	34	201	228	1000	97	63	222	19	400	147	106	105	115	400
48	34	35	236	1000	98	64	63	467	600	148	232	110	368	400
49	36	35	7	1000	99	65	64	21	600	149	303	106	430	400
50	36	37	644	1000	100	66	65	130	600	150	107	303	297	400

Table 2. (Continued)

Pipe ID	Start Node	End Node	L (m)	D (mm)	Pipe ID	Start Node	End Node	L (m)	D (mm)	Pipe ID	Start Node	End Node	L (m)	D (mm)
151	336	107	363	400	201	134	136	289	300	251	249	248	127	400
152	231	336	746	400	202	135	137	329	300	252	178	249	98	400
153	108	231	337	400	203	138	317	379	300	253	178	179	367	400
154	109	108	116	400	204	317	139	822	400	254	179	53	486	400
155	109	291	728	400	205	341	139	688	400	255	52	185	124	600
156	291	232	636	400	206	140	341	271	400	256	185	186	214	600
157	40	233	140	600	207	100	140	111	400	257	186	187	328	600
158	233	111	99	600	208	139	273	83	400	258	188	187	167	600
159	111	112	820	600	209	132	243	512	300	259	189	188	150	600
160	111	318	419	300	210	243	138	522	300	260	190	189	279	600
161	113	112	109	600	211	4	141	69	400	261	191	190	133	600
162	114	113	646	600	212	141	142	498	400	262	192	191	69	600
163	115	114	60	600	213	142	143	75	400	263	193	192	296	600
164	29	115	91	600	214	143	144	318	400	264	194	193	69	600
165	198	234	156	500	215	144	145	147	400	265	195	194	188	600
166	234	116	191	500	216	145	146	336	400	266	196	195	145	600
167	116	30	444	500	217	146	147	153	400	267	197	196	59	600
168	112	30	483	500	218	147	38	445	400	268	278	196	354	300
169	60	235	9	300	219	150	153	53	400	269	18	197	181	600
170	235	117	459	300	220	244	150	101	400	270	276	197	294	300
171	117	118	53	300	221	244	156	418	400	271	277	276	99	300
172	235	199	406	300	222	156	157	1037	400	272	278	277	226	300
173	118	119	120	300	223	157	158	641	400	273	279	278	112	300
174	119	120	33	300	224	158	159	1071	400	274	279	280	27	300
175	120	61	230	300	225	159	323	722	400	275	21	279	26	300
176	120	121	161	300	226	323	322	323	400	276	280	281	159	300
177	121	122	96	300	227	322	160	424	400	277	281	282	148	300
178	122	123	49	300	228	160	161	943	400	278	324	224	568	900
179	123	78	49	300	229	162	161	633	400	279	225	324	652	900
180	124	125	259	300	230	163	162	482	400	280	226	225	38	900
181	125	126	102	300	231	62	163	968	400	281	77	226	427	900
182	126	236	101	300	232	163	164	402	400	282	341	313	131	300
183	236	127	164	300	233	168	164	28	400	283	313	314	60	300
184	128	33	45	900	234	63	168	1454	400	284	314	315	256	300
185	128	213	14	600	235	164	165	111	400	285	314	316	179	300
186	213	129	125	600	236	165	166	179	400	286	113	253	35	400
187	129	130	27	400	237	166	337	349	300	287	252	253	32	300
188	130	241	40	400	238	337	167	497	300	288	253	254	34	300
189	241	131	34	400	239	168	169	250	400	289	149	252	449	300
190	131	127	299	400	240	169	170	138	300	290	148	254	450	300
191	2	132	40	400	241	170	171	55	300	291	148	149	81	300
192	132	133	288	400	242	171	172	554	300	292	30	148	61	400
193	133	242	363	400	243	167	240	285	300	293	185	183	81	300
194	242	134	83	400	244	11	246	266	600	294	183	250	60	300
195	134	135	103	400	245	246	247	345	600	295	250	184	475	300
196	135	255	365	400	246	247	173	275	600	296	184	180	600	300
197	133	136	196	300	247	173	174	67	600	297	181	180	236	300
198	136	137	150	300	248	174	175	277	600	298	251	181	306	300
199	137	325	188	300	249	176	175	124	600	299	183	251	631	300
200	325	138	485	300	250	248	176	146	400	300	283	284	23	400

Table 2. (Continued)

Pipe ID	Start Node	End Node	L (m)	D (mm)	Pipe ID	Start Node	End Node	L (m)	D (mm)
301	284	285	929	400	351	260	261	147	1200
302	285	286	210	300	352	264	260	220	1200
303	44	308	15	300	353	259	264	45	1200
304	308	307	273	300	354	207	259	431	1200
305	307	306	99	300	355	206	207	87	1200
306	306	326	537	300	356	206	205	18	1400
307	305	326	634	300	357	208	206	175	1200
308	304	305	246	300	358	209	208	165	1200
309	303	304	135	300	359	35	209	9	1200
310	334	297	462	300	360	209	210	175	1200
311	333	298	469	300	361	210	211	29	1000
312	335	334	723	300	362	211	245	423	1000
313	332	333	716	300	363	245	244	21	600
314	295	335	456	300	364	153	154	94	400
315	296	332	459	300	365	154	155	676	400
316	293	295	246	400	366	155	151	779	300
317	293	294	19	400	367	127	237	19	300
318	294	296	251	400	368	237	238	31	300
319	292	293	531	400	369	238	239	643	300
320	110	294	175	400	370	271	124	135	300
321	302	110	535	400	371	271	1	54	600
322	301	302	14	400	372	270	271	30	600
323	290	292	634	400	373	269	270	172	600
324	289	290	728	400	374	268	269	24	600
325	289	109	22	400	375	267	268	34	600
326	288	289	169	400	376	339	267	123	600
327	28	288	164	600	377	213	339	165	600
328	10	256	10	300	378	204	128	14	600
329	256	257	872	300	379	203	204	31	600
330	246	321	607	300	380	267	266	58	1000
331	247	320	641	300	381	266	265	35	1000
332	257	219	335	300	382	265	264	293	1000
333	219	274	567	300	383	200	36	49	600
334	274	177	23	300	384	37	275	28	1000
335	177	212	19	300	385	275	228	413	400
336	41	178	498	600	386	338	31	140	600
337	262	4	12	300	387	0*	200	5	600
338	262	319	1169	300	388	0*	34	5	1000
339	7	319	12	1200	389	0*	203	5	600
340	319	340	423	1200					
341	340	258	16	1200					
342	340	263	2612	1200					
343	263	20	55	1200					
344	214	256	836	300					
345	138	310	571	300					
346	310	311	177	300					
347	311	312	123	300					
348	85	309	532	300					
349	309	96	352	300					
350	261	262	86	1200					

0* means reservoir

Total length of pipes = 117425 m
92 pipes of 300 mm diameter
122 pipes of 400 mm diameter
5 pipes of 500 mm diameter
71 pipes of 600 mm diameter
5 pipes of 800 mm diameter
29 pipes of 900 mm diameter
15 pipes of 1000 mm diameter
49 pipes of 1200 mm diameter
1 pipe of 1400 mm diameter

Table 3. Results of hydraulic analysis of original network (Nodes pressure heads)

Node ID	Head (m)	Node ID	Head (m)	Node ID	Head (m)	Node ID	Head (m)	Node ID	Head (m)	Node ID	Head (m)	Node ID	Head (m)
1	48.61	51	37.97	101	49.11	151	51.23	201	49.15	251	48.48	301	45.30
2	46.93	52	43.16	102	49.44	152	51.02	202	49.14	252	51.64	302	45.30
3	46.93	53	48.37	103	49.35	153	52.70	203	49.17	253	51.64	303	51.53
4	46.93	54	52.01	104	49.98	154	52.64	204	49.13	254	51.36	304	51.51
5	44.74	55	51.94	105	49.98	155	49.59	205	51.26	255	47.95	305	51.40
6	42.65	56	51.89	106	50.99	156	52.22	206	51.26	256	38.02	306	47.04
7	42.30	57	51.81	107	51.19	157	52.77	207	51.24	257	39.19	307	47.14
8	41.57	58	52.01	108	52.58	158	51.82	208	50.00	258	41.57	308	47.42
9	39.45	59	52.28	109	53.15	159	53.07	209	49.54	259	49.14	309	52.25
10	38.03	60	52.44	110	43.14	160	52.20	210	52.44	260	49.56	310	47.38
11	38.03	61	51.39	111	44.51	161	50.30	211	52.44	261	49.32	311	47.58
12	37.83	62	51.88	112	50.71	162	52.00	212	44.39	262	48.49	312	47.88
13	36.73	63	51.88	113	51.51	163	52.00	213	49.10	263	28.52	313	50.61
14	34.73	64	51.38	114	50.52	164	52.00	214	41.57	264	49.13	314	50.58
15	34.12	65	51.39	115	50.54	165	52.30	215	43.63	265	48.94	315	50.72
16	32.52	66	51.31	116	50.17	166	52.29	216	44.51	266	48.94	316	50.78
17	32.52	67	51.32	117	51.60	167	47.57	217	44.51	267	48.94	317	45.26
18	29.02	68	51.23	118	51.60	168	52.00	218	47.46	268	48.93	318	45.15
19	28.52	69	51.24	119	51.60	169	52.30	219	40.39	269	48.93	319	42.30
20	28.02	70	51.16	120	51.60	170	52.50	220	47.44	270	49.32	320	37.58
21	30.51	71	51.17	121	51.49	171	52.50	221	51.31	271	49.31	321	35.46
22	29.00	72	51.11	122	51.39	172	53.80	222	51.88	272	49.33	322	52.62
23	34.29	73	51.05	123	51.29	173	39.30	223	49.39	273	45.86	323	52.30
24	35.23	74	51.07	124	49.59	174	38.90	224	50.55	274	44.39	324	49.23
25	43.30	75	51.08	125	48.64	175	40.50	225	50.97	275	51.15	325	45.24
26	45.30	76	51.01	126	47.03	176	41.50	226	50.98	276	28.50	326	49.99
27	50.38	77	51.04	127	45.29	177	44.39	227	51.03	277	28.00	327	51.72
28	52.88	78	51.39	128	49.12	178	41.50	228	51.16	278	27.80	328	37.80
29	50.59	79	51.39	129	49.19	179	48.49	229	52.03	279	30.51	329	39.05
30	50.17	80	51.39	130	49.16	180	49.23	230	47.98	280	30.51	330	39.62
31	51.08	81	51.30	131	49.10	181	49.24	231	50.38	281	31.50	331	44.30
32	51.49	82	51.20	132	46.82	182	52.03	232	51.14	282	31.50	332	49.86
33	49.12	83	51.12	133	49.47	183	43.21	233	45.01	283	43.16	333	46.36
34	50.42	84	51.05	134	48.47	184	45.61	234	48.98	284	43.16	334	47.10
35	49.54	85	50.95	135	47.86	185	42.93	235	52.44	285	36.46	335	50.60
36	49.54	86	50.99	136	48.86	186	41.13	236	46.51	286	37.16	336	51.48
37	51.15	87	51.07	137	46.24	187	39.92	237	45.22	287	50.38	337	52.27
38	43.53	88	51.00	138	43.50	188	37.72	238	45.14	288	52.86	338	48.61
39	43.63	89	51.03	139	45.86	189	37.22	239	45.27	289	53.16	339	49.01
40	44.51	90	51.12	140	49.02	190	36.24	240	47.57	290	53.14	340	41.57
41	45.01	91	51.30	141	47.30	191	35.25	241	49.13	291	53.14	341	50.51
42	49.68	92	52.09	142	44.22	192	34.75	242	48.49	292	51.12		
43	49.68	93	52.09	143	44.09	193	32.97	243	45.58	293	43.10		
44	47.44	94	51.99	144	43.14	194	32.27	244	52.42	294	43.10		
45	46.63	95	51.43	145	42.62	195	32.29	245	52.42	295	49.60		
46	47.73	96	51.36	146	44.07	196	30.49	246	38.41	296	49.52		
47	48.43	97	50.62	147	45.05	197	30.50	247	41.00	297	49.10		
48	45.42	98	49.18	148	50.55	198	49.49	248	41.50	298	48.36		
49	39.43	99	49.35	149	50.95	199	51.13	249	41.50	299	50.36		
50	37.73	100	49.11	150	52.73	200	49.95	250	43.17	300	49.62		

Max. Head = 53.80 m
Min. Head = 27.80 m
Mean Head = 46.85 m

Table 4. Commercially available pipe sizes and cost per meter

Diameter (m)	Cost (L.E.)/m	Material
0.30	150	u. P.V.C.
0.35	250	
0.40	320	
0.45	400	
0.50	500	
0.60	625	
0.80	1500	Ductile Iron
0.90	2000	
1.00	2600	
1.20	3300	
1.40	4100	

Table 5. Micro-genetic algorithm parameters

Parameter	Value
GA Type	Binary
Population Size	12
Crossover	Uniform
Probability of Crossover	0.5
No. of Generations	1000
Initial Random Number Seed for the GA run	-100
No. of Possibilities per Parameter	32

Table 6. Results of optimized network for H_{min} = 27 m (Nodes pressure heads)

Node ID	Head (m)	Node ID	Head (m)	Node ID	Head (m)	Node ID	Head (m)	Node ID	Head (m)	Node ID	Head (m)	Node ID	Head (m)
1	47.84	51	36.60	101	49.77	151	50.29	201	49.51	251	47.34	301	43.08
2	47.69	52	41.63	102	49.97	152	49.54	202	48.97	252	50.41	302	43.08
3	47.24	53	46.99	103	49.82	153	51.94	203	48.76	253	50.41	303	50.90
4	47.19	54	51.27	104	50.34	154	51.69	204	48.74	254	50.41	304	50.90
5	44.95	55	51.26	105	50.08	155	48.60	205	50.83	255	48.98	305	50.79
6	42.66	56	51.04	106	50.43	156	51.48	206	50.83	256	37.56	306	45.86
7	42.30	57	51.18	107	50.41	157	52.26	207	50.79	257	38.86	307	45.86
8	41.13	58	51.46	108	50.79	158	51.46	208	49.75	258	41.13	308	45.86
9	38.99	59	51.69	109	51.29	159	52.90	209	49.45	259	48.32	309	51.70
10	37.56	60	51.88	110	41.10	160	51.75	210	52.34	260	48.45	310	49.39
11	37.55	61	50.79	111	43.80	161	49.75	211	52.34	261	48.16	311	49.59
12	37.35	62	51.25	112	49.56	162	51.45	212	44.06	262	47.22	312	49.89
13	36.24	63	51.25	113	50.36	163	51.45	213	48.73	263	27.95	313	51.87
14	34.24	64	50.37	114	49.40	164	51.45	214	41.13	264	48.30	314	51.87
15	33.62	65	50.37	115	49.41	165	51.75	215	43.08	265	48.40	315	52.06
16	32.00	66	50.27	116	48.91	166	51.74	216	43.88	266	48.40	316	52.07
17	32.00	67	50.27	117	51.07	167	47.01	217	43.57	267	48.40	317	47.53
18	28.28	68	50.17	118	51.07	168	51.45	218	45.88	268	48.40	318	44.59
19	27.92	69	50.17	119	51.04	169	51.75	219	40.06	269	48.33	319	42.29
20	27.43	70	50.08	120	51.02	170	51.95	220	45.83	270	48.68	320	37.01
21	29.74	71	50.08	121	50.92	171	51.95	221	50.71	271	48.56	321	34.99
22	28.12	72	49.99	122	50.82	172	53.25	222	51.25	272	49.02	322	52.15
23	33.01	73	49.89	123	50.71	173	38.44	223	47.99	273	47.25	323	51.76
24	33.06	74	49.89	124	48.86	174	38.04	224	49.19	274	44.06	324	48.11
25	41.08	75	49.89	125	47.99	175	39.62	225	49.73	275	50.83	325	46.65
26	43.08	76	49.79	126	46.39	176	40.61	226	49.75	276	27.74	326	49.36
27	48.29	77	49.80	127	44.96	177	44.06	227	49.81	277	27.24	327	49.60
28	50.79	78	50.81	128	48.74	178	40.53	228	50.17	278	27.04	328	35.64
29	49.41	79	50.81	129	48.81	179	47.51	229	51.25	279	29.74	329	36.93
30	48.92	80	50.81	130	48.80	180	48.14	230	48.46	280	29.74	330	37.53
31	50.41	81	50.71	131	48.62	181	48.14	231	48.89	281	30.74	331	42.08
32	50.85	82	50.64	132	47.67	182	51.27	232	49.11	282	30.74	332	48.35
33	48.74	83	50.54	133	50.42	183	41.85	233	44.32	283	41.63	333	44.85
34	50.79	84	50.44	134	49.49	184	44.44	234	47.71	284	41.63	334	45.10
35	49.58	85	50.01	135	48.89	185	41.35	235	51.88	285	34.93	335	48.60
36	49.59	86	50.01	136	49.88	186	39.55	236	45.89	286	35.63	336	50.56
37	50.87	87	50.00	137	47.37	187	38.35	237	44.96	287	48.29	337	51.71
38	43.09	88	49.90	138	45.41	188	36.22	238	44.94	288	50.79	338	47.88
39	43.09	89	49.90	139	47.25	189	35.72	239	46.62	289	51.29	339	48.44
40	43.89	90	49.91	140	49.93	190	35.49	240	47.01	290	51.27	340	41.45
41	44.03	91	50.36	141	47.47	191	34.52	241	48.66	291	51.14	341	51.67
42	48.30	92	51.28	142	44.24	192	34.03	242	49.49	292	49.16		
43	48.29	93	51.27	143	44.12	193	32.23	243	47.35	293	41.10		
44	45.86	94	51.17	144	43.14	194	31.54	244	51.61	294	41.10		
45	45.02	95	50.78	145	42.63	195	31.54	245	51.61	295	47.60		
46	46.01	96	50.77	146	43.67	196	29.74	246	37.89	296	47.51		
47	46.63	97	50.67	147	44.64	197	29.75	247	40.22	297	47.10		
48	43.30	98	49.50	148	49.32	198	48.21	248	40.58	298	46.85		
49	37.27	99	49.79	149	49.71	199	50.54	249	40.58	299	48.26		
50	35.56	100	49.92	150	51.95	200	49.64	250	41.85	300	47.41		

Max. Head = 53.25 m
Min. Head = 27.04 m
Mean Head = 46.15 m

Table 7. Results of optimized network for H_{min} = 25 m (Nodes pressure heads)

Node ID	Head (m)	Node ID	Head (m)	Node ID	Head (m)	Node ID	Head (m)	Node ID	Head (m)	Node ID	Head (m)	Node ID	Head (m)
1	47.81	51	34.70	101	49.7	151	50.43	201	48.98	251	45.47	301	40.59
2	47.75	52	39.78	102	47.89	152	47.82	202	48.91	252	49.18	302	40.60
3	47.73	53	45.58	103	46.79	153	51.95	203	48.44	253	49.18	303	48.36
4	47.52	54	51.24	104	47.36	154	51.89	204	48.42	254	49.15	304	48.35
5	44.27	55	51.21	105	47.35	155	48.79	205	51.49	255	48.86	305	48.25
6	42.15	56	51.19	106	47.95	156	51.13	206	51.49	256	35.60	306	43.35
7	41.84	57	51.09	107	47.93	157	51.86	207	51.27	257	36.77	307	43.35
8	40.37	58	51.54	108	48.32	158	51.02	208	50.21	258	40.39	308	43.35
9	38.08	59	51.83	109	48.75	159	52.31	209	49.73	259	48.89	309	51.96
10	35.60	60	52.02	110	38.69	160	51.62	210	52.59	260	48.66	310	48.87
11	35.60	61	50.93	111	42.41	161	49.72	211	52.58	261	48.39	311	49.07
12	35.40	62	51.42	112	48.23	162	51.43	212	41.97	262	47.52	312	49.37
13	34.20	63	51.40	113	49.03	163	51.44	213	48.34	263	25.95	313	51.76
14	32.18	64	50.89	114	47.78	164	51.44	214	40.36	264	48.34	314	51.76
15	31.58	65	50.90	115	47.79	165	51.74	215	41.79	265	48.24	315	51.96
16	29.96	66	50.97	116	47.67	166	51.74	216	42.55	266	48.24	316	51.96
17	29.96	67	50.97	117	51.14	167	47.02	217	42.52	267	48.24	317	47.02
18	26.43	68	50.87	118	51.14	168	51.44	218	44.55	268	48.20	318	43.20
19	25.93	69	50.87	119	51.14	169	51.74	219	37.97	269	48.20	319	41.84
20	25.45	70	50.89	120	51.14	170	51.94	220	43.34	270	48.57	320	35.16
21	27.92	71	50.91	121	51.04	171	51.94	221	50.84	271	48.54	321	33.10
22	25.74	72	50.81	122	50.94	172	53.24	222	51.42	272	48.53	322	52.03
23	31.02	73	50.72	123	50.84	173	36.88	223	46.48	273	47.10	323	51.63
24	30.76	74	50.73	124	48.84	174	36.48	224	48.09	274	41.97	324	49.03
25	38.59	75	50.73	125	48.01	175	38.08	225	50.59	275	50.63	325	46.41
26	40.59	76	50.65	126	46.42	176	39.08	226	50.59	276	25.92	326	46.85
27	45.82	77	50.66	127	44.77	177	41.97	227	50.66	277	25.42	327	47.18
28	48.27	78	50.94	128	48.35	178	39.09	228	50.52	278	25.22	328	33.30
29	47.90	79	50.94	129	48.43	179	46.08	229	51.25	279	27.92	329	34.33
30	47.67	80	50.94	130	48.43	180	46.25	230	48.40	280	27.92	330	34.91
31	50.38	81	50.90	131	48.42	181	46.25	231	46.33	281	28.92	331	39.60
32	50.76	82	50.80	132	47.73	182	51.25	232	46.69	282	28.92	332	46.01
33	48.41	83	50.71	133	50.28	183	40.05	233	42.92	283	39.78	333	42.51
34	50.71	84	50.62	134	49.36	184	42.65	234	46.47	284	39.78	334	42.69
35	49.76	85	50.52	135	48.76	185	39.56	235	52.02	285	33.08	335	46.19
36	49.78	86	50.54	136	49.76	186	37.70	236	45.97	286	33.78	336	47.65
37	50.63	87	50.56	137	47.25	187	36.50	237	44.77	287	45.82	337	51.72
38	42.01	88	50.46	138	44.89	188	34.31	238	44.77	288	48.26	338	47.83
39	42.06	89	50.66	139	47.10	189	33.81	239	46.45	289	48.75	339	48.29
40	42.57	90	50.68	140	49.79	190	32.96	240	47.02	290	48.73	340	40.39
41	42.99	91	50.71	141	47.49	191	31.97	241	48.42	291	48.72	341	51.56
42	47.03	92	51.38	142	43.86	192	31.47	242	49.38	292	46.71		
43	46.93	93	51.38	143	43.49	193	30.34	243	47.29	293	38.69		
44	43.35	94	51.28	144	42.50	194	29.65	244	51.56	294	38.69		
45	42.52	95	51.25	145	41.22	195	29.71	245	51.57	295	45.19		
46	43.58	96	51.25	146	42.62	196	27.92	246	36.00	296	45.02		
47	43.98	97	51.10	147	43.58	197	27.92	247	38.58	297	44.69		
48	40.96	98	49.42	148	48.06	198	46.97	248	39.08	298	44.51		
49	34.96	99	49.71	149	48.46	199	50.71	249	39.08	299	45.82		
50	33.26	100	49.79	150	51.96	200	49.88	250	40.05	300	44.93		

Max. Head = 53.24 m
Min. Head = 25.22 m
Mean Head = 45.27 m

Table 8. Cost of original network (Pipe diameters and costs)

Pipe ID	D (mm)	Cost (L.E.)	Pipe ID	D (mm)	Cost (L.E.)	Pipe ID	D (mm)	Cost (L.E.)	Pipe ID	D (mm)	Cost (L.E.)
1	300	8550	51	1000	304200	101	600	17500	151	400	116160
2	1200	138600	52	1000	145600	102	600	24375	152	400	238720
3	1200	488400	53	1200	188100	103	600	48750	153	400	107840
4	1200	2247300	54	1200	42900	104	600	56875	154	400	37120
5	1200	1026300	55	1200	2102100	105	600	45625	155	400	232960
6	1200	580800	56	1200	402600	106	600	109375	156	400	203520
7	1200	1333200	57	1200	82500	107	600	128750	157	600	87500
8	1200	69300	58	1200	1108800	108	600	59375	158	600	61875
9	1200	1386000	59	1200	151800	109	600	18125	159	600	512500
10	1200	1303500	60	1200	194700	110	600	98125	160	300	62850
11	1200	39600	61	1200	633600	111	600	46875	161	600	68125
12	1200	115500	62	1200	2574000	112	600	55000	162	600	403750
13	1200	412500	63	1200	1003200	113	400	7360	163	600	37500
14	1200	650100	64	900	48000	114	400	144960	164	600	56875
15	1200	409200	65	500	541500	115	400	4160	165	500	78000
16	1200	851400	66	900	778000	116	400	6720	166	500	95500
17	1200	49500	67	900	1482000	117	400	43200	167	500	222000
18	1200	2267100	68	900	616000	118	400	16640	168	500	241500
19	1200	990000	69	900	746000	119	400	54080	169	300	1350
20	1200	198000	70	900	1140000	120	400	30080	170	300	68850
21	1200	1131900	71	900	296000	121	400	58240	171	300	7950
22	1200	1818300	72	900	1148000	122	400	33600	172	300	60900
23	600	690625	73	600	319375	123	400	31680	173	300	18000
24	1200	2174700	74	900	1932000	124	400	60800	174	300	4950
25	600	348125	75	900	1302000	125	400	24960	175	300	34500
26	900	4870000	76	900	1006000	126	400	21440	176	300	24150
27	600	832500	77	800	1159500	127	400	25600	177	300	14400
28	600	453750	78	800	1015500	128	400	49280	178	300	7350
29	600	230625	79	800	30000	129	400	15680	179	300	7350
30	600	68750	80	800	1125000	130	400	127680	180	300	38850
31	600	18125	81	800	516000	131	400	15680	181	300	15300
32	900	900000	82	600	223750	132	400	55040	182	300	15150
33	900	2294000	83	400	2560	133	400	15360	183	300	24600
34	900	976000	84	400	34880	134	400	35840	184	900	90000
35	900	1008000	85	600	105000	135	400	169920	185	600	8750
36	900	1220000	86	400	21440	136	400	33280	186	600	78125
37	900	64000	87	600	20625	137	400	222400	187	400	8640
38	900	2664000	88	400	117440	138	400	187520	188	400	12800
39	900	3584000	89	400	152000	139	400	54080	189	400	10880
40	900	1892000	90	400	17280	140	400	36160	190	400	95680
41	900	570000	91	400	116480	141	400	297920	191	400	12800
42	900	1090000	92	400	48000	142	400	29120	192	400	92160
43	900	830000	93	400	180800	143	400	192000	193	400	116160
44	1200	656700	94	400	96960	144	400	91200	194	400	26560
45	1000	231400	95	400	171200	145	400	164480	195	400	32960
46	1000	78000	96	400	29760	146	400	14720	196	400	116800
47	1000	592800	97	400	6080	147	400	36800	197	300	29400
48	1000	613600	98	600	291875	148	400	117760	198	300	22500
49	1000	18200	99	600	13125	149	400	137600	199	300	28200
50	1000	1674400	100	600	81250	150	400	95040	200	300	72750

Table 8. (Continued)

Pipe ID	D (mm)	Cost (L.E.)	Pipe ID	D (mm)	Cost (L.E.)	Pipe ID	D (mm)	Cost (L.E.)	Pipe ID	D (mm)	Cost (L.E.)
201	300	43350	251	400	40640	301	400	297280	351	1200	485100
202	300	49350	252	400	31360	302	300	31500	352	1200	726000
203	300	56850	253	400	117440	303	300	2250	353	1200	148500
204	400	263040	254	400	155520	304	300	40950	354	1200	1422300
205	400	220160	255	600	77500	305	300	14850	355	1200	287100
206	400	86720	256	600	133750	306	300	80550	356	1400	73800
207	400	35520	257	600	205000	307	300	95100	357	1200	577500
208	400	26560	258	600	104375	308	300	36900	358	1200	544500
209	300	76800	259	600	93750	309	300	20250	359	1200	29700
210	300	78300	260	600	174375	310	300	69300	360	1200	577500
211	400	22080	261	600	83125	311	300	70350	361	1000	75400
212	400	159360	262	600	43125	312	300	108450	362	1000	1099800
213	400	24000	263	600	185000	313	300	107400	363	600	13125
214	400	101760	264	600	43125	314	300	68400	364	400	30080
215	400	47040	265	600	117500	315	300	68850	365	400	216320
216	400	107520	266	600	90625	316	400	78720	366	300	116850
217	400	48960	267	600	36875	317	400	6080	367	300	2850
218	400	142400	268	300	53100	318	400	80320	368	300	4650
219	400	16960	269	600	113125	319	400	169920	369	300	96450
220	400	32320	270	300	44100	320	400	56000	370	300	20250
221	400	133760	271	300	14850	321	400	171200	371	600	33750
222	400	331840	272	300	33900	322	400	4480	372	600	18750
223	400	205120	273	300	16800	323	400	202880	373	600	107500
224	400	342720	274	300	4050	324	400	232960	374	600	15000
225	400	231040	275	300	3900	325	400	7040	375	600	21250
226	400	103360	276	300	23850	326	400	54080	376	600	76875
227	400	135680	277	300	22200	327	600	102500	377	600	103125
228	400	301760	278	900	1136000	328	300	1500	378	600	8750
229	400	202560	279	900	1304000	329	300	130800	379	600	19375
230	400	154240	280	900	76000	330	300	91050	380	1000	150800
231	400	309760	281	900	854000	331	300	96150	381	1000	91000
232	400	128640	282	300	19650	332	300	50250	382	1000	761800
233	400	8960	283	300	9000	333	300	85050	383	600	30625
234	400	465280	284	300	38400	334	300	3450	384	1000	72800
235	400	35520	285	300	26850	335	300	2850	385	400	132160
236	400	57280	286	400	11200	336	600	311250	386	600	87500
237	300	52350	287	300	4800	337	300	1800	387	600	3125
238	300	74550	288	300	5100	338	300	175350	388	1000	13000
239	400	80000	289	300	67350	339	1200	39600	389	600	3125
240	300	20700	290	300	67500	340	1200	1395900			
241	300	8250	291	300	12150	341	1200	52800			
242	300	83100	292	400	19520	342	1200	8619600			
243	300	42750	293	300	12150	343	1200	181500			
244	600	166250	294	300	9000	344	300	125400			
245	600	215625	295	300	71250	345	300	85650			
246	600	171875	296	300	90000	346	300	26550			
247	600	41875	297	300	35400	347	300	18450			
248	600	173125	298	300	45900	348	300	79800			
249	600	77500	299	300	94650	349	300	52800			
250	400	46720	300	400	7360	350	1200	283800			

Total Cost

116,164,195 L.E.

Table 9. Results of optimized network for H_{min} = 27 m (Pipe diameters and costs)

Pipe ID	D (mm)	Cost (L.E.)	Pipe ID	D (mm)	Cost (L.E.)	Pipe ID	D (mm)	Cost (L.E.)	Pipe ID	D (mm)	Cost (L.E.)
1	800	85500	51	800	175500	101	800	42000	151	600	226875
2	450	16800	52	400	17920	102	450	15600	152	450	298400
3	1000	384800	53	900	114000	103	600	48750	153	450	134800
4	1000	1770600	54	900	26000	104	350	22750	154	800	174000
5	800	466500	55	800	955500	105	900	146000	155	450	291200
6	1000	457600	56	600	76250	106	800	262500	156	600	397500
7	400	129280	57	900	50000	107	900	412000	157	500	70000
8	1000	54600	58	800	504000	108	800	142500	158	600	61875
9	900	840000	59	800	69000	109	800	43500	159	450	328000
10	1000	1027000	60	300	8850	110	450	62800	160	800	628500
11	600	7500	61	600	120000	111	350	18750	161	600	68125
12	900	70000	62	500	390000	112	800	132000	162	500	323000
13	800	187500	63	500	152000	113	400	7360	163	600	37500
14	1000	512200	64	600	15000	114	500	226500	164	1000	236600
15	600	77500	65	400	346560	115	800	19500	165	800	234000
16	800	387000	66	450	155600	116	800	31500	166	500	95500
17	600	9375	67	800	1111500	117	800	202500	167	500	222000
18	450	274800	68	600	192500	118	350	13000	168	450	193200
19	350	75000	69	800	559500	119	800	253500	169	900	18000
20	600	37500	70	500	285000	120	800	141000	170	1000	1193400
21	400	109760	71	400	47360	121	1000	473200	171	1000	137800
22	500	275500	72	400	183680	122	350	26250	172	450	162400
23	900	2210000	73	800	766500	123	600	61875	173	450	48000
24	400	210880	74	400	309120	124	600	118750	174	400	10560
25	800	835500	75	600	406875	125	800	117000	175	450	92000
26	300	365250	76	600	314375	126	500	33500	176	800	241500
27	350	333000	77	450	309200	127	800	120000	177	600	60000
28	600	453750	78	400	216640	128	400	49280	178	300	7350
29	450	147600	79	600	12500	129	800	73500	179	600	30625
30	800	165000	80	450	300000	130	400	127680	180	600	161875
31	500	14500	81	450	137600	131	900	98000	181	800	153000
32	500	225000	82	600	223750	132	600	107500	182	1000	262600
33	450	458800	83	900	16000	133	800	72000	183	350	41000
34	600	305000	84	800	163500	134	800	168000	184	800	67500
35	500	252000	85	450	67200	135	600	331875	185	1000	36400
36	600	381250	86	350	16750	136	800	156000	186	800	187500
37	1000	83200	87	600	20625	137	800	1042500	187	800	40500
38	500	666000	88	1000	954200	138	600	366250	188	400	12800
39	450	716800	89	800	712500	139	900	338000	189	500	17000
40	800	1419000	90	600	33750	140	600	70625	190	800	448500
41	600	178125	91	800	546000	141	600	581875	191	800	60000
42	350	136250	92	800	225000	142	450	36400	192	600	180000
43	800	622500	93	400	180800	143	800	900000	193	800	544500
44	600	124375	94	450	121200	144	800	427500	194	900	166000
45	600	55625	95	600	334375	145	800	771000	195	800	154500
46	400	9600	96	800	139500	146	350	11500	196	600	228125
47	1000	592800	97	900	38000	147	350	28750	197	450	78400
48	600	147500	98	400	149440	148	900	736000	198	1000	390000
49	800	10500	99	400	6720	149	1000	1118000	199	800	282000
50	800	966000	100	600	81250	150	500	148500	200	900	970000

Table 9. (Continued)

Pipe ID	D (mm)	Cost (L.E.)	Pipe ID	D (mm)	Cost (L.E.)	Pipe ID	D (mm)	Cost (L.E.)	Pipe ID	D (mm)	Cost (L.E.)
201	800	433500	251	900	254000	301	400	297280	351	800	220500
202	600	205625	252	400	31360	302	350	52500	352	600	137500
203	600	236875	253	600	229375	303	900	30000	353	800	67500
204	450	328800	254	350	121500	304	600	170625	354	600	269375
205	600	430000	255	450	49600	305	1000	257400	355	800	130500
206	450	108400	256	1000	556400	306	800	805500	356	500	9000
207	600	69375	257	800	492000	307	600	396250	357	600	109375
208	1000	215800	258	300	25050	308	1000	639600	358	600	103125
209	800	768000	259	500	75000	309	600	84375	359	400	2880
210	400	167040	260	300	41850	310	800	693000	360	800	262500
211	500	34500	261	500	66500	311	800	703500	361	1000	75400
212	600	311250	262	600	43125	312	900	1446000	362	350	105750
213	800	112500	263	1000	769600	313	800	1074000	363	500	10500
214	800	477000	264	600	43125	314	900	912000	364	300	14100
215	900	294000	265	1000	488800	315	400	146880	365	350	169000
216	500	168000	266	1000	377000	316	450	98400	366	500	389500
217	800	229500	267	600	36875	317	900	38000	367	600	11875
218	900	890000	268	900	708000	318	400	80320	368	400	9920
219	500	26500	269	600	113125	319	450	212400	369	800	964500
220	300	15150	270	450	117600	320	600	109375	370	1000	351000
221	600	261250	271	800	148500	321	450	214000	371	800	81000
222	800	1555500	272	1000	587600	322	600	8750	372	350	7500
223	1000	1666600	273	450	44800	323	400	202880	373	600	107500
224	600	669375	274	1000	70200	324	600	455000	374	400	7680
225	350	180500	275	900	52000	325	450	8800	375	900	68000
226	800	484500	276	900	318000	326	900	338000	376	800	184500
227	600	265000	277	600	92500	327	800	246000	377	500	82500
228	350	235750	278	600	355000	328	900	20000	378	800	21000
229	450	253200	279	900	1304000	329	600	545000	379	800	46500
230	600	301250	280	800	57000	330	1000	1578200	380	900	116000
231	500	484000	281	800	640500	331	600	400625	381	600	21875
232	400	128640	282	800	196500	332	600	209375	382	350	73250
233	800	42000	283	900	120000	333	600	354375	383	1000	127400
234	800	2181000	284	600	160000	334	800	34500	384	400	8960
235	800	166500	285	450	71600	335	800	28500	385	350	103250
236	300	26850	286	350	8750	336	350	124500	386	900	280000
237	300	52350	287	900	64000	337	450	4800	387	600	3125
238	500	248500	288	900	68000	338	500	584500	388	1000	13000
239	1000	650000	289	400	143680	339	800	18000	389	300	750
240	1000	358800	290	800	675000	340	1000	1099800			
241	600	34375	291	350	20250	341	350	4000			
242	300	83100	292	1000	158600	342	600	1632500			
243	1000	741000	293	900	162000	343	500	27500			
244	600	166250	294	900	120000	344	800	1254000			
245	450	138000	295	900	950000	345	450	228400			
246	500	137500	296	600	375000	346	600	110625			
247	900	134000	297	600	147500	347	300	18450			
248	800	415500	298	500	153000	348	1000	1383200			
249	600	77500	299	600	394375	349	400	112640			
250	450	58400	300	600	14375	350	600	53750			

Total Cost

107,508,725 L.E.

Table 10. Results of optimized network for H_{min} = 25 m (Pipe diameters and costs)

Pipe ID	D (mm)	Cost (L.E.)	Pipe ID	D (mm)	Cost (L.E.)	Pipe ID	D (mm)	Cost (L.E.)	Pipe ID	D (mm)	Cost (L.E.)
1	1000	148200	51	450	46800	101	1000	72800	151	350	90750
2	1000	109200	52	1000	145600	102	800	58500	152	800	1119000
3	800	222000	53	1000	148200	103	1000	202800	153	600	210625
4	350	170250	54	1000	33800	104	300	13650	154	350	29000
5	450	124400	55	600	398125	105	400	23360	155	600	455000
6	900	352000	56	1000	317200	106	800	262500	156	600	397500
7	450	161600	57	450	10000	107	600	128750	157	450	56000
8	500	10500	58	1000	873600	108	800	142500	158	800	148500
9	500	210000	59	800	69000	109	1000	75400	159	500	410000
10	350	98750	60	800	88500	110	500	78500	160	600	261875
11	800	18000	61	1000	499200	111	450	30000	161	900	218000
12	900	70000	62	600	487500	112	800	132000	162	600	403750
13	450	50000	63	600	190000	113	1000	59800	163	500	30000
14	800	295500	64	350	6000	114	600	283125	164	350	22750
15	900	248000	65	300	162450	115	450	5200	165	1000	405600
16	800	387000	66	500	194500	116	1000	54600	166	800	286500
17	800	22500	67	350	185250	117	400	43200	167	600	277500
18	800	1030500	68	800	462000	118	1000	135200	168	350	120750
19	600	187500	69	600	233125	119	800	253500	169	450	3600
20	300	9000	70	600	356250	120	800	141000	170	350	114750
21	600	214375	71	300	22200	121	800	273000	171	800	79500
22	350	137750	72	800	861000	122	900	210000	172	500	203000
23	400	353600	73	450	204400	123	500	49500	173	450	48000
24	800	988500	74	400	309120	124	600	118750	174	450	13200
25	600	348125	75	600	406875	125	800	117000	175	800	345000
26	350	608750	76	400	160960	126	300	10050	176	600	100625
27	600	832500	77	500	386500	127	800	120000	177	600	60000
28	500	363000	78	350	169250	128	800	231000	178	450	19600
29	400	118080	79	800	30000	129	800	73500	179	900	98000
30	1000	286000	80	400	240000	130	600	249375	180	450	103600
31	500	14500	81	350	86000	131	900	98000	181	800	153000
32	450	180000	82	400	114560	132	350	43000	182	400	32320
33	400	367040	83	800	12000	133	1000	124800	183	900	328000
34	400	156160	84	800	163500	134	600	70000	184	600	28125
35	800	756000	85	800	252000	135	500	265500	185	1000	36400
36	350	152500	86	800	100500	136	800	156000	186	900	250000
37	900	64000	87	800	49500	137	600	434375	187	900	54000
38	400	426240	88	500	183500	138	400	187520	188	800	60000
39	400	573440	89	800	712500	139	800	253500	189	900	68000
40	600	591250	90	800	81000	140	900	226000	190	800	448500
41	400	91200	91	800	546000	141	500	465500	191	800	60000
42	600	340625	92	600	93750	142	450	36400	192	450	115200
43	900	830000	93	350	141250	143	350	150000	193	800	544500
44	1000	517400	94	1000	787800	144	350	71250	194	350	20750
45	600	55625	95	600	334375	145	900	1028000	195	450	41200
46	800	45000	96	1000	241800	146	800	69000	196	600	228125
47	800	342000	97	350	4750	147	350	28750	197	800	294000
48	500	118000	98	600	291875	148	800	552000	198	800	225000
49	600	4375	99	450	8400	149	600	268750	199	450	75200
50	600	402500	100	300	19500	150	600	185625	200	450	194000

Table 10. (Continued)

Pipe ID	D (mm)	Cost (L.E.)	Pipe ID	D (mm)	Cost (L.E.)	Pipe ID	D (mm)	Cost (L.E.)	Pipe ID	D (mm)	Cost (L.E.)
201	900	578000	251	1000	330200	301	600	580625	351	900	294000
202	600	205625	252	450	39200	302	300	31500	352	800	330000
203	600	236875	253	800	550500	303	600	9375	353	350	11250
204	500	411000	254	350	121500	304	600	170625	354	600	269375
205	800	1032000	255	600	77500	305	500	49500	355	500	43500
206	400	86720	256	350	53500	306	600	335625	356	350	4500
207	800	166500	257	900	656000	307	800	951000	357	1000	455000
208	600	51875	258	400	53440	308	800	369000	358	1000	429000
209	600	320000	259	600	93750	309	800	202500	359	600	5625
210	400	167040	260	400	89280	310	450	184800	360	800	262500
211	450	27600	261	600	83125	311	350	117250	361	600	18125
212	600	311250	262	1000	179400	312	400	231360	362	450	169200
213	500	37500	263	300	44400	313	800	1074000	363	800	31500
214	900	636000	264	500	34500	314	600	285000	364	400	30080
215	450	58800	265	450	75200	315	800	688500	365	350	169000
216	900	672000	266	600	90625	316	800	369000	366	300	116850
217	900	306000	267	800	88500	317	1000	49400	367	600	11875
218	1000	1157000	268	1000	920400	318	350	62750	368	900	62000
219	600	33125	269	900	362000	319	600	331875	369	800	964500
220	1000	262600	270	400	94080	320	600	109375	370	1000	351000
221	300	62700	271	350	24750	321	350	133750	371	800	81000
222	500	518500	272	450	90400	322	350	3500	372	600	18750
223	500	320500	273	600	70000	323	600	396250	373	1000	447200
224	400	342720	274	800	40500	324	600	455000	374	900	48000
225	450	288800	275	800	39000	325	900	44000	375	600	21250
226	800	484500	276	400	50880	326	600	105625	376	1000	319800
227	600	265000	277	800	222000	327	800	246000	377	1000	429000
228	600	589375	278	350	142000	328	800	15000	378	450	5600
229	500	316500	279	900	1304000	329	300	130800	379	800	46500
230	350	120500	280	1000	98800	330	600	379375	380	1000	150800
231	350	242000	281	600	266875	331	300	96150	381	800	52500
232	600	251250	282	900	262000	332	600	209375	382	600	183125
233	900	56000	283	1000	156000	333	300	85050	383	900	98000
234	350	363500	284	500	128000	334	600	14375	384	600	17500
235	900	222000	285	800	268500	335	800	28500	385	450	165200
236	500	89500	286	450	14000	336	400	159360	386	800	210000
237	300	52350	287	800	48000	337	800	18000	387	600	3125
238	300	74550	288	500	17000	338	800	1753500	388	900	10000
239	600	156250	289	450	179600	339	900	24000	389	400	1600
240	300	20700	290	800	675000	340	600	264375			
241	800	82500	291	350	20250	341	800	24000			
242	450	221600	292	350	15250	342	450	1044800			
243	1000	741000	293	1000	210600	343	600	34375			
244	1000	691600	294	900	120000	344	400	267520			
245	450	138000	295	900	950000	345	400	182720			
246	600	171875	296	300	90000	346	500	88500			
247	400	21440	297	400	75520	347	1000	319800			
248	600	173125	298	350	76500	348	400	170240			
249	600	77500	299	350	157750	349	800	528000			
250	900	292000	300	600	14375	350	800	129000			

Total Cost

87,838,050 L.E.