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APPLICATION OF WATER CYCLE ALGORITHM FOR OPTIMAL COST DESIGN OF WATER DISTRIBUTION SYSTEMS

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ABSTARCT

Water distribution system (WDS) design is considered as a class of large combinatorial non-linear optimization problems having complex implicit constraints such as conservation of mass and energy equations. Due to the complexity and large feasible solution, traditional optimization techniques are not capable to tackle these kinds of problems. Recently, applications of metaheuristic algorithms, due to their efficiencies and performances, are increased dramatically. In this paper, water cycle algorithm (WCA), a recently developed population-based algorithm, coupled with hydraulic simulator, EPANET, are applied for finding the optimal cost design of WDS. The performance of the WCA is shown using well-known Balerma benchmark problem widely used in the literature. The obtained optimization results using the WCA are compared with other optimizers such as genetic algorithm, simulated annealing, and harmony search. Comparisons of obtained statistical results show the superiority of the WCA over other optimization methods in terms of convergence rate and solution quality.

INTRODUCTION

Water distribution systems (WDSs) consist of an interconnected series of pipes, storage facilities (reservoirs), and components that convey drinking water and meeting fire protection needs for cities, homes, and other facilities. Public water systems depend on distribution systems to provide an uninterrupted supply of pressurized safe drinking water to all consumers.

It is the distribution system mains that carry water from the treatment plant (or from the source in the absence of treatment) to the consumer. The WDSs represent the vast majority of physical infrastructure for water supplies.

By considering assumptions and simplifications for solving WDSs, traditionally, classical optimization methods such as linear programming [1], dynamic programming [2], and nonlinear programming [3] have been utilized. However, real model of WDSs have its own difficulties and complexities which conventional methods cannot overcome, known as NP-hard combinatorial problem [4]. Therefore, in this situation, the need of approaches for solving these kinds of problems is understood.

In recent years, metaheuristic algorithms have been more popular optimization methods due their simplicity and generality to link any simulation model. The concepts of metaheuristic algorithms are inspired by various events in nature such as natural selection and evolution processes used in genetic algorithms (GAs) [5] or animal behavior and their search abilities for finding food such as particle swarm optimization (PSO) [6], and improvisation process of musicians motivated in harmony search (HS) [7].

Applications of metaheuristic methods had not been hidden from researchers' eyes for solving and optimizing WDSs. For instance, many authors studied application of GAs for challenging WDS problems [8,9]. Accordingly, the PSO and its variations were applied for reducing the construction cost of WDSs [10,11].

Recently, in order to increase the performance of the PSO and improving the optimization results, many researchers developed hybrid methods based on the concept of PSO. For instance, Geem [12] utilized the HS [7] coupled with the concepts of PSO to form a hybrid method known as particle swarm harmony search (PSHS).

For calculating the nodes' pressures and perfuming simulation of hydraulic, EPANET is a popular simulator joined with optimization methods. The EPANET is a free and widely used water distribution network solver. It employs the gradient method proposed by Todini and Pilati [13] for determining the mass and energy conservation equations.

The aim of this paper is improving the reported network design (i.e., Balerma network) in terms of construction cost using the developed optimizer called as water cycle algorithm (WCA). The concepts of WCA are motivated by the observation of water cycle process [14]. The WDS addressed in this paper is solved via linking the WCA with the hydraulic simulator EPANET 2.0 [13] with pipe diameters as decision variables.

FORMULATION OF WATER DISTRIBUTION SYSTEM

A water distribution system is a collection of many components such as pipes, reservoirs, pumps and valves which are connected to each other to provide water to consumers. The WDSs design can be formulated as an optimization problem with the purpose of finding pipe diameters (i.e., design variables).

To make the optimization model more realistic, pipe layout and its connectivity, nodal demand, and minimum head requirements are consider as imposed constraints. Therefore, the objective function (cost function) which is finding minimum construction cost of WDS can be defined in mathematical form given as follows [12]:

$$Min \quad Construction \quad Cost = \sum_{i=1}^{npipe} C_i(D_i) \times L_i \tag{1}$$

where $C_i(D_i)$ is the cost per unit length of pipe diameter D_i; L_i is the length of pipe i; and *npipe* is the number of pipes in the network (number of design variable). In order to calculate residual head at each node using hydraulic analysis, the WCA is combined with a powerful network simulator, EPANET 2.0. To clarify further, the EPANET 2.0 uses the following Hazen-Williams equation [17]:

$$h_f = 4.727 R_i^{-1.852} \times Q_i^{1.852} \times D_i^{-4.871} \times L_i \tag{2}$$

where h_f is the head loss along the pipe i, R_i is the Hazen-Williams roughness coefficient, Q_i is the flow rate (cfs), D_i is the pipe diameter, and L_i is the pipe length. Equation (1) is imposed to many constraints given in the following subsections.

Minimum pressure constraint

The optimal design (pipe configuration) should satisfy the minimal pressure requirement at each demand node given as follows:

$$H_j^{\min} \le H_j \qquad j = 1, 2, 3, \ldots, \mathrm{nn} \tag{3}$$

where $H_{j,}$ $H_j^{\min}$, and *nn*, respectively, are the pressure head at node *j*, the minimum required pressure head at node *j*, and the number of nodes in the network.

Energy conservation constraint

For each loop in the network, the conservation of energy constraint can be defined as follows [12]:

$$\sum_{K \in Loop\ l} \Delta H_k = 0, \qquad \forall l \in NL \tag{4}$$

where ΔH_k is head loss in pipe *k*; and *NL* is the total number of loops in the system. The head loss in each pipe is the head difference between connected nodes, and can be computed using the Hazen-Williams equation:

$$\Delta H_k = H_{1,k} - H_{2,\mathrm{k}} = \omega \frac{L_k}{C_k^{\alpha} D_k^{\beta}} Q_k \left| Q_k \right|^{\alpha - 1}, \qquad \forall k \in npipe \tag{5}$$

where $H_{1,k}$ and $H_{2,k}$ are heads of both ends of pipe *k*; ω is a numerical conversion constant (dependent on units); C_k is roughness coefficient of pipe *k* (dependent on material); α and β are regression coefficients. The values of 10.667, 1.852, and 4.871, respectively, are chosen for the coefficients of the Hazen–Williams equation, namely ω, α, and β, as used in EPANET 2.0.

Mass conservation constraint

For each junction node, the mass conservation law should be fulfilled as follows [12]:

$$\sum Q_{in} - \sum Q_{out} = Q_e \tag{6}$$

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

WATER CYCLE ALGORITHM

The idea of water cycle algorithm (WCA) is inspired from nature and based on the observation of water cycle process. Similar to other metaheuristic algorithms, the WCA begins with an initial population so called the streams. First, we assume that we have rain or precipitation. The best individual (best stream) is chosen as a sea.

Then, a number of good streams are chosen as a river and the rest of the streams flow to the rivers and sea. Depending on their magnitude of flow, each river absorbs water from the streams. In fact, the amount of water in a stream entering a rivers and/or sea varies from other streams. In addition, rivers flow to the sea which is the most downhill location [14].

As in nature, the streams are created from the rain water and join each other to form new rivers. Some of the streams may also flow directly to the sea. All rivers and streams end up in sea (best optimal point). The schematic view of the WCA is depicted in Figure 1 where circles, stars, and the diamond correspond to streams, rivers, and sea, respectively. From Figure 1, the white (empty) shapes refer to the new positions found by streams and rivers.

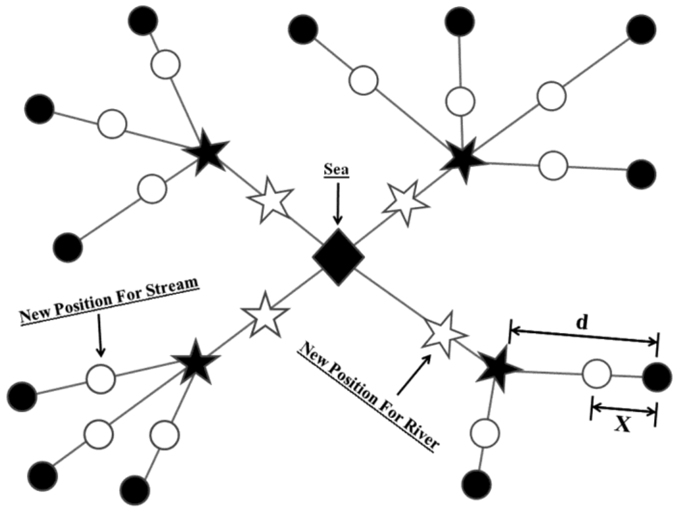

Figure 1. Schematic of the WCA optimization process

By observing Figure 1, distance X between the stream and the river may be randomly updated as the following relation:

$$X \in (0, C \times d), \qquad 1 \prec C \prec 2 \tag{7}$$

The best value for C may be chosen as 2. The current distance between stream and river is represented as d. The value of X in relation (7) corresponds to a distributed random number (uniformly or may be any appropriate distribution) between 0 and ($C \times d$).

Setting $C > 1$ allows streams to flow in different directions towards rivers. This concept may also be used to describe rivers flowing to the sea. Therefore, as the exploitation phase in the WCA, the new position for streams and rivers may be given in the following equations [14]:

$$\vec{X}^{i+1}_{Stream} = \vec{X}^{i}_{Stream} + rand \times C \times (\vec{X}^{i}_{River} - \vec{X}^{i}_{Stream}) \tag{8}$$

$$\vec{X}^{i+1}_{River} = \vec{X}^{i}_{River} + rand \times C \times (\vec{X}^{i}_{Sea} - \vec{X}^{i}_{River}) \tag{9}$$

where *rand* is a uniformly distributed random number between 0 and 1. Notations having vector sign corresponds vector values, otherwise the rest of notations and parameters consider as scalar values If the solution given by a stream is better than its connecting river, the positions of river and stream are exchanged (i.e., stream becomes river and river becomes stream). Such exchange can similarly happen for rivers and sea.

Introducing another operator, evaporation process is one of the most important factors that can prevent the algorithm from premature convergence. In the WCA, the evaporation process causes the sea water to evaporate as rivers/streams flow to the sea. In fact, if the river/stream is close enough to the sea, then the evaporation process occurs and we have a raining or precipitation process on the solution domain. This assumption is proposed in order to avoid getting trapped in local optima.

After satisfying the evaporation process, the raining process is applied. In the raining process, the new streams in the different locations are formed (acting similar to mutation operator in the GAs) [14].

BALERMA NETWORK

The Balerma network, first presented by Reca and Martinez [15], has four reservoirs, eight loops, 454 pipes (i.e., 454 design variables), and 443 demand nodes (i.e., 443 constraints), as shown in Figure 2. The absolute roughness coefficient, *R*, is 0.0025 mm at each pipe, and minimal head requirement is 20 meter at each node for the Balerma network.

Figure 2. Schematic view of the Balerma network layout

The discrete commercial diameter size available in the market accompanied with their cost (in $) per length are given in Table 1. Note that by observing Table 1, one can be seen that each pipe can choose any suggested diameter (out of 10 pipe diameter) which means the total enumeration is 10^{454} configurations.

Table 1. Commercial pipe diameters and their costs per length for the Balerma network

Pipe No.	Pipe Diameter (mm)	Cost ($/m)
1	113	7.22
2	126.6	9.1
3	144.6	11.92
4	162.8	14.84
5	180.8	18.38
6	226.2	28.6
7	285	45.39
8	361.8	76.32
9	452.2	124.64
10	581.8	215.85

OPTIMIZATION RESULTS AND DISCUSSION

To perform fair comparison and in order to obtain statistically significant results, fifty independent optimization runs were carried out for the Balerma network. The MATLAB programming software was used for coding and implementation purposes. Regarding the initial parameters of WCA, values 50, 8, and 1e-5, respectively, were set as total population size (N_{total}), number of rivers, and d_{max} (i.e., evaporation condition constant).

Applying the WCA for optimization purpose, the worst, average, and best optimized cost of 2,954,098.496 ($), 2,433,212.512 ($), and 2,306,612.152 ($), respectively, are obtained for the Balerma network problem. In terms of stability of optimized costs, the value of 57,840.12 ($) is attained as standard deviation for the obtained statistical results.

Table 2 shows the comparison of the best optimized cost using the WCA and other reported optimizers in literature. In order to perform fair comparison with other studies, the same number of function evaluations (NFEs) (i.e., 45,400) is used by the WCA as stopping condition for the Balerma network problem.

Table 2. Comparison of the best optimized cost using various optimizers for the Balerma network

Method	Best Optimized Cost (M$)	NFEs
GA [16]	3.738	45,400
SA [16]	3.476	45,400
MSATS [16]	3.298	45,400
PSHS [12]	2.633	45,400
HS [17]	2.601	45,400
WCA	2.306	45,400

Looking at Table 2, the WCA is superior over other methods in terms of having minimum construction cost at the predefined NFEs so far. The WCA has reduced the best optimized cost ($ 2,306,612.152) so far obtained by the HS ($M 2.601) [17] almost %11 (almost $ 295,000 saving money). The minimum pressure of 20.018 is reported by the WCA for node number 188th for the Balerma network problem.

Figure 3 demonstrates the convergence rate (cost reduction) of Balerma network using the PSHS, HS, and WCA. From Figure 3, the WCA could reduce considerably the construction cost at early iterations and finally stopped at final iteration offering the cheapest design so far. Fast convergence and providing the best design are considered as advantages of the WCA for the Balerma network problem.

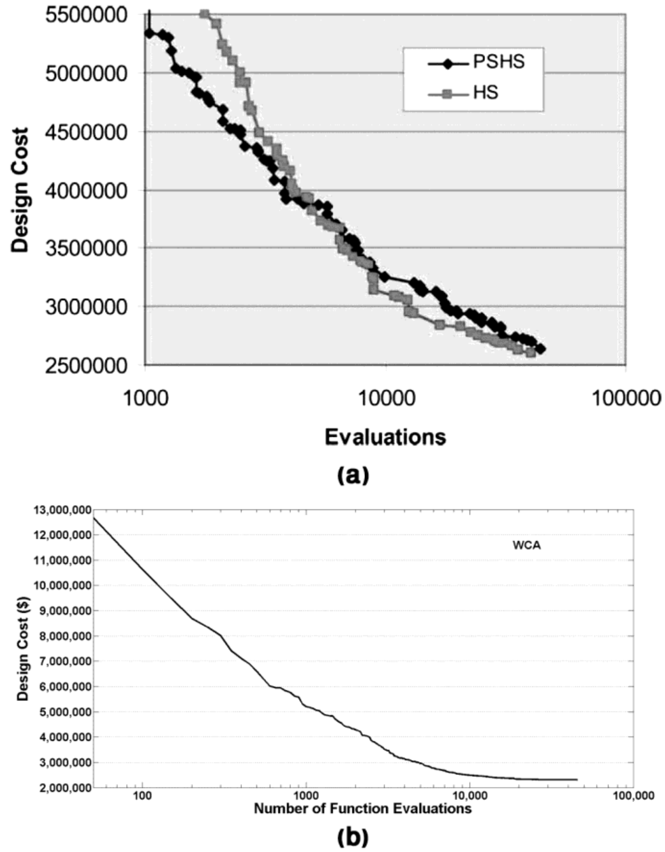

Figure 3. Reduction construction cost history using: (a) PSHS and HS [12], and (b) WCA

CONCLUSIONS

In this paper, a recently developed optimizer, namely water cycle algorithm (WCA), inspired by observation of water cycle process, was proposed for finding the best design network of water distribution system (WDS). The WCA was linked with EPANET 2.0, a well-known hydraulic simulator, in order to find the best pipe diameter sizes for minimizing the construction cost.

Comparison with other reported algorithms have been carried out in terms of statistical optimized cost and computational efforts (i.e., number of function evaluations). Based on the obtained optimization results, the WCA offered cheaper design (i.e., configuration of pipe diameters) compared with other optimizers ($ 295,000 saving money) having faster convergence rate.

The cost reduction of the Balerma network was almost % 11 lower than the best reported cost in literature so far. Therefore, the WCA may be used for solving the complex WDSs which require significant computational efforts efficiently with acceptable degree of accuracy for the network designed.

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REFERENCES

[1] Eiger G., Shamir U. and Ben-Tal A., “Optimal design of water distribution networks”, *Water Resources Research*, Vol. 30, No. 9, (1994), pp 2637-2646.

[2] Schaake J.C. and Lai D., “*Linear programming and dynamic programming applications to water distribution network design*”, Hydrodynamics Laboratory, MIT, Cambridge, MA, (1969).

[3] Varma K.V.K., Narasimhan S. and Bhallamudi S.M., “Optimal design of water distribution systems using an NLP method”, Journal of Environmental Engineering, Vol. 123, No. 4, (1997), pp 381-388.

[4] Yates D.F., Templemen A.B. and Boffey T.B., “The computational complexity of the problem of determining least capital cost designs for water supply networks”, *Engineering Optimization*, Vol. 7, No. 2, (1984), pp 142-155.

[5] Goldberg D., “*Genetic algorithms in search, optimization and machine learning*”, Addison Wesley, Reading, MA, (1989).

[6] Kennedy J. and Eberhart R., “Particle swarm optimization”, *Proc. of the IEEE international conference on neural networks*, Perth, Australia, (1995), pp 1942-1948.

[7] Geem Z.W., Kim J. and Loganathan G.V., “A new heuristic optimization algorithm: Harmony Search”, *Simulation*, Vol. 76, (2001), pp 60-68.

[8] Vairavamoorthy K. and Ali M., “Optimal design of water distribution systems using genetic algorithms”, *Computer-Aided Civil and Infrastructure Engineering*, Vol. 15, No. 5, (2000), pp 374-382.

[9] Prasad D.T. and Park N.S., “Multiobjective genetic algorithms for design of water distribution networks”, *Journal of Water Resources Planning and Management*, Vol. 130, No. 1, (2004), pp 73-82.

[10] Montalvo I., Izquierdo J., Pérez R. and Tung M.M., “Particle Swarm Optimization applied to the design of water supply systems”, *Computers & Mathematics with Applications*, Vol. 56, No. 3, (2008), pp 769-776.

[11] Sedki A. and Ouazar D., “Hybrid particle swarm optimization and differential evolution for optimal design of water distribution systems”, *Advanced Engineering Informatics*, Vol. 26, (2012), pp 582-591.

[12] Geem Z.W., “Particle-swarm harmony search for water network design”, *Engineering Optimization*, Vol. 41, No. 4, (2009), pp 297-311

[13] Rossman L.A., “*EPANET, User Manual*”, U.S. Environmental Protection Agency, Cincinnati, (2000).

[14] Eskandar H., Sadollah A., Bahreininejad A. and Hamdi M., “Water cycle algorithm – A novel metaheuristic optimization method for solving constrained engineering optimization problems”, Computers & Structures, Vol. 110-111, (2012), pp 151-166.

[15] Reca J. and Martinez J., “Genetic algorithms for the design of looped irrigation water distribution networks”, *Water Resources Research*, Vol. 42, No. 5, (2006), DOI: 10.1029/2005WR004383.

[16] Reca J., Martínez J., Gil C. and Baños R., “Application of several meta-heuristic techniques to the optimization of real looped water distribution networks”, *Journal Water Resources Management*, Vol. 22, No. 10, (2008), pp 1367-1379.

[17] Geem Z.W., “Optimal cost design of water distribution networks using harmony search”, *Engineering Optimization*, Vol. 38, No. 3, (2006), pp 259-280.