RELIABILITY-BASED OPTIMAL DESIGN FOR WATER DISTRIBUTION NETWORKS OF EL-MOSTAKBAL CITY, EGYPT (CASE STUDY)

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ABSTRACT

An approach to the Reliability-based optimization of water distribution systems is presented and applied to a case study. The approach links a genetic algorithm (GA) as the optimization tool, the Newton method as the hydraulic simulation solver with the chance constraint combined with the Monte Carlo simulation to estimate network capacity reliability. The source of uncertainty analyzed is the future nodal external demands which are assumed to be random normally distributed variables with given mean and standard deviations. 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 Reliability based-optimization problems.

INTRODUCTION

The complexity of (WDS) makes it difficult to obtain least-cost design systems considering other constraints such as reliability. A completely satisfactory water distribution system (WDS) should supply water in the required quantities at desired residual heads throughout its design period. How well a WDS can satisfy this goal can be determined from water supply reliability. However, evolution of WDS reliability is extremely complex because reliability depends on a large number of parameters, some of which are quality and quantity of water available at source; failure rates of supply pumps; power outages; flow capacity of transmission mains; roughness characteristics influencing the flow capacity of the various links of the distribution network; pipe breaks and valve failures; variation in daily, weekly, and seasonal demands; as well as demand growth over the years.

There is currently no universally accepted definition of reliability of WDS. However, reliability is usually defined as the probability that a system performs its mission within specified limits for a given period of time in a specified environment. For a large system, it is difficult to analytically compute reliability in a mathematical form. Accurate calculation of a mathematical reliability requires knowledge of the exact reliability of the basic components of WDS and the impact on system performance caused by possible failures in the components.

Reliability models to compute system reliability have been developed since 1980s. These models allow a modeler to determine the reliability of a system and account for such factors as the probability and duration of pipe and pump failure, the uncertainty in demands, and the variability in the deterioration of pipes. Some of these reliability models which have been commonly used in literature are cut-set method, Monte Carlo simulation, chance constraints, significance index method, and frequency duration analysis.

Su et al. (1987) developed a reliability based optimization model that determined the least-cost design of water distribution system subject to continuity, conservation of energy, nodal head bounds, and reliability constraints. The steady-state simulation model (KYPIPE) by Wood (1980), was used to implicitly solve the continuity and energy constraints and was used in the reliability model to define minimum cut sets. The reliability model, which was based on a minimum cut-set method, determined the values of system and nodal reliability. The optimization model was based on a generalized reduced-gradient method (GRG2) by Lasdon and Waren (1979, 1984) which solved an optimization problem with a nonlinear objective function and nonlinear constraints.

Lansey et al. (1989) were among the first to present a chance constraint model for the least-cost design of water distribution systems. The uncertainty in the required demand, pressure heads, and pipe roughness coefficient were explicitly accounted for in the model. The generalized reduced gradient (GRG2) technique was used to solve the nonlinear programming single-objective chance constrained minimization model. The methodology assumed nodal heads to be random, normally distributed variables with given mean and standard deviation. Since head values are functions of many parameters, some of which could be uncertain, they should be treated as a response function rather than independent stochastic variables. Also, the generalized reduced gradient method (GRG2) is a local search method which could be easily trapped in the local minimum (Savic and Walters, (1997)).

Bao et al. (1990) presented a Monte Carlo simulation model that estimated the nodal and system hydraulic reliabilities of water distribution systems that accounted for uncertainties. The model consisted of three major components; random number generation, hydraulic network simulation, and computation of reliability. The model could be applied in the analysis of existing water distribution systems or in the design of new or expanding systems.

Goulter et al. (1990) incorporated reliability concept into optimal design models for pipe network systems. The measure of the system reliability was used as a criterion to improve the system distribution. The chance constraints were the probability of pipe failure for each link and the probability of demand exceeding design values at each node in the network.

Xu and Goulter (1998) developed an approach in which a probabilistic hydraulic model was used for the first time in the WDS design optimization. In the hydraulic model uncertainties were quantified using the analytical technique known as the first order second moment (FOSM) reliability method. This method assumes that a relationship between uncertain and response variables is very close to linear, which is often not the case for water distribution systems.

Xu and Goulter (1999) used the first order reliability-method-based (FORM) algorithm that computed the capacity reliability of water distribution networks. The sensitivity-analysis-based technique was used to derive the first order derivatives. The (FORM) algorithm required repetitive calculation of the first order derivatives and matrix inversion which was very computationally demanding even in small networks and may lead to a number of numerical problems.

Rayan et al. (2003) used the sequential unconstrained minimization technique (SUMT) to solve the optimal design of El-Mostkbal city which is an extension of Ismailia city (Egypt) combined with the Newton-Raphson method for the hydraulic analysis of the network.

Xu et al. (2003) introduced two algorithms for determining the capacity reliability of ageing water distribution systems considering uncertainties in nodal demands and pipe capacity. The mean value first order second moment (MVFOSM) method and the first order reliability model (FORM) were used as a probabilistic hydraulic models for reliability assessment. Both models provided reasonably accurate estimates of capacity reliability in cases that the uncertainty in the random variables was small. In cases involving large variability in the nodal demands and pipe roughness, FORM performed much better.

Savic (2005) through the application of various approaches for optimal design and rehabilitation of urban water systems under the condition of inherent uncertainty; namely, the use of standard safety margins (redundant design methodology) and the stochastic robustness/risk evaluation models with both single-objective and multiobjective optimization methods on the New York water supply tunnels problem and the Anytown network clearly demonstrated that neglecting uncertainty in the design process might lead to serious under-design of water distribution networks.

Tolson et al. (2004) used GAs to solve the optimal water distribution system design problems along with the first order reliability method (FORM) method to quantify uncertainties. They demonstrated that the Monte Carlo Simulation critical node capacity reliability approximation can significantly underestimate the true Monte

Carlo Simulation network capacity reliability. Therefore, they developed a more accurate FORM approximation to network capacity reliability that considers failure events at the two most critical nodes in the network.

Abdel-Gawad (2005) presented an approach for water network optimization under a specific level of uncertainty in demand, pressure heads, and pipe roughness coefficient. The approach depends on using the chance constrained model to convert uncertainties in the design parameters to form a deterministic formulation of the problem. The GA method was adopted to solve the nonlinear optimization problem settled in a deterministic form. A hypothetical example was solved and compared with previous solution from the gradient approach [3]. From the results it can be found that the construction cost of the pipe system increases, with an increasing rate, as the reliability requirement increases. Uncertainties in demand nodes or roughness coefficients have a more pronounced effect on final construction cost, than the effect of the required minimum pressure heads.

Babayan et al. (2005) presented a methodology for the least cost design of water distribution networks considering uncertainty in node demand. The uncertain demand was assumed to follow both truncated Gaussian (normal) probability density function (PDF) and uniform probability density function. The genetic algorithm was used to solve the equivalent deterministic model for the original stochastic one to find reliable and economic design for the network and the system reliability was then determined using full Mont Carlo simulation with 100,000 sampling points. The model was tested on the New York tunnels and Anytown problems and then compared to available deterministic solutions. The results demonstrated the importance of applying the uncertainty concept in designing water distribution systems.

Babayan et al. (2006) developed two new methods to solve an optimization problem under uncertainty. Uncertainty sources used were both future water consumption and pipe roughness. The stochastic formulation after being replaced by a deterministic one using numerical integration method, while the optimization model was solved using a standard genetic algorithm. The sampling method solved the stochastic problem directly by using the newly developed robust chance constraint genetic algorithm both methods had there own benefits and drawbacks.

Nodal and System Reliability

Bao and Mays (1990) defined nodal reliability R_n as the probability that a given node receives sufficient flow rate at the required pressure head. Theoretically, therefore, the nodal reliability is a joint probability of flow rate and pressure head being satisfied at the given nodes.

They also stated that system reliability is such an index difficult to define because of the dependence of the computed nodal reliabilities. Three heuristic definitions of the system reliability are therefore proposed:

(1) The system reliability R_{sm} could be defined as the minimum nodal reliability in the system

$$R_{sm} = \min(R_{ni}) \qquad i = 1,2, \ldots, I \qquad (4.4)$$

where R_{ni} is the nodal reliability at node *i*; and *I* is the number of demand nodes of interest.

(2) The system reliability could be the arithmetic mean R_{sa}, which is the mean of all nodal reliabilities.

$$R_{sa} = \frac{\sum_{i=1}^{I} R_{ni}}{I} \qquad (4.5)$$

(3) The system reliability is defined as a weighted average R_{sw}, which is a weighted mean of all nodal reliabilities weighted by the water supply at the node.

$$R_{sw} = \frac{\sum_{i=1}^{I} R_{ni}\, Q_{si}}{\sum_{i=1}^{I} Q_{si}} \qquad (4.6)$$

where Q_{si} is the mean value of water supply at node *i*.

Approaches for Assessment of Network Reliability

Two main approaches are available for assessment of reliability, (Goulter et al., 2000):

- **Analytical approach.** A closed form of solution for the reliability is derived directly from the parameters which define the network demands and the ability of network to meet these demands.
- **Simulation approach.** The network is evaluated using different user defined scenarios or during extended period simulations (Goulter et al., 2000).

4.6.1 Advantages and Disadvantages of the Analytical Approach

(a) Advantages:

1. Considers the complete network rather than samples.
2. Less computational time.

(b) Disadvantages:

1. Requires a simplified description of the water system.
2. Simplistic interpretation of reliability, e.g., connectivity versus hydraulic performance.

4.6.2 Advantages and Disadvantages of the Simulation Approach

(a) Advantages:

1. A number of reliability measures can be calculated.
2. Allows the analysis of a system with complicated interactions.
3. Allows the detailed modeling of the behavior of the system.

(b) Disadvantages:

1. Time consuming in both terms of computer per time per analysis and in terms of time to set up and use such a program.
2. Its runs are hard to optimize and can be hard to generalize beyond a very specific system.

Thus perhaps the best approach to performing a reliability assessment is to use both simulation and analytical methods.

The previous literature review demonstrates that both analytical and simulation methods should be used together. This can be achieved by applying the chance constraint method to take the uncertainty of different pipe network parameters into account, and a Monte Carlo simulation to determine its nodal and system reliabilities more accurately.

The present study of uncertainty-based optimization of water distribution systems and for a specified level of uncertainty aims to search the optimal diameters which minimize the cost and fulfill the pressure constraints at nodes. The uncertainty-based optimization was achieved by the chance constraint formulation which is discussed later. The Monte Carlo simulation is used to find the node and network reliabilities for the optimal diameters of the network.

In the present investigation, (GACCnet)is used to solve the uncertainty based-optimal design of the network The optimization tool is the Genetic Algorithm (GA) which is linked in the present work with the uncertainty formulation. Expressed by the chance constraint method, and Monte Carlo Simulation to estimate the nodal and network reliabilities.

The case study is a real network. It is an extension to an existing distribution network of Ismailia City named El-Mostkbal City.

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).

1- Deterministic Model

The formulation of the optimization model for water distribution system design can be generally written in the following form:[3]

Objective function:

$$\text{Min. Cost} = \text{min. } C_T = \sum_{i,j \in M} f\left(D_{i,j}\right) \tag{1}$$

Model Constraints:

$$\sum_j q_{i,j} = Q_j \qquad j = 1,\dots, J \text{ (nodes)} \tag{2}$$

$$\sum_{i,j \in n} h_{f_n} = 0 \qquad n = 1,\dots, N \text{ (loops)} \tag{3}$$

$$H_j \geq H_{j,\min} \qquad j = 1,\dots, J \text{ (nodes)} \tag{4}$$

$$D_{\min} \leq D_{i,j} \leq D_{\max} \tag{5}$$

The main objective of the model, Eq. (1), is to minimize the construction cost of the water distribution network as a function of the pipe diameter $D_{i,j}$, for the set of possible links, *M*, connecting nodes *i*, *j* in the system. $q_{i,j}$ is the flow rate in the pipe connecting nodes *i*, *j*. h_f is the head loss in the pipe and expressed by the Hazen-Williams formula:

$$h_f = \frac{K}{C_{i,j}^{\ 1.852}} \frac{L_{i,j}\ q_{i,j}^{\ 1.852}}{D_{i,j}^{\ 4.8704}} = H_i - H_j \tag{6}$$

where *K* is a conversion factor which accounts for the system of units used, ($K = 10.6744$ for $q_{i,j}$ in m^3/s and $D_{i,j}$ and $L_{i,j}$ in m), $C_{i,j}$ is the Hazen-Williams roughness coefficient for the pipe connecting nodes *i*, *j*, $L_{i,j}$ is the length of the pipe connecting nodes *i*, *j* , and H_i, H_j are the pressure heads at nodes *i*, *j*. Then, the flow rate in the pipe is calculated as:

$$q_{i,j} = K^{-0.54}\, C_{i,j} \left[\frac{H_i - H_j}{L_{i,j}}\right]^{0.54} D_{i,j}^{\ 2.63} \tag{7}$$

Eq. (2) represents the law of conservation of mass (continuity equation) which states that the summation of the flow rates in the pipes at node *j* must be equal to the external demand, Q_j, at that node. It has to be noticed that the continuity constraint must be satisfied for each node, *j*, in the network.

Eq. (3) in the model constraints simply states that the algebraic summation of the head loss, h_{f_n}, around each loop $n = 1,\dots, N$ must be equal to zero. The lower limit, $H_{j,\min}$, of the pressure head, H_j, at each node, *j*, is accounted for in the model by Eq. (4).

Finally, Eq. (5) defines the constraint on the pipes diameters in the network where $D_{\min}$ and $D_{\max}$ are the minimum and maximum diameters, respectively.

Substitution of the Hazen-Williams formula, Eq. (7) back into Eq. (2) automatically satisfies Eq. (3), and which in turn reduces the deterministic model constraints to equations (4), (5), and (7) in combination with (2).

2- Stochastic (Chance Constraint) Model

The deterministic optimization model described above is transformed into a stochastic (chance constraint) formulation by considering that the future demand, Q_j, is uncertain because of the unknown future conditions of the system and can be considered as an independent random variable.

The chance constraint formulation can now be expressed as Lansey et al. (1989):

Objective function:

$$\text{Minimum Cost} = \min. \sum_{i,j \in M} f\left(D_{i,j}\right) \tag{8}$$

Subject to the constraints:

$$P\left[\sum_j K^{-0.54}.C_{i,j}\left(\frac{H_i - H_j}{L_{i,j}}\right)^{0.54} D_{i,j}^{2.63} \geq Q_j\right] \geq \alpha_j \tag{9}$$

$$H_j \geq H_{j,\min} \tag{10}$$

$$D_{\min} \leq D_{i,j} \leq D_{\max} \tag{11}$$

Eq. (9) is the probability, P ( ), that the node demands are equaled or exceeded with probability level, α_j, The probability level α_j, is defined as the constraint performance reliability which accounts for the effect of uncertainty of the future demand.

3- Deterministic Chance Constraint Model

The chance constraint model is now transformed from a stochastic form into a deterministic one through applying the cumulative probability distribution concept by considering the future demand, to be represented by normal random variables with mean, μ, and standard deviation, σ, as:

$$Q \sim N(\mu_Q, \sigma_Q)$$

Similarly, Eq. (9) is transformed into a deterministic form as follows:

$$P\left[\sum_j K^{-0.54} C_{i,j} \left[\frac{H_i - H_j}{L_{i,j}}\right]^{0.54} D_{i,j}^{2.63} - Q_j \le 0\right] = P\left[W_j \le 0\right] \le 1 - \alpha_j \qquad (12)$$

Where W_j is a normal random variable with mean:

$$\mu_{W_j} = \sum_j K^{-0.54} C_{i,j} \left[\frac{H_i - H_j}{L_{i,j}}\right]^{0.54} D_{i,j}^{2.63} - \mu_{Q_j} \qquad (13)$$

and standard deviation:

$$\sigma_{W_j} = \left\{\left[\sum_j [\ K^{-0.54} . C_{i,j} \left[\frac{H_i - H_j}{L_{i,j}}\right]^{0.54} D_{i,j}^{2.63}\right]^2 + \sigma_{Q_j}^2\right\}^{1/2} \qquad (14)$$

Eq. (12) can be rewritten as:

$$P\left[\frac{W_j - \mu_{W_j}}{\sigma_{W_j}} \le \frac{0 - \mu_{W_j}}{\sigma_{W_j}}\right] \le 1 - \alpha_j \qquad (15)$$

or in a simplified form:

$$\phi\left[\frac{-\mu_{W_j}}{\sigma_{W_j}}\right] \le 1 - \alpha_j \qquad (16)$$

where ϕ is the cumulative distribution function and $\phi[\ ]$ is the standard normal distribution function.

The final deterministic form of the constraint Eq. (12) is now written as:

$$\frac{\mu_{W_j}}{\sigma_{W_j}} \le \phi^{-1}\left(1 - \alpha_j\right) \qquad (17)$$

where μ_{W_j} and σ_{W_j} are determined using Eqs. (13) and (14).

The final deterministic chance constraint model for water distribution networks is given by the objective function Eq. (8) subject to the constraints Eqs. (17) and (11). The model is nonlinear because of the nonlinear objective function Eq. (8) and the non linear constraint Eq. (17) for every node. The other constraint given by Eq. (11) for every pipe is considered to be simple bound. The genetic algorithm (GA) will be used as a technique to solve the deterministic chance constrained model for water distribution networks.

GACC*net* PROGRAM:

GACC*net* program, it is consisted of: Ezzeldin (2007)

1. Genetic algorithm technique to produce the optimal diameters. The GA source code used is similar to that used in Abdel-Gawad (2001).
2. Newton method to analyze the network using The *H*-equations solution method.
3. Chance Constraint for the uncertainties.
4. Monte Carlo technique to compute the reliability of the optimal set of pipe diameters.

CASE STUDY

An actual water network has been selected to apply the developed program for the uncertainty-based 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 data of this network are taken from Herrick (2001) and Rayan et al. (2003). The layout of the network and the index numbers of the nodes and pipes are shown in Figure 1. As the original index numbers are great, the corresponding modified index numbers are shown in Figure 1(b). Similarly, in Table 1, these modified indices are given.

The data for the studied network is shown in Table 2. It includes the new index (ID) for each node and pipe. The extension network has 31 nodes (excluding node 32 which is taken as the supplying node, Fig. 1(b)) and 43 pipes. For the nodes, the elevation and specified demands are given, while for the pipes their lengths and diameters are represented.

(a)

(b)

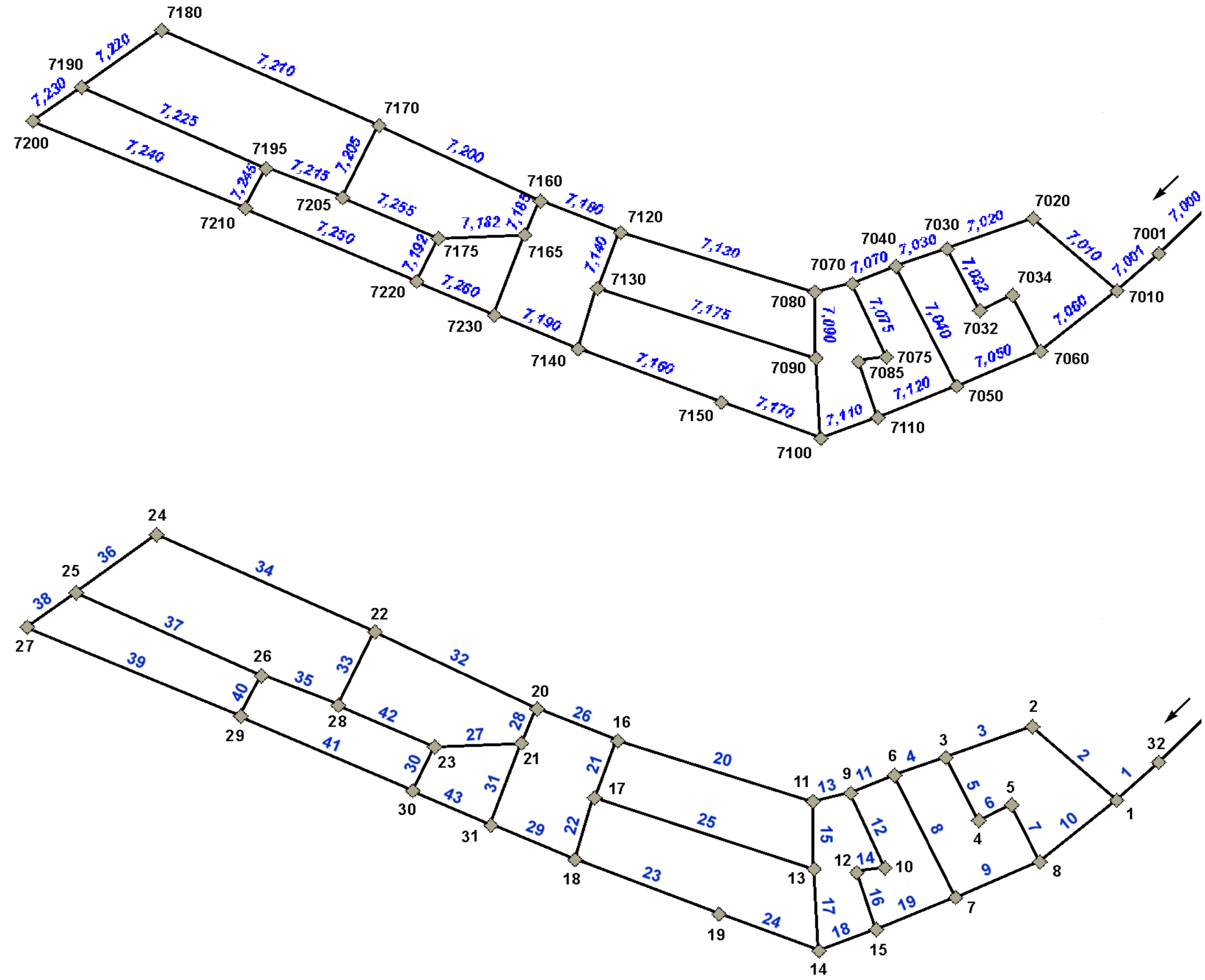

Figure 1. El-Mostakbal City water distribution network (a) Original ID for nodes and pipes, Herrick (2001) (b) Modified ID for nodes and pipes used in this study

Table 1. El-Mostakbal City network

Original Node ID	New Node ID
7001	32
7010	1
7020	2
7030	3
7032	4
7034	5
7040	6
7050	7
7060	8
7070	9
7075	10
7080	11
7085	12
7090	13
7100	14
7110	15
7120	16
7130	17
7140	18
7150	19
7160	20
7165	21
7170	22
7175	23
7180	24
7190	25
7195	26
7200	27
7205	28
7210	29
7220	30
7230	31

Original Pipe ID	Start Node	End Node	New Pipe ID	Start Node	End Node
7001	7001	7010	1	32	1
7010	7010	7020	2	1	2
7020	7020	7030	3	2	3
7030	7030	7040	4	3	6
7032	7030	7032	5	3	4
7034	7032	7034	6	4	5
7036	7034	7060	7	5	8
7040	7040	7050	8	6	7
7050	7050	7060	9	7	8
7060	7060	7010	10	8	1
7070	7040	7070	11	6	9
7075	7070	7075	12	9	10
7080	7070	7080	13	9	11
7085	7075	7085	14	10	12
7090	7080	7090	15	11	13
7095	7085	7110	16	12	15
7100	7090	7100	17	13	14
7110	7100	7110	18	14	15
7120	7110	7050	19	15	7
7130	7080	7120	20	11	16
7140	7120	7130	21	16	17
7150	7130	7140	22	17	18
7160	7140	7150	23	18	19
7170	7150	7100	24	19	14
7175	7090	7130	25	13	17
7180	7120	7160	26	16	20
7182	7165	7175	27	21	23
7185	7160	7165	28	20	21
7190	7140	7230	29	18	31
7192	7175	7220	30	23	30
7195	7165	7230	31	21	31
7200	7160	7170	32	20	22
7205	7170	7205	33	22	28
7210	7170	7180	34	22	24
7215	7205	7195	35	28	26
7220	7180	7190	36	24	25
7225	7195	7190	37	26	25
7230	7190	7200	38	25	27
7240	7200	7210	39	27	29
7245	7195	7210	40	26	29
7250	7210	7220	41	29	30
7255	7175	7205	42	23	28
7260	7220	7230	43	30	31

Table 2. El-Mostakbal City network data (Original design)

(a) Nodes

Node ID	Elevation (m)	Demand (LPS)
1	14.0	24.00
2	14.0	0
3	14.0	19.20
4	14.0	0
5	14.0	0
6	14.0	19.20
7	14.0	20.80
8	14.0	17.60
9	14.0	0
10	14.0	0
11	14.0	24.00
12	14.0	0
13	14.0	0
14	14.0	19.20
15	14.0	0
16	15.0	24.00
17	15.0	19.20
18	15.0	34.09
19	15.0	0
20	15.0	16.00
21	15.5	0
22	15.5	16.00
23	15.5	0
24	15.5	16.00
25	15.5	19.20
26	15.5	0
27	15.5	19.20
28	15.5	0
29	15.5	24.00
30	15.5	0
31	15.5	20.80
32	15.0	0

Total Demand = 352.49 LPS

(b)pipes

Pipe ID	Length (m)	Diameter (mm)
1	100.00	600
2	328.00	300
3	80.00	300
4	152.50	300
5	149.30	150
6	67.00	150
7	184.30	150
8	341.65	150
9	100.00	400
10	288.00	400
11	70.70	300
12	172.00	150
13	127.60	250
14	109.00	150
15	164.60	150
16	104.70	150
17	98.40	150
18	123.50	400
19	155.00	400
20	309.15	250
21	163.40	150
22	134.20	150
23	198.00	300
24	225.50	400
25	357.90	150
26	92.70	200
27	156.50	150
28	84.90	200
29	100.00	300
30	101.00	150
31	226.30	200
32	230.50	200
33	145.80	150
34	370.60	150
35	109.90	150
36	184.00	150
37	257.40	150
38	120.00	150
39	181.90	150
40	114.90	150
41	262.60	200
42	185.00	150
43	217.00	300

The cost values used in the optimization problem are the real costs that are used in the Suez Canal Authority water sector, Herrick (2001). There are 10 commercially available diameters for ductile pipes, Table 3. All pipes are selected from ductile although Rayan et al. (2003) gave other options for pipes less than 6 inches which is unpractical in water distribution networks.

Table 3. Commercially available pipe sizes and cost per meter

Diameter (inches)	Diameter (mm)	Unit Cost (L.E./m)	Pipe Type
6	150	188	Ductile
8	200	255	Ductile
10	250	333	Ductile
12	300	419	Ductile
16	400	570	Ductile
20	500	735	Ductile
24	600	1110	Ductile
30	800	1485	Ductile
40	1000	2505	Ductile
48	1200	3220	Ductile

As mentioned in Rayan et al. (2003), the designer of this network chose 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, Fig. 1(a)) between the two networks is 600 mm diameter with 8692.7 meter long. To solve this drawback, 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). The connection pipe is 800 mm diameter with length about 2463 meters long. According to this, their study showed a decreasing in the total cost of this pipe of LE 5,990,565. It is worth to mention that the original existing design of the extended network costs LE 11,868,999. On the other hand, the total cost of pipes for the existing network without including pipe 7000 is LE 2,220,879.

The resulted new network under investigation has node 32 as a source with a total head of 50.856 m and the total demand for the network is 352.49 LPS. The minimum acceptable pressure head requirements for all nodes of the network are set as 22 meters.

Differences with Previous Studies

The main differences between the present study and the study of Herrick (2001) and

Rayan et al. (2003) are:

1. The present study is uncertainty-based optimization while the study of Herrick (2001) and Rayan et al. (2003) is optimization only.

2. In Herrick (2001) and Rayan et al. (2003), the Sequential Unconstrained Minimization Technique (SUMT) was applied to solve the optimal design of network for the pipe network optimization. The SUMT was first suggested by Carroll (1961) and thoroughly investigated by Fiacco and McCormick (1964). The explanation of the optimization model formulation is given by Djebedjian et al. (2000). In the present study, the genetic algorithms are used for the pipe network optimization.

3. In Herrick (2001) and Rayan et al. (2003), the head loss h_f in the pipe was expressed by the Darcy-Weisbach formula and the friction factor f_i was calculated by the expression proposed by Swamee and Jain (1975).
   In the present study, the Hazen-Williams formula is used. Numerical tests for the frictional losses calculated by Darcy-Weisbach and Hazen-Williams formulae for El-Mostakbal network were done using EPANET 2 and the corresponding approximate Hazen-Williams coefficient was found to be 130 (i.e. smooth pipe). As this value decreases with pipes ageing, the Hazen-Williams roughness coefficient is taken as 100 for all pipes throughout this case study.

Computational Results of Optimization

The first part of the present study is dedicated to find the optimal diameters and the corresponding total cost. For the studied network, it should be mentioned that for 43 pipes and a set of 10 commercial pipes, the total number of designs is 10^{43}. 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 optimal diameters found by GACC*net* program are listed in Table 4. The optimal cost is LE 2,234,046 compared to LE 2,220,879 for the original design.

Table 4. Optimal pipe diameters for El-Mostakbal City network (α = 0.5)

Pipe ID	Diameter (mm)	Pipe ID	Diameter (mm)
1	500	26	250
2	150	27	150
3	150	28	150
4	150	29	300
5	150	30	150
6	150	31	150
7	150	32	250
8	150	33	150
9	500	34	150
10	500	35	200
11	150	36	150
12	150	37	200
13	200	38	150
14	150	39	200
15	200	40	150
16	150	41	250
17	250	42	150
18	400	43	300
19	500		
20	250		
21	150		
22	150		
23	400		
24	400		
25	150		

Although the optimal cost is not less than the original network cost, but the nodal pressure heads requirements are fulfilled. The genetic algorithm parameters used for solving this case study are mentioned in Appendix D. The hydraulic analysis results of the case study network before and after optimization are shown in Table 5 and Fig. 2. For the network before optimization and as seen from Table 5 and Fig. 2, there are some nodes (22 and 24 to 29) with pressure head values less than 22 m, which is the minimum pressure criterion. As expected, the nodal pressure heads in the extended network after optimization is higher than that of the original design. The pressure heads at all nodes of the optimized network are greater than 22 meters which is the minimum acceptable pressure head requirements. Also, the average nodal pressure head in the optimized network is greater than that of the original design due to the well-known fact that decreasing the diameter of a pipe increases the friction losses and consequently decreases the pressure head at the downstream node. It can be concluded that the optimization of the water distribution system of El-Mostakbal City overcomes the drawback of low nodal pressure heads of the original network. For the optimized network, the utilization of optimization technique perhaps results in not minimizing the cost but increasing the pressure heads at all nodes of the network to be greater than the minimum acceptable pressure head.

Table 5. Results of hydraulic analysis of El-Mostakbal City network before and after optimization optimized network

Node ID	Nodal Pressure Head (m)	
	Before Optimization*	After Optimization**
1	36.487	35.960
2	33.086	31.559
3	32.256	30.485
4	32.551	31.768
5	32.684	32.343
6	31.025	29.292
7	32.077	33.350
8	33.048	33.927
9	30.580	28.872
10	30.742	30.565
11	28.411	27.988
12	30.845	31.639
13	28.589	30.401
14	30.083	31.251
15	30.944	32.670
16	24.245	25.207
17	24.320	26.329
18	24.632	27.966
19	28.108	29.034
20	22.952	24.892
21	22.550	24.907
22	**20.012**	23.771
23	22.160	24.899
24	**15.618**	22.106
25	**15.600**	22.391
26	**18.516**	23.397
27	**15.608**	22.521
28	**19.997**	23.679
29	**18.498**	23.492
30	22.571	25.482
31	23.254	26.468
Average Pressure (m)	**26.1951**	**28.020**
Minimum Pressure (m)	**15.600**	**22.106**
Maximum Pressure (m)	**36.487**	**35.960**

* Original design (Table 9.2), ** Optimal design (Table 9.4)

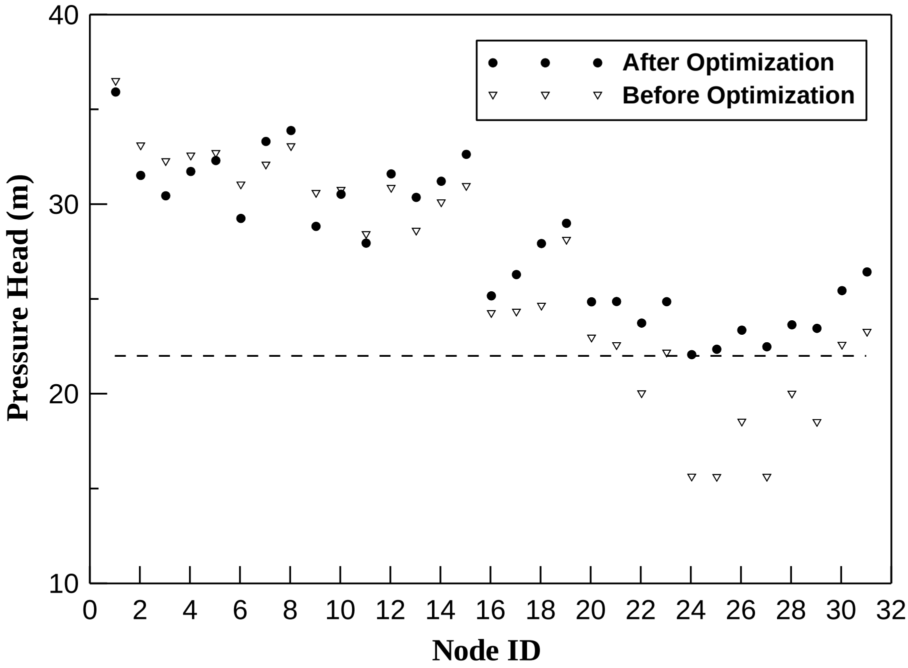

Figure 2. Comparison of nodal pressure heads between El-Mostakbal City original design and optimized network

Computational Results of Uncertainty-Based Optimization

The second part of the present study is dedicated to find the optimal diameters and the corresponding total cost for specified levels of uncertainty. Table 6 lists the optimum design of El-Mostakbal City network under six levels of uncertainty for a coefficient of variation in nodal demands $COV_Q = 10\%$. The nodal pressure heads for these optimal networks are given in Table 7. The results of nodal and system reliabilities from the Monte Carlo simulation associated with these six different levels of uncertainty are given in Table 8.

Table 6. Optimal pipe diameters for El-Mostakbal City network for different network uncertainties at COV_Q = 10%

Pipe ID	Diameter (mm)					
	α = 0.5	α = 0.6	α = 0.7	α = 0.8	α = 0.9	α = 0.99
1	500	500	500	500	500	500
2	150	150	150	500	400	500
3	150	150	200	500	300	500
4	150	150	150	500	300	400
5	150	150	150	150	150	200
6	150	150	150	150	200	150
7	150	150	150	150	150	150
8	150	150	150	150	150	150
9	500	500	500	300	500	300
10	500	500	500	300	500	400
11	150	150	200	500	400	400
12	150	150	150	150	200	150
13	200	200	200	400	300	500
14	150	150	150	150	150	200
15	200	200	300	150	150	150
16	150	150	150	150	150	150
17	250	250	400	150	250	150
18	400	500	500	200	400	300
19	500	500	500	200	400	400
20	250	200	400	400	400	400
21	150	200	150	150	150	150
22	150	150	150	400	150	150
23	400	400	300	150	300	250
24	400	400	300	150	300	250
25	150	150	150	150	150	150
26	250	250	300	400	300	400
27	150	150	150	200	200	250
28	150	150	150	250	150	250
29	300	300	250	150	300	200
30	150	150	150	150	150	200
31	150	150	150	150	150	150
32	250	200	300	300	250	300
33	150	150	200	200	150	250
34	150	200	150	200	200	250
35	200	150	250	400	200	300
36	150	150	150	150	150	150
37	200	200	200	150	150	200
38	150	150	150	150	200	150
39	200	200	200	250	400	150
40	150	150	200	200	150	150
41	250	250	200	200	250	250
42	150	150	150	150	200	250
43	300	300	250	200	200	200
Cost (LE)	**2,234,046**	**2,240,746**	**2,330,245**	**2,380,332**	**2,517,901**	**2,584,412**

Table 7. Nodal pressure heads of best solutions of El-Mostakbal City network for different network uncertainties at COV_Q = 10%

Node ID	Pressure Head (m)					
	α = 0.5	**α = 0.6**	**α = 0.7**	**α = 0.8**	**α = 0.9**	**α = 0.99**
1	35.960	35.918	35.871	35.816	35.736	35.536
2	31.559	31.740	30.938	33.993	34.418	33.989
3	30.485	30.721	30.642	33.549	33.113	33.611
4	31.768	31.860	31.758	33.586	33.678	33.642
5	32.343	32.371	32.259	33.603	33.740	33.699
6	29.292	29.815	29.586	32.805	31.054	31.777
7	33.350	33.163	32.997	33.213	34.081	32.162
8	33.927	33.776	33.638	33.650	34.437	33.855
9	28.872	29.622	29.531	32.499	30.844	31.051
10	30.565	30.873	30.733	32.076	31.191	31.457
11	27.988	29.083	28.974	30.956	28.913	30.580
12	31.639	31.666	31.495	31.808	32.085	31.521
13	30.401	31.072	31.249	29.572	31.746	30.290
14	31.251	31.897	31.670	29.659	32.168	30.662
15	32.670	32.427	32.227	31.550	32.944	31.768
16	25.207	24.975	26.984	27.337	26.862	27.153
17	26.329	25.631	26.881	23.699	26.593	25.828
18	27.966	28.221	26.896	23.678	26.579	25.611
19	29.034	29.472	28.660	26.007	28.724	27.505
20	24.892	24.727	26.288	26.893	26.174	26.715
21	24.907	24.756	25.541	25.852	24.846	25.637
22	23.771	22.852	24.889	24.973	24.079	24.969
23	24.899	24.727	24.914	24.584	23.985	24.946
24	**22.106**	**22.009**	**22.050**	22.745	22.265	23.966
25	22.391	22.027	22.145	**22.198**	**22.062**	23.159
26	23.397	22.744	23.322	23.560	23.055	24.586
27	22.521	22.128	22.159	22.213	22.135	**22.557**
28	23.679	23.103	23.834	23.620	23.601	24.772
29	23.492	23.090	22.960	22.499	22.183	23.792
30	25.482	25.420	24.940	23.170	23.555	24.486
31	26.468	26.578	25.571	23.148	25.610	24.620
Average Pressure (m)	**28.020**	**28.015**	**28.116**	**28.210**	**28.466**	**28.577**
Minimum Pressure (m)	**22.106**	**22.009**	**22.050**	**22.198**	**22.062**	**22.557**
Maximum Pressure (m)	**35.960**	**35.918**	**35.871**	**35.816**	**35.736**	**35.536**

Table 8. Node and network reliabilities of best solutions of El-Mostakbal City network for different network uncertainties at COV_Q = 10%

Node ID	Node Reliability, R_{ni} (%)					
	α = 0.5	α = 0.6	α = 0.7	α = 0.8	α = 0.9	α = 0.99
1	100	100	100	100	100	100
2	100	100	100	100	100	100
3	100	100	100	100	100	100
4	100	100	100	100	100	100
5	100	100	100	100	100	100
6	100	100	100	100	100	100
7	100	100	100	100	100	100
8	100	100	100	100	100	100
9	100	100	100	100	100	100
10	100	100	100	100	100	100
11	100	100	100	100	100	100
12	100	100	100	100	100	100
13	100	100	100	100	100	100
14	100	100	100	100	100	100
15	100	100	100	100	100	100
16	100	100	100	100	100	100
17	100	100	100	100	100	100
18	100	100	100	100	100	100
19	100	100	100	100	100	100
20	100	100	100	100	100	100
21	100	100	100	100	100	100
22	99.92	98.54	100	100	100	100
23	100	100	100	100	100	100
24	**51.04**	**80.21**	**96.61**	99.98	100	100
25	62.93	81.36	97.57	**99.87**	99.99	100
26	95.94	97.56	99.98	100	100	100
27	69.63	85.21	97.75	99.88	99.99	100
28	99.92	99.48	100	100	100	100
29	97.78	99.35	99.93	99.95	99.99	100
30	100	100	100	100	100	100
31	100	100	100	100	100	100
Network Reliability, R_{sm} (%)	**51.04**	**80.21**	**96.61**	**99.87**	**99.99**	**100**
Network Reliability, R_{sa} (%)	**93.02**	**96.74**	**99.52**	**99.98**	**99.99**	**100**
Network Reliability, R_{sw} (%)	**93.95**	**97.17**	**99.59**	**99.98**	**99.99**	**100**

For major values of uncertainty, Table 7 show that nodes 24, 25, 27 and 29 are the critical nodes in the network, which have nodal pressure heads not far from the required minimum pressure head. Therefore, their node reliabilities and mainly that of node 24 are affecting the network reliability, Table 8. It is worth to mention that the Monte Carlo simulation with 10,000 samples was performed to calculate the nodal and network reliabilities of El-Mostakbal City network. Also, from Table 8 the weighted system reliability came out to be higher than arithmetic system reliability results and the latter is greater than the minimum nodal system reliability.

Similar to the previous study, the optimum designs of El-Mostakbal City network under the same previous levels of uncertainty for a coefficient of variation in nodal demands $COV_Q = 20\%$ are given in Table 9. The nodal pressure heads for these optimal networks are given in Table 10. The calculated nodal capacity and system reliabilities from the Monte Carlo simulation associated with these six different levels of uncertainty are summarized in Table 11. For this COV_Q, it is observed that the minimum nodal pressure heads are at nodes 24, 25 and 27 depending on the specified level of uncertainty and that node 24 has very low nodal reliability compared to that for other nodes for $\alpha = 0.5$ and 0.6. Similar to $COV_Q = 10\%$, the obtained weighted system reliability is higher than the arithmetic system reliability and the minimum nodal system reliability.

Table 9. Optimal pipe diameters for El-Mostakbal City network for different network uncertainties at COV_Q = 20%

Pipe ID	Diameter (mm)					
	α = 0.5	α = 0.6	α = 0.7	α = 0.8	α = 0.9	α = 0.99
1	500	500	500	500	500	600
2	150	150	400	500	250	400
3	150	150	500	400	200	400
4	150	150	500	500	250	400
5	150	150	150	150	150	150
6	150	200	150	150	150	150
7	150	150	150	150	150	200
8	150	150	150	150	250	150
9	500	500	400	400	500	500
10	500	500	400	400	500	500
11	150	200	500	500	400	400
12	150	150	150	200	150	150
13	200	150	500	500	400	400
14	150	150	150	150	150	150
15	200	200	150	150	150	150
16	150	150	150	150	150	250
17	250	250	150	150	200	150
18	400	500	250	300	500	500
19	500	500	250	250	400	500
20	250	200	400	400	400	400
21	150	150	150	250	150	150
22	150	150	150	150	200	150
23	400	400	200	200	400	400
24	400	400	200	200	400	400
25	150	150	150	150	150	150
26	250	200	500	500	400	250
27	150	150	200	150	200	250
28	150	150	250	200	150	200
29	300	400	200	150	300	400
30	150	150	200	150	150	200
31	150	200	150	150	150	150
32	250	200	300	300	250	250
33	150	150	150	400	150	200
34	150	150	250	150	200	200
35	200	150	150	250	250	150
36	150	150	200	150	150	200
37	200	200	150	250	250	150
38	150	150	150	150	200	200
39	200	200	200	200	200	250
40	150	150	150	200	150	150
41	250	300	200	150	250	250
42	150	150	150	150	250	200
43	300	300	150	200	250	300
Cost (LE)	**2,234,046**	**2,251,260**	**2,386,508**	**2,490,224**	**2,586,316**	**2,755,927**

Table 10. Nodal pressure heads of best solutions of El-Mostakbal City network for different network uncertainties at COV_Q = 20%

Node ID	Pressure Head (m)					
	α = 0.5	**α = 0.6**	**α = 0.7**	**α = 0.8**	**α = 0.9**	**α = 0.99**
1	35.960	35.875	35.778	35.662	35.490	36.108
2	31.559	31.876	32.095	34.106	31.871	33.640
3	30.485	30.900	31.792	32.981	29.254	33.038
4	31.768	32.061	32.752	33.507	30.635	33.678
5	32.343	32.190	33.182	33.743	31.255	33.965
6	29.292	30.098	31.256	32.328	27.985	32.097
7	33.350	32.978	34.061	34.116	32.246	33.623
8	33.927	33.623	34.367	34.393	32.959	34.159
9	28.872	30.074	31.023	32.051	27.807	31.747
10	30.565	31.019	31.409	32.068	29.036	32.498
11	27.988	28.645	30.574	31.540	27.403	31.030
12	31.639	31.618	31.654	32.111	29.815	32.973
13	30.401	30.797	30.147	31.279	29.391	31.324
14	31.251	31.617	30.458	31.557	30.161	32.563
15	32.670	32.193	31.890	32.153	30.564	33.011
16	25.207	25.080	27.245	27.818	25.619	28.854
17	26.329	26.134	25.443	27.476	26.241	28.287
18	27.966	27.618	24.698	25.874	26.828	28.634
19	29.034	29.020	26.923	28.063	27.919	30.003
20	24.892	24.799	27.104	27.667	25.467	27.318
21	24.907	25.466	26.086	26.520	24.478	26.741
22	23.771	23.456	25.310	25.079	23.543	25.388
23	24.899	25.198	24.693	25.114	23.756	26.544
24	**22.106**	**22.066**	23.460	22.429	22.124	22.545
25	22.391	22.534	22.485	22.693	22.124	**22.476**
26	23.397	23.480	22.980	23.665	22.838	23.820
27	22.521	22.884	**22.051**	**22.370**	**22.074**	22.637
28	23.679	23.743	24.398	24.930	23.262	25.446
29	23.492	24.206	22.326	22.762	22.652	23.464
30	25.482	25.470	24.079	24.651	24.011	26.580
31	26.468	26.755	24.100	24.673	25.531	27.812
Average Pressure (m)	**28.020**	**28.177**	**28.252**	**28.883**	**27.237**	**29.419**
Minimum Pressure (m)	**22.106**	**22.066**	**22.051**	**22.370**	**22.074**	**22.476**
Maximum Pressure (m)	**35.960**	**35.875**	**35.778**	**35.662**	**35.490**	**36.108**

Table 11. Node and network reliabilities of best solutions of El-Mostakbal City network for different network uncertainties at COV_Q = 20%

Node ID	Node Reliability, R_{ni} (%)					
	α = 0.5	**α = 0.6**	**α = 0.7**	**α = 0.8**	**α = 0.9**	**α = 0.99**
1	100	100	100	100	100	100
2	100	100	100	100	100	100
3	100	100	100	100	100	100
4	100	100	100	100	100	100
5	100	100	100	100	100	100
6	100	100	100	100	100	100
7	100	100	100	100	100	100
8	100	100	100	100	100	100
9	100	100	100	100	100	100
10	100	100	100	100	100	100
11	100	100	100	100	100	100
12	100	100	100	100	100	100
13	100	100	100	100	100	100
14	100	100	100	100	100	100
15	100	100	100	100	100	100
16	99.68	99.99	100	100	100	100
17	100	100	100	100	100	100
18	100	100	99.98	100	100	100
19	100	100	100	100	100	100
20	99.53	99.94	100	100	100	100
21	99.64	99.99	100	100	100	100
22	94.92	98.06	100	100	100	100
23	99.61	99.99	99.99	100	100	100
24	**49.05**	**80.58**	99.81	99.84	100	100
25	55.98	89.59	98.16	99.91	99.99	100
26	80.29	98.05	99.33	99.99	100	100
27	60.21	93.70	**95.73**	**99.81**	99.99	100
28	94.40	99.01	99.99	100	100	100
29	84.57	99.59	97.13	99.93	100	100
30	99.86	99.99	99.96	100	100	100
31	100	100	99.94	100	100	100
Network Reliability, R_{sm} (%)	**49.05**	**80.58**	**95.73**	**99.81**	**99.99**	**100**
Network Reliability, R_{sa} (%)	**90.82**	**97.73**	**99.46**	**99.97**	**100**	**100**
Network Reliability, R_{sw} (%)	**91.80**	**98.09**	**99.46**	**99.97**	**100**	**100**

The information on the trade-off between cost and uncertainty is shown in Fig. 3, which gives the relationship or trade-off between cost and uncertainty requirements for a range of uncertainty requirements on the degraded network configurations. It is evident from Figure 3 that, for a given level of uncertainty, the cost of the design increases with the increase in the coefficient of demand variation.

As mentioned previously, using a Monte Carlo simulation, the nodal reliability at every node is calculated and the network reliability is derived from them. The results of the network reliability given in Tables 8 and 11 are plotted in Fig. 4. It is clear that the network reliability is 100% for $\alpha = 0.99$ which means very reliable network under uncertainty in nodal demands up to COV_Q = 20%.

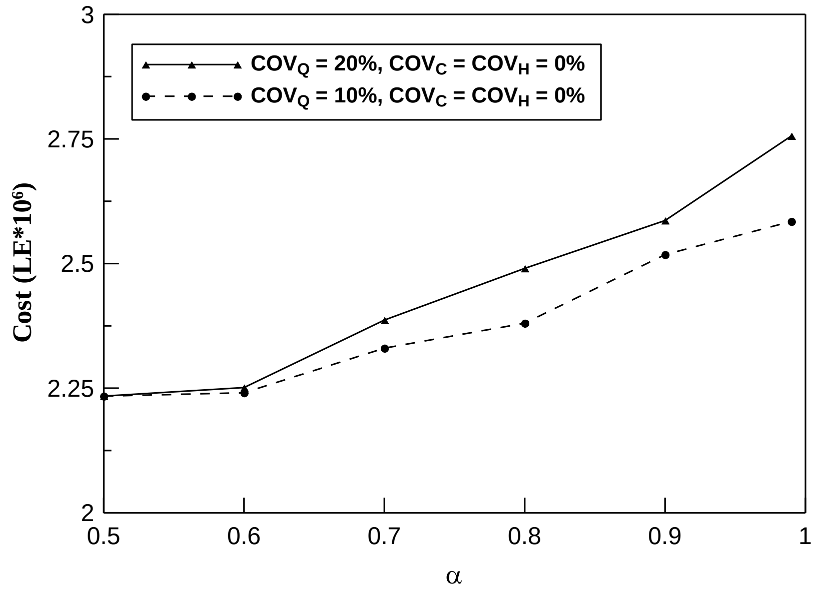

Figure 3. Total cost of network versus uncertainty α for El-Mostakbal City network for COV_Q = 10% and 20%

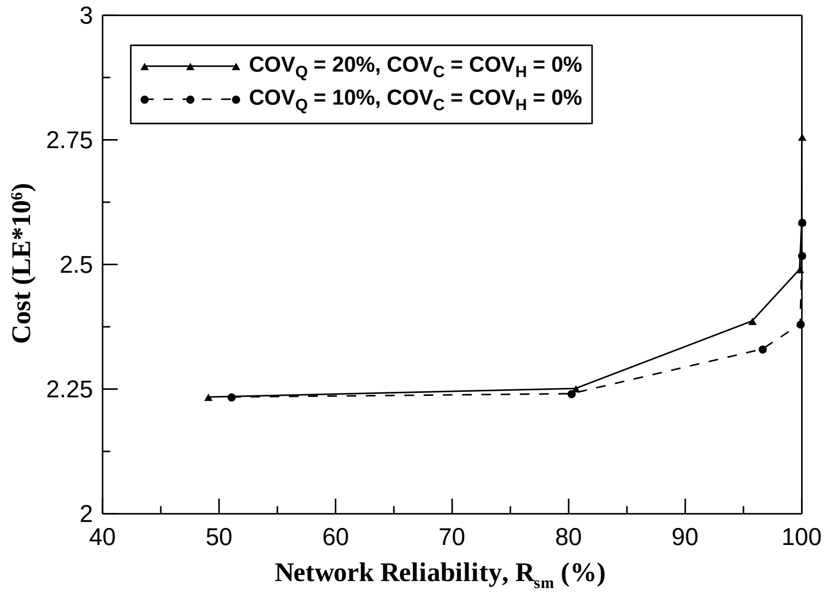

Figure 4. Total cost of network versus network reliability for El-Mostakbal City network for COV_Q = 10% and 20%

CONCLUSIONS

The Reliability-based optimization of water distribution networks is presented and applied to a case study. The approach links a genetic algorithm (GA) as the optimization tool, the Newton method as the hydraulic simulation solver with the chance constraint combined with the Monte Carlo simulation to estimate network capacity reliability. The source of uncertainty analyzed is the future nodal external demands.

The results at two values of coefficient of variation reveal the well known relation between the total cost and network reliability, that the higher the reliability requirement, the greater the design cost. The high reliability of network increases the performance of the network at normal conditions.

NOMENCLATURE

$C_{i,j}$	Hazen-Williams roughness coefficient for pipe connecting nodes *i*, *j*
C_T	total cost
$D_{i,j}$	diameter of pipe connecting nodes *i*, *j* in the system (m)
$D_{\max}$	maximum diameter, (m)
$D_{\min}$	minimum diameter, (m)
H_j	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)
K	conversion factor which accounts for the system of units used.
$L_{i,j}$	length of pipe connecting nodes *i*, *j*, (m)
M	total number of nodes in the network
N	total number of pipes
N_s	total number of Monte Carlo simulations
$P(\ )$	probability
Q_j	discharges into or out of the node *j*, (m^3/s)
Q_{si}	mean value of water supply at node *i*, (m^3/s)
$q_{i,j}$	flow in pipe connecting nodes *i*, *j*, (m^3/s)
R_s	system reliability
R_N	nodal capacity reliability
x	Independent variable
Z	objective function

Greek Symbols

α_j	probability level for the node demands

ϕ cumulative distribution function
μ_Q mean of random variable Q, (m^3/s)
σ_Q standard deviation of random variable Q, (m^3/s)

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