A Systematic Approach for Design a Flexible Water Treatment Network

M.A. Mousa*[1], G.M. Abdellalem[2], M.E. Elsokary[2]*

[1] Technical office section head for Chairman and CE&O of Alexandria National Refinery & Petrochemical Company (ANRPC) Alexandria – Egyptian Petroleum Ministry

[2] Petroleum Research Institute, Cairo, Egypt

[2]* Suez University, Faculty of Petroleum & Mining Engineering, Petroleum Refinery & Petrochemical Engineering Department, Suez, Egypt

*Email address: mohamed.IbMo@pme.suezuni.edu.eg

Abstract:

Some of the impacts of climate changes could affect human health, food security, water resources, and ecosystems. Both water supply and wastewater disposal require a lot of energy. The collection, transport, and finally, treating water till be capable of using drinking purposes consume massive amounts of energy, leading to releasing huge amounts of carbon dioxide per annum. A better design of these water infrastructure systems could no doubt achieve substantial energy savings through reducing emissions at a reasonable cost. This research investigates the alternatives for designing such water distribution systems considering CO_2 emissions and costs together as objectives. The trade-offs between these three parameters are investigated to perform optimal water network. For understanding these trade-offs, a multi-objective GA optimization module was created.

***Keywords**: water networks, optimization, carbon dioxide reductions, flexible design.*

I. INTRODUCTION

Any planning process of water distribution system design involves determination of average and peak demands, system layout with optimal dimensions for system main elements like pipes and pumps. Optimization is vital to any problem involving critical decision making. The final design should reflect the best interests of the society. Engineers should design systems that combine between sustainability and flexibility, resulting in the lowest possible cost and inflicting the least amount of harm to the environment and society while being adaptable, reliable and flexible in both normal and abnormal situations. As a result, this study proposes a multi-objective genetic algorithm optimization method for the design of water networks with the goal of decreasing costs and carbon emissions while preserving acceptable flexibility limits over time. It is challenging to utilize rigorous methods to identify the global optimal solution based on the non-structure. Various studies had been given on a water network's optimal design. Optimization approaches were used in the field of water distribution network design. Like, stochastic approaches e.g., genetic algorithms which can produce the highest yield. The tool illustrated in this research utilizes a multi- objective genetic algorithm technique among software for simulating water network. EPANET can be used to combine between flexibility and sustainability of water network.

II. LITERATURE SURVEY

The concept of how to design an optimum water network appeared in the literature since 1960s. A lot of research by scholars and academics took place for developing a model to achieve the target of how to design a water distribution network optimally. There are numerous optimization techniques available, and scholars could choose one the following methods can better design the water distribution network: deterministic, random, or heuristic. (Shamir's) work is based on considering the diameter of pipelines of water network to be the decision variable and his work and model had been established by using gradient techniques. (Kally) considered the length of pipeline as the decision variable and his work is based on doing several iterations. An improvement to the model created by (Jocoby). The main improvements are the addition of both of nodal pressure and demand flowrate as constraints. (Alperovits, Quindry) created a similar formula model in 1981, among them, the node head is used to estimate the optimal cost, and the node head is considered to represent the decision variable. However, most of water distribution networks are naturally non-linear problems that's why linear programming methods unfortunately, does not provide optimum global solution. This issue had been raised by several researchers such as, (Lansey and Mays) in 1989, where they developed a general formula, which is valid to be used for any water distribution network. In that issue, the problem was by using the same approaches developed by Shamir. Later, in 1987 Khang et al. used a quasi-Newton approach for determining the direction of the gradient. The most important advantage for quasi- Newton approach that its convergence rate is rapid and faster than the primarily linear programming approaches. An exploration was conducted in 1994 by Eiger et al. explained the sophistication occurred during using both above methods. According to Eiger et al., there is no change in the objective function of a network. As a result, when employing algorithm issues that are described as non-smooth, a dual theory mechanism is necessary. Like that the use of heuristics for optimizing, designing, or solving water distribution network is made by Morgan et al. in 1985.

The term "meta-heuristic" refers to a computational method of problem optimization that repeatedly tries to improve candidate solutions for specific indications of effectiveness. Make minimum assumptions related to optimization problems and be able to search for a very wide range of possible solutions. It can use several techniques such as, stochastic optimization methods; however, the global optimum solution isn't guaranteed. From now on, the phrases "meta-heuristic" and "stochastic" will be used equally in this dissertation, and they both signify the same thing. The first usage of Genetic Algorithm for optimizing water network had been made by the aid of Simpson and Murphy. The main purpose of their work is to determine the optimum cost for rehabilitation processes for simple water network system. In this minor problem, the basic GA exceeded other optimization approaches. Later, several improvements for GA were made by Dandy et al. to have an optimal water network. Power scaling concepts is the main principle used to achieve these modifications. The performance of the improved GA was found to be better than the ordinary methods. In addition to that, elimination of some solutions in every generation can be made as a new improvement methodology for GA and it's reported by Montesinos et al. Crossovers and mutations are ranked together in the modified GA. The main advantage of GA improvement is that the value of algorithm convergence's can be raised.

Several disturbances can occur during the routine functioning of a water network, including fire, emergency, peak flows, pipeline breaks, and so on. A flexible water supply network system must be able to operate efficiently under all conditions. Su et al., declared that flexibility is the ability of any system to perform and perform related tasks in each period and environment. The efficiency of any water network can be measured via using reliability indicators that's to assure that the system can be able to deliver water with the required quality, quantity, and pressure to all consumers. Unfortunately, we cannot find a standard measure tool for measuring the reliability of water networks. Due to the flexibility cannot be measured by a direct method that's because of its not considered to be a system property. Assessing or calculation of network Flexiblity can be made by considering the network characteristics according to Tabesh et al. in 2009. Pipeline breaks are the major factors for losing huge amount of water in water network. Failures in pipelines can be classified according to the main cause of nature as follows;

1. Mechanical Failure: usually this occurs due to failure of one or more than one component(s) of water distribution network.
2. Hydraulic Failure: mainly, it's occurred due to demand oscillation, such as peak flow leading to an increase in water flow or head pressure at the demand node.

Care had been paid to infrastructure design especially after the cascade terror attach in New York in 2011

III. MODEL FORMULATION

In this study, a model for designing water networks is built with the option of minimizing costs, minimizing CO2 emissions, and maintaining or maximizing system reliability. Reliability is constrained in some of the scenarios so that the optimal design produced by the model is certainly reliable for the life cycle. This model is an integration of multi- objective genetic algorithm optimization with hydraulic solver, EPANET with reliability incorporated as a constraint. Genetic algorithm (GA) is one of the popular stochastic optimization techniques in meta-heuristic methods.

GA is an optimization technique that handles optimization problems, it parallels biological evolution. GA evolves a superior solution for a given issue by combining selection, recombination, and mutation. Occasionally, a gene may be mutated that will result in a completely new trait in the offspring. GA follows the same principles to arrive at the best possible solution for a given problem. In a randomly selected potential solution set, not many solutions might give a desired result and thus need to be deleted; some of them could be considered even if they fare only poorly but are promising to lead to better solutions in further generations. These promising chromosomes are allowed to reproduce. These offspring would form the next generation forming a pool of candidate solutions. Candidate solutions that are worsened by the changes in their chromosome are deleted. The random variation introduced during the mutation may have improved the candidate solutions making them more efficient solutions to the given problem. These candidate solutions are again combined similarly by introducing random changes in the chromosome to form the third generation and this process goes on as illustrated in Figure 1.

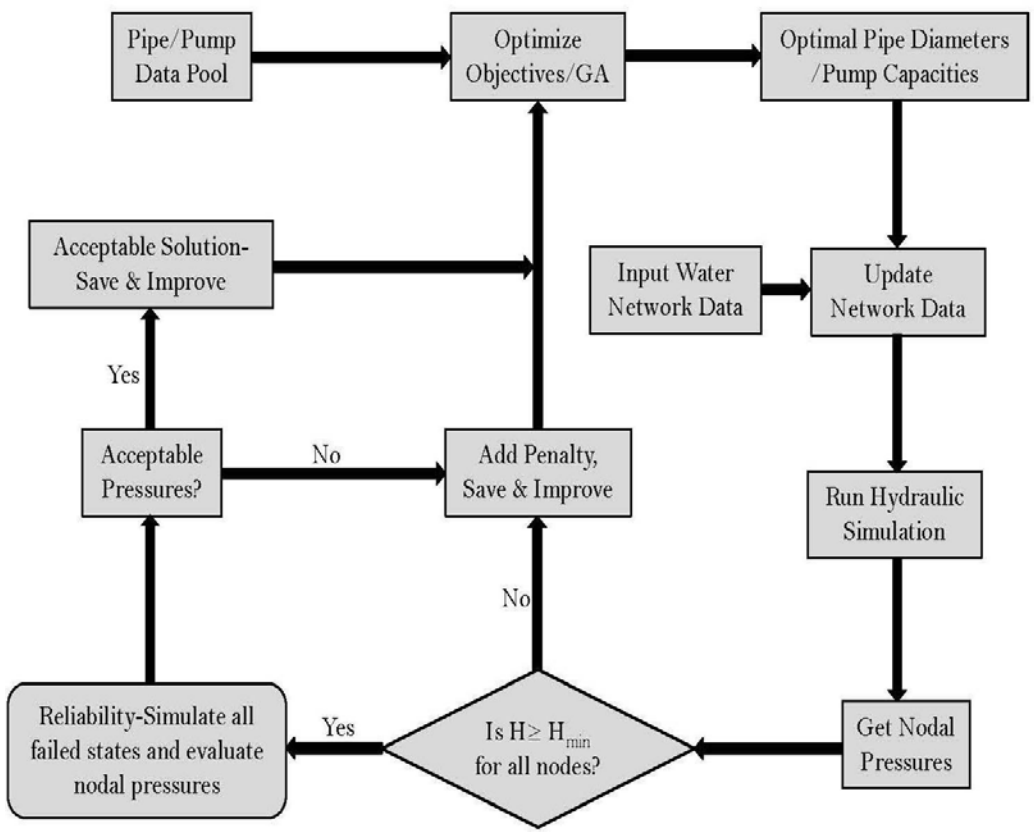

Figure 1: Genetic Algorithm Cycle

GANetXL is a user-friendly interface that makes it simple to formulate multi-objective problems in Microsoft Excel. GANetXL comes with a set of control buttons that may be used to traverse around the issue formation. Configure Wizard tab guides the user to find the variables on the worksheet that need to be optimized, connect the restrictions, choose choices, and give parameters. The user may pick among single-objective and multi-objective optimization, population numbers, crossover rate, mutation rate, number of genes per run, and number of iterations using the "Configuration Wizard." A simulation tab in the "Configuration Wizard" allows the user tointegrate the optimization tool with any external simulation tool for fitness evaluation using a visual basic for applications (VBA) macro. A dynamic library link can be used to implement the interface (DLL). After configuring the program, the optimization the "Run" button on the interface toolbar can be used to launch the programme. The optimized performance form for single and multi-objective optimization, can be used to monitor the progress of the optimal control process. Formulating a problem requires user to create a spreadsheet with decision variables, constraints and objective functions listed like the formulation GANetXL allows you to customize the genetic algorithm efficiency settings for your analysis. By using Microsoft Excel 2007 and 2010, GANetXL can handle over 16000 decision variables.

System flexibility is evaluated and madeas a constraint along with minimum pressure requirements in the optimization process such that the optimal design obtained that will lead to having a non-reliable system. Minimum cut-set method is used to evaluate reliability in this research. An appropriate code in visual basic for applications is written and is added to the existing GA optimization + EPANET tool. The VBA code for the simulation part of the algorithm for solving a pump included water network.

System flexibility is evaluated using the solution set of each generation from the optimization algorithm. flexibility does not have a unique definition and is often interpreted in different ways. To minimize this ambiguity and to reduce the computational intensity, resilience metric is considered to quantify the system performance behavior in extreme conditions. Such an alternative is thoroughly investigated in this research. Three popularly used resilience metrics in the water distribution network design area are evaluated to understand the most efficient metric. Resilience metrics are easy to compute and consumes less computational time when compared to the reliability metric. Subsequently, it would be efficient to use the resilience metric especially for larger networks.

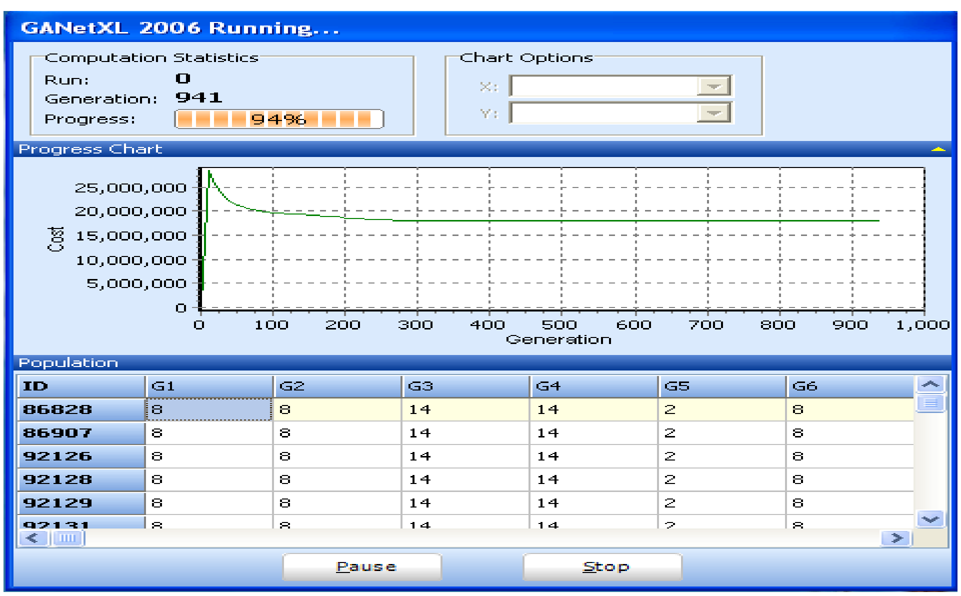

Figure 2: Progress of single objective optimization in GANetXL

IV. CASE STUDIES

In this study, three water networks are investigated to design and evaluate their levels in different predicted failure scenarios. The three water networks are: a) WDN-1, a simple 8-pipe water network with a tank, b) WDN-3, a modified WDN-2, and c) WDN-4, a 123-node network. The objective is to learn how the three flexible measures function on different types of water networks. WDN-3 is made by removing the tanks from WDN-2, as well as the connecting pipe connections to the tanks. WDN-4 is a water network designed to function with a nodal electrical structure. Each node is supposed to indicate a group of dwellings that need to be joined to a water system.

Figure 3: WDN-1 Layout

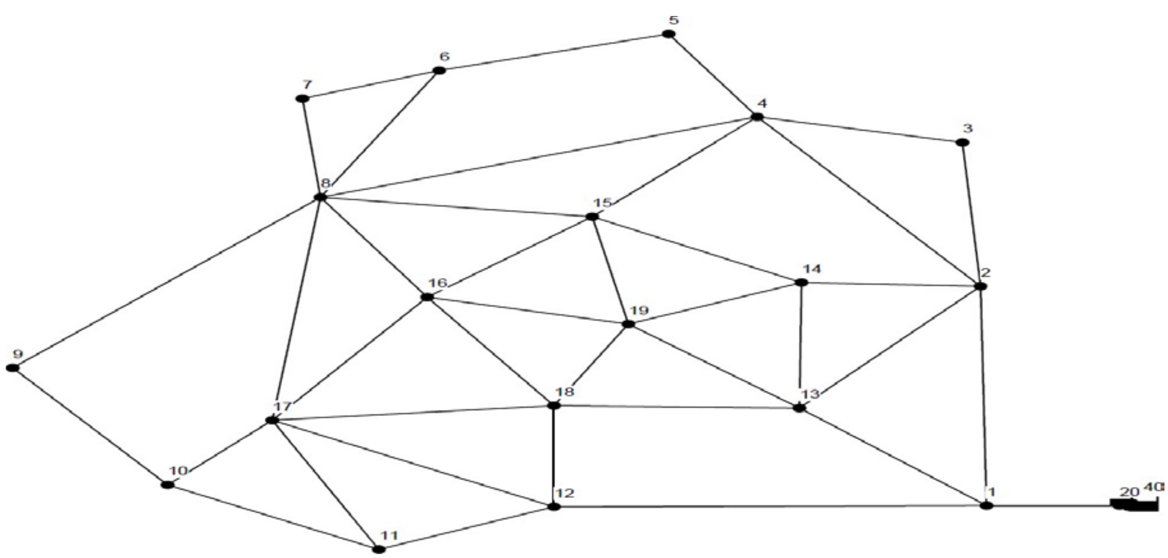

Figure 4: WDN-2 Layout

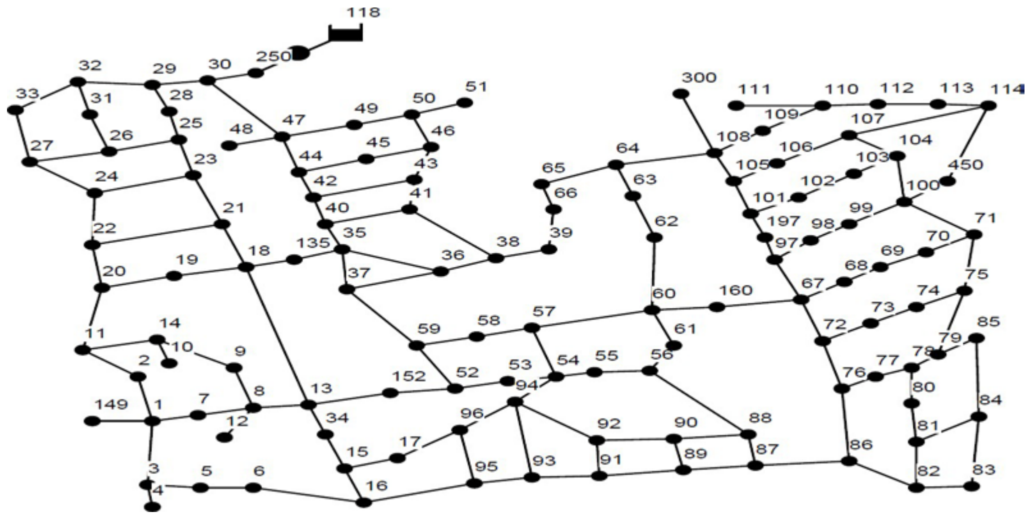

Figure 5: WDN-4 Layout

The decision variable set for the optimization framework for all the scenarios consists of the diameters for the eight-pipe links of WDN-1. The pipe material for this example is ductile iron. The coefficient of Hazen-Williams equal to130. The algorithm searches for various combinations of these diameters for the eight-pipe links that will result in the best objective value for each scenario. The model is run on WDN-1 for each of the eight scenarios and the results from this demonstration. Although WDN-1looks simply, there could be 12^8 potential design solutions.

V. RESULTS & DISCUSSIONS

For the past three decades, there has been a lot of research on the best design of water networks. Researchers are still confused as to how to get up with an efficient proposed method to the complexity of such a design challenge. Efficient algorithms are used to generate efficient solutions. If the goal of the challenge was simply to reduce the cost of installing pipes in a water system. However, limiting installation costs alone may not be adequate when designing network. The system flexibility of the network built by reducing installation cost is only 54 percent, which is not a desirable number, according to the study in this research (scenario 1). In order to remain operational in the event of pipe failures, the planned network must be flexible to an appropriate degree. Following that, flexibility is introduced as a constraint in the design optimization problem. In scenario 2, this constraint is introduced to the model such that a defined degree of system flexibility (80%) is achieved until decommissioning, which is anticipated to take 50 years. When a flexibility restriction is introduced, the cost rises from EGP 31.4 million to EGP 36.45 million. Results for different solutions for WDN-1 are shown in table 1.

Table 1: Comparison between different solutions

Scenario	Flexibility %	Cost (EGP Million)	LCC (EGP Million)	LCE (Ton of CO2)
1	54	31.4	86.92	2638
2	88.5	36.5	96.4	2991
3	0	36.7	64.1	3021
4	88.5	42.77	69.4	3401
5	54.4	31.39	86.9	2638
6	88.5	3.5	96.4	2990
7	61.4	31.9	82.7	2671
8	88.5	35	88	3034

The design of WDN-2 includes pump-capital costs, pump-operationalcosts. The developed model in this research is used to investigate various design alternatives for WDN-2 considering scenarios 3 to 8. Three solutions for each of the scenarios 7 and 8 (labeled as 7i, 7ii, 7iii, 8i, 8ii, and 8iii) are obtained in this research. Table II shows optimization results for the second water treatment network.

Table 2: Expected Cost For Different Scenarios

Scenario	Capital Costs (Million EGP)	LCC (Million EGP)	LCE (tons)
3	273.53	485.8	318,310,120
4	328.1	547.1	340,878,519
5	350.43	518.82	266,005,185
6	391.39	592.53	317,259,746
7i	288.01	488.74	299,768,317
7ii	288.9	489.52	299,748,726
7iii	297.5	495.1	298,973,335
8i	361.89	565	319,002,470
8ii	355	561.46	321,532,790
8iii	355.54	561.93	321,469,793

Three feasible scenarios for scenario 7 illustrate design choices where costs are lower than in scenario 5, and CO2 emissions are lower than in scenario 3. These three solutions 7a, 7b and 7c are non-dominant (i.e., not any one of these solutions is better than others both in cost and CO_2 emissions). This investigation using SRNET produced five different optimal solutions for WDN-II. These solutions could be further analyzedto choose the best one that suits the stakeholder's interest. Serchuk (2009) valued the greenhouse gas production at EGP 316 per ton (EGP 316/t) which is in a reasonable range of various carbon tax estimates. It can be observed that solutions 7a and 7b both result in better cost savings (than EGP 316/t) for unit reduction in CO_2 emissions compared to scenario 1. If the objective is to reduce CO_2 emissions by paying the least possibleprice, then 7a seems to be the best solution. Subsequently, the results of this demonstration reveal that the cost of reducing CO_2 emissions which equal EGP 159/t (when flexibility is not mentioned in the optimization). Similarly, all three multi-objective solutions 8a, 8b and 8c seem to represent designs that would cost mor e than EGP 315/t reduction in CO2 emissions compared to scenario 4. Scenario 8b results in the least cost per tons reduction of CO2 emissions of approximately EGP741/t compared to scenario 4. This investigation gives more information to the decision maker to select a better design. If the decision maker feels it is worth to invest EGP741/t for one ton reduction in CO2.

VI. CONCLUSION

Sustainability and flexibility are two major aspects in infrastructure systems planning and management. This study creates a modelling framework for examining different water distribution network design alternatives in effort to allow them more sustainable and flexible. Three critical parameters are considered as having an impact on the sustainability and reliability aspects of water networks. The demonstration of the model on WDN-1 confirms the assertion of Neelakantan et al. (2008) that the consideration of life cycle costs instead of capital costs in the design results in significant overall cost savings. Depending on the reliability considerations, the cost savings observed in the case of WDN-1 ranged between 26-28% while that reported by Neelakantan et al. equals 12%. (2008). The demonstration of the model on WDN-2 revealed that it costs only about EGP160 /ton for reduction of CO_2 emissions when reliability is not considered, and about 739,000/ton when reliability is a constraint. These values are considerably less than those obtained from the WDN-1 demonstration. This difference can be explained by the presence of a pump in the case of WDN-2. In comparison to other periods of the life cycle, overall contribution to life cycle expenses is not very significant.

REFERENCES

1. Eusuff, M. M. and Lansey, E. K. 2003. ***Optimization of water distribution network design using the shuffled frog leaping algorithm***. Journal of Water Resources Planning Management. 129(3): 210–225.
2. Farmani, R., Savic, D.A. and Walters, G. A. 2005. ***Evolutionary multi- objective optimization in water distribution network design.*** Journal of Engineering Optimization, 37(2): 167-183.
3. Farmani, R., Walters, G. and Savic, D.A. 2006. ***Evolutionary multi- objective optimization of the design and operation of water distribution network: total cost vs. reliability vs. water quality.*** Journal of Hydroinfotmatics, 8(3): 165- 179.
4. Farmani, R., Henriksen, H. J. and Savic, D.A. 2008. ***An evolutionary Bayesian belief network methodology for optimum management of groundwater contamination.*** Environment Model Software. 24 (3): 303-310.
5. Featherstone, R., and El-Jumaily, K. (1983). ***Optimal diameter selection for pipe networks.*** Journal of Hydraulics Engineering 109(2): 221–234.
6. Fujiwara, O. and Khang, D. B. 1990. ***A two-phase decomposition method for optimal design of water distribution networks.*** Water Resources Research, 26(4): 539–549.
7. Fujiwara, O. and Tung, H. 1991. ***Reliability improvement for water distribution networks through increasing pipe size.*** Water Resources Research,27(7): 1395- 1402.
8. Geem, Z. W., Kim, J. H. and Loganathan, G. V. 2002. ***Harmony search optimization: Application to pipe network design.*** International Journal of Modelling and Simulation., 22(2): 125–133.
9. Geem, Z. W. 2006. ***Optimal cost design of water distribution networks using harmony search.*** Engineering Optimization, 38(3): 259–280.
10. ***Intergovernmental Panel on Climate Change (IPCC).*** 2007. Climate Change 2007. Geneva, Switzerland: IPCC.
11. John,T.A. Verhoeven, B. Arheimer, C. Yin, and M.M. Hefting. ***Regional and global concerns over wetlands and water quality***. **Trends in Ecology & Evolution, 21(2):96– 103, 2016.**
12. Jacoby, S. L. S. 1968. ***Design of optimal hydraulic networks.*** Journal of the Hydraulics Division, 94(3): 641–661.
13. Jayaram, N. and Srinivasan, K. 2008. ***Performance-based optimal design and rehabilitation of water distribution networks using life cycle costing.*** Water Resource Res 44: W01417.