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Research Article / Araştırma Makalesi

MINIMUM-COST DESIGN OF WATER DISTRIBUTION LINE WITH DIFFERENTIAL EVOLUTION ALGORITHM

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ABSTRACT

In this study, a design approach which minimizes the construction and operation costs of water distribution line with differential evolution algorithm is proposed. Digital Elevation Model, monthly water demand, technical codes and unit prices of construction items are defined to optimization module in order to realize the cost optimum design. Pump, pipe diameter and type are defined as design variables. Construction cost of the design is computed by the unit price of the cost items. To determine the annual operation costs, flow is computed according to the Darcy-Weisbach equations. Pumping duration is determined and annual energy cost is computed. Net present value of the investment is computed by considering the time value of the money which is evaluated by the debt interest rate. Minimum-cost design alternative is searched by differential evolution algorithm. As a result, the best pump and pipe combination is obtained and summation of the construction and operation costs are minimized. Minimization of the sum of the investment and operation costs may provide the opportunity of significant improvement in the budget of the municipalities in the long run. Consequently, implementation of the proposed design approach will be beneficial for the local authorities.
Keywords: Optimization, differential evolution, pipeline, water distribution network.

1. INTRODUCTION

Expenditures on the solution of water demand problem of a city can be examined as construction cost and operating costs. Construction cost involves any labor, machinery, material, and overhead costs which are necessary to execute the construction. On the other hand, operating cost involves necessary energy, labor, and maintenance costs. Municipalities deal with both construction cost and operating costs of water distribution lines throughout their service life. Therefore, designing the infrastructure facility by only considering design code and technical specifications must not be adequate and satisfactory for municipalities. Otherwise, cost of the supplied water would be too high for the municipalities and the consumers would have to pay more than usual price if the municipality can not compensate the excessive cost.

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Design, construction and operation of pressurized water distribution line can not be handled independently. Pumping duration and power of the pump thus the energy consumption is directly related with water demand and diameter of the pipe. Conventional design approach aims to satisfy the daily water demand of the city and finishes the design if a feasible pipe and pump combination is obtained. However, the obtained solution is not usually the most economical solution, since there might exist additional pump and pipe combinations which have less total cost.

Construction cost of water distribution line increases if wider pipes are selected. However, head loss significantly decreases thus energy consumption reduces. In other words enlargement of pipe diameter increases the construction cost while decreases the operating cost. There is a particular pipe diameter and pump preference which has minimum total cost. In order to have an efficient infrastructure system, design of the system should search for the best pipe and pump combination. Therefore the design of the water distribution line should involve an optimization process. In the literature there are various optimization algorithms implemented for the optimization of water distribution lines to reduce energy cost.

Yagi and Shiba (1999) employed fuzzy control and genetic algorithm to obtain optimum operation of pump stations of sewage systems. Rasoulzadeh-Gharibdousti et al. (2011) proposed utilizing genetic algorithm and nonlinear programming together to minimize energy and operating costs of water distribution systems. Hashemi et al. (2014) used Ant Colony Optimization algorithm to minimize energy cost and optimize pumping schedule of pumps of water distribution systems. Boano et al. (2015) optimized pump management of water distribution systems by genetic algorithm and reduced energy consumption of the system. Mambretti and Orsi (2016) applied Genetic Algorithm method to decide the optimal operation conditions to reduce energy consumption at pumping stations. They compared the results of models and real data and stated that application of optimization algorithm can improve the energy cost savings. Negharchi et al. (2016) optimized the pump stations by using three optimization methods to define the exact operating point of pump curves and to decrease the energy consumption. Olszewski (2016) applied the genetic algorithm method for optimizing analysis of a complex pumping system to minimize the power and energy consumption.

Napolitano et al. (2015) determined optimum water supply method and pumping schedule of water distribution systems with multiple cisterns by proposing a method which takes cost-risk balance into account. Zeng and Huang (2015) suggest two-stage pump stations and prepared a mathematical model to improve energy efficiency and pumping schedule of large water distribution systems. Dynamic modeling is employed to minimize electricity cost. González Perea et al. (2016) implemented genetic algorithm to minimize energy cost during watering seasons of pressurized watering systems. Proposed Hybrid Harmony algorithm and Monte Carlo simulation to model stochastic behavior of rain and optimize pumping schedule of drainage pumps of urban drainage systems.

In this study, a design approach of water distribution line is proposed which minimizes the sum of construction and operating costs with differential evolution algorithm. Developed software gets surface model, population of the region, technical codes and unit prices of construction items as input. Prices and properties of 41 pipe and 17 pump types are registered to the developed system. Pump type and pipe diameter and type are the design variables of the optimization procedure. The developed system computes construction cost and pumping durations of each design alternative. Differential Evolution algorithm searches for better design opportunity among the registered pipe and pump types. Net present value of the energy cost is computed by using the interest rate of governmental bonds. In the next section computation of construction costs, operating costs and optimization algorithm is briefly explained. In the third section, the proposed design algorithm is tested on a water distribution line of Hacıyusuflar village. In the last section the obtained results are concluded.

2. MATERIAL AND METHOD

Optimum design of the pipeline is based on the minimization of the summation of the construction and operation costs and obtaining the design alternative with the minimum total cost. For this reason, methodology of this research consists of three steps which are; computation of construction costs, computation of operational costs, and minimization of the total cost.

2.1. Computation of Construction Costs

Design of water distribution line has to be concordant with the technical specifications and design codes. Requirements related with the channel dimensions are given in Figure 1.

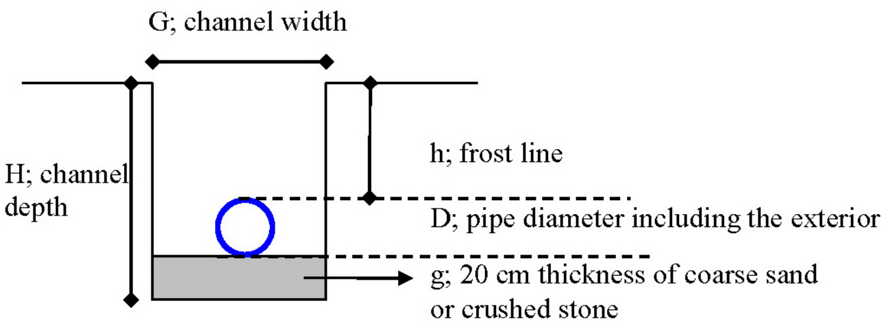


Figure 1. Dimensions of the water distribution line

Minimum depth of the channel which prevents freezing of the ground layer is defined as frost line. Relationship between the elevation of the topography and frost line is shown in Table 1.

Table 1. Minimum frost line versus elevation for water distribution channels

Elevation (m)	Frost Line (h)
0 - 600	1.00
600 - 1200	1.25
> 1200	1.50

Channel depth is equal to the summation of frost line, pipe diameter, and thickness of bedding layer. This relationship is represented in Equation (1).

$$H = h + D + g \tag{1}$$

Channel depth is determined by leaving at least 20 cm spacing on both sides of the pipe. If diameter of the pipe is less than 20 cm, then width of the channel is taken as 60 cm. Volume of excavation is computed by multiplying the depth of the channel, width of the channel and the length of the channel. Obtained volume of excavation is multiplied by the unit price index of Ministry of Environment and Urbanization to obtain the cost of excavation. After the excavation crushed stone or coarse sand with 20 cm thickness is laid. Cost of bedding layer is determined by using the item number of Y.15.140/01 of Ministry of Environment and Urbanization.

In the analyses polyethylene and PVC type pipes with 8, 10, 16 and 32 bar allowable pressure are used. Apart from pipe, 17 pumps with different power are also used for the design of water distribution line. Unit prices of the pipes and pumps are obtained by a market survey conducted in 2016 and 42 different pipe types are analyzed for the design. In the rural areas, excavated loose earth is used as backfill material while crushed stone is used as backfill material in the urban areas. Cost of backfilling is computed according to the Y.15.140/01 item number, while in the rural areas backfilling is computed by considering the cost of compaction with a compactor. Direct cost of construction is determined by the summation of the costs of excavation, bedding layer, pipe, pipe fittings, pump, backfill, cistern, and watering trough.

2.2. Computation of Operating Costs

Required flow of water is estimated by using the population data of the region. Water demand per capita is determined according to the design specifications of the Iller Bank. Daily average water demand is estimated for each month of the year since population may significantly fluctuate throughout the year. According to the daily water demand, daily pumping duration thus the energy cost is obtained.

Through the design phase, flow rate and headloss are not known. Flow rate and headloss are computed by using the headloss equation developed by Darcy-Weisbach (Crowe et al., 2001).

$$h_k = \frac{\lambda}{D}\frac{V^2}{2g}L \tag{2}$$

In equation 2, h_k represents headloss caused by the flow of the water through the pipe. D is the diameter of the pipe, V is the velocity of the water, L is the length of the pipe, g is the gravitational acceleration, and λ is the coefficient of friction between the pipe and water. Initially headloss and velocity of the water are not known. Velocity of the water and the headloss is computed by forming energy equation from the reservoir water surface to the cistern. Energy equation is represented in Equation 3 (Crowe et al., 2001).

$$\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 + h_p = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_1 + \frac{\lambda}{D}\frac{V_2^2}{2g}L \tag{3}$$

The energy equation is formed for particular problem where the water is inert and there is only one pump. In this case equation 3 can be simplified as shown in equation 4 (Crowe et al., 2001).

$$h_p = \left(z_1 - z_2\right)\frac{V^2}{2g}\left(1 + \frac{\lambda L}{D}\right) \tag{4}$$

Initially both pump head and discharge rate is not known. Both unknowns are solved iteratively by using pump curves. Pump curves of commercially available pumps are digitized by reading data points. Equation 4 is solved iteratively by interpolating between discrete data points and iteration stops if change in discharge between successive iteration is less than a predefined threshold. As a result, discharge rate is obtained by iteratively solving the system curve and head versus discharge curve of pump.

Daily pumping duration obtained by considering daily average demand and discharge rate. Energy cost of the pumping is computed by multiplying the pumping duration, power of pump, and the unit energy price. Design life of the infrastructure facility is assumed to be 30 years. Throughout this period it is expected that the pipeline will not need any maintenance cost but the pump should be replaced with the same pump model after 50,000 hours of operation. There will be no salvage value for the replaced pump. Present equivalent of the annual energy cost is computed by considering the time value of money with equal-payment series present worth factor given in equation 5.

$$P = A\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] \tag{5}$$

Similarly, present value of the cost of the pump purchased at the n^{th} year is computed by single-payment present worth factor given in equation 6.

$$P = F\left[\frac{1}{(1+i)^n}\right] \tag{6}$$

Present equivalent of all of the cost items are summed and total equivalent cost of the infrastructure is computed. Minimum total cost is obtained by optimization procedure.

2.3. Differential Evolution Algorithm

Differential Evolution Algorithm is a meta-heuristic optimization algorithm developed by Storn and Price (1997). Differential Evolution is a modified version of Genetic Algorithm which is not very good at local search. In the literature, there are many different versions of crossover and mutation operations proposed for the Differential Evolution. In this study mutation operator implemented by Das and Suganthan (2011) and Ghosh (2012) is preferred. Implemented mutation operator is given in Equation 7.

$$j = 1:z, \qquad U_{i,j} = \left\{X_{r3,j} + f \times \left(X_{r1,j} - X_{r2,j}\right)\right. \tag{7}$$

Individuals are represented as i and design variable is illustrated as j in equation 7. Number of design variables is represented as z. Individual to be mutated is represented by X, and U represents the mutated state of the individual. Generated random numbers to produce a mutated individual are represented by r_1, r_2 and r_3. Random numbers are generated between 1 and population size, n. Finally, f is a constant which scales the difference vector (Ghosh et al. 2012).

A random number is generated for each individual to determine the individuals to be mutated. The generated random numbers represent probability of mutation and if the assigned probability is less than a predefined threshold value the individual is mutated, otherwise the individual is not mutated. If the individual is mutated by using the equation 7 there can be two possibilities. First, the resulting individual can be worse than its initial state. In this case, the mutation is rejected and the initial state is preserved. Second possibility is that, the mutated individual can be equal to its initial state or can be better than its initial state. In this case, the mutation is accepted and the gene representation of the individual is altered. An acceptance criterion of the mutation is represented in equation 8.

$$U_i = \begin{cases} f(U_i) \leq f(X_i) \rightarrow U_i \\ f(U_i) > f(X_i) \rightarrow X_i \end{cases} \tag{8}$$

In this study, only mutation operator is implemented and crossover operator is not employed. Differential Evolution starts by creating a population. Initially the population contains a predetermined number of random solutions. Pump type and pipe diameter are design variables which affect the total cost of the investment. Table 3 represents the number of design variables and types of variables for each design alternative. A unique integer identification number is assigned for each pipe and pump and each individual X, stores a randomly assigned design combination. Total cost of the water distribution line is computed by considering the randomly assigned pipe and pump combinations. Then mutation operator is implemented on the population, in order to obtain better solutions. Pipe and pump assignments are executed by implementing equation 7. However, equation 7 ends up with floating numbers which is not suitable for pump and pipe selection. The obtained floating number is rounded to nearest integer and the corresponding pump or pipe is assigned as design variable. If the obtained design costs less than its initial state, then the mutation is accepted. Otherwise the mutation is rejected and the initial state of the design is preserved. The mutation continues until the predefined stopping criterion is met.

3. CASE STUDY

Proposed optimization method for design of water distribution line is tested on Hacıyusuflar village water distribution line which is transferred to Malatya Water and Sewage system Administration from Special Provincial Administration in 2014. Map of the village and water distribution line is shown in Figure 2. Population of Hacıyusuflar village is represented in Table 2 in monthly basis.

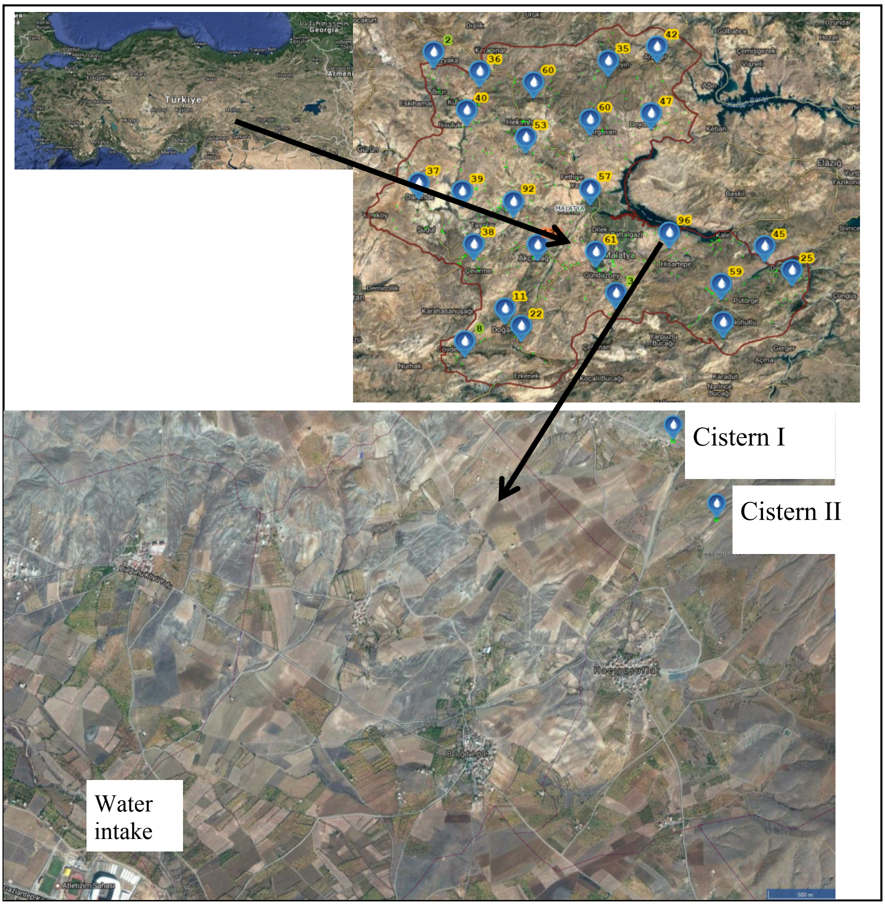
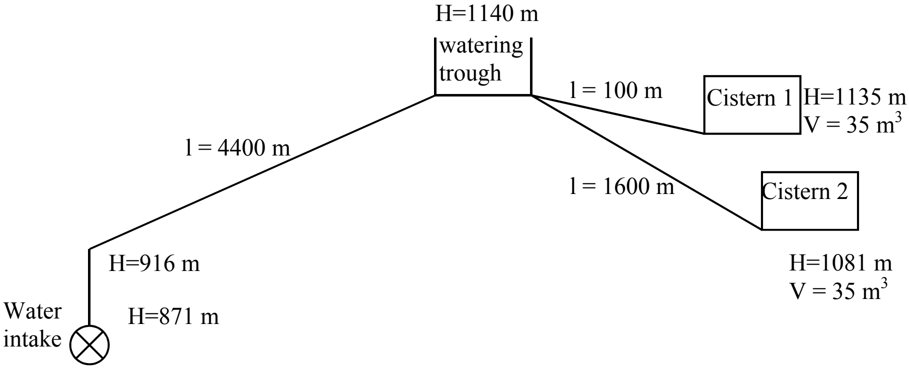


Figure 2. Study area

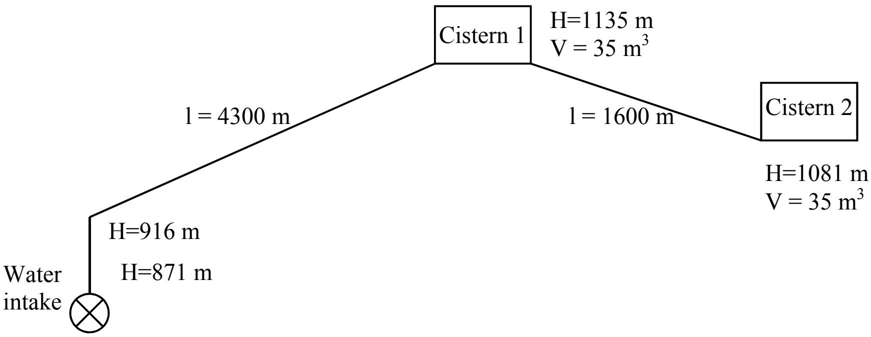
Table 2. Monthly population of Hacıyusuflar village

Months	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Population	425	425	425	425	600	600	1000	1000	600	600	425	425

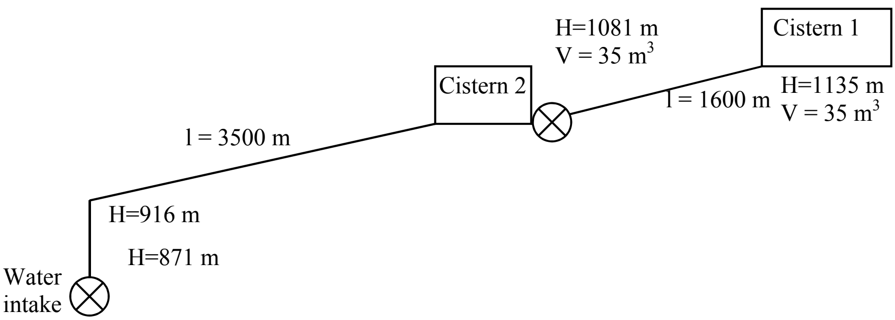
Design Alternative 1



Design Alternative 2



Design Alternative 3



Design Alternative 4

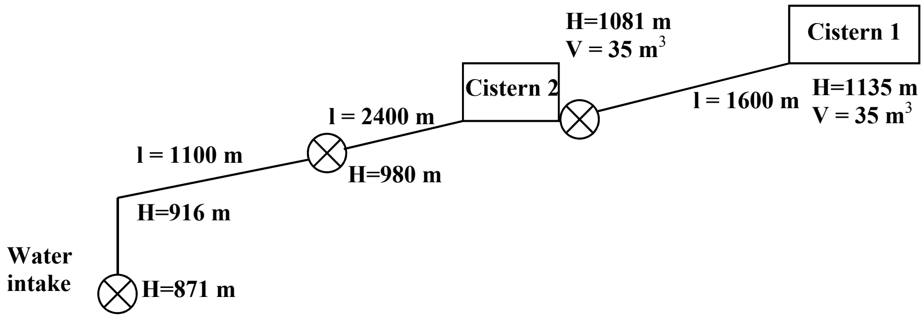


Figure 3. Representation of design alternatives

Design variables of the design alternatives are represented in Table 3. These variables will be treated as unknowns throughout the optimization procedure.

Table 3. Design variables of the design alternatives

Alternative	Design Variables				
Alt 1	Pump1	Pipe1	Pipe2	Pipe3	
Alt 2	Pump1	Pipe1	Pipe2		
Alt 3	Pump1	Pipe1	Pump2	Pipe2	
Alt 4	Pump1	Pipe1	Pump2	Pump3	Pipe2

Optimization procedure aims to minimize the summation of construction and operation costs of the infrastructure system. Objective function illustrates the total cost of the infrastructure system which is given in equation 9.

$$min \quad \{ const + (aoc) * (P/A, i, n) + \sum_{j=1}^{m} (repc_j *(P/F, i, n_j)) + penalty\} \qquad (9)$$

In equation 9, *const* represents the construction cost of the infrastructure system which is equal to the summation of all cost items formed by the combination of pump and pipe choices. Construction cost is computed as Turkish Lira. Annual operating cost is represented as *aoc* in equation 9 which is the electric cost of pumping water. This cost item is multiplied by factor (P/A, i, n) and net present value of the electric cost is computed. In the equation, *i* represents the interest rate and *n* represents useful life of the facility. During the useful life of the infrastructure if there are m times pump replacement, $repc_j$ represents the replacement cost of the j^{th} pump replacement, and $(repc_j *(P/F, i, n_j))$ term represents the net present value of the j^{th} pump replacement. The net present value of the m pump replacements are summed by the summation operator. Pump and pipe alternatives are randomly matched throughout the optimization procedure. For this reason, there can be some pump and pipe matches which do not satisfy the water demand even though water is pumped 24 hours a day. In this case 1 million TL penalty is added to the design alternative in order to make it sure that the improper design will not be a feasible result. Penalty will be zero for a proper design.

Population size is set as 100 and the optimization is stopped after 200 iterations. Probability of mutation is set as 70% and 0.2 is assigned for scaling constant. Population is generated randomly among the 17 pump and 41 pump alternatives. Each individual of the population represents a design candidate of the water distribution line. Flow rate is computed by considering the pump and pipe diameter. Daily pumping duration, thus electric cost is computed and each cost item is summed and total cost of the infrastructure is computed. Optimization procedure is completed in 1 minute on a laptop computer with i5 CPU.

Search domain of the problem is relatively large since there are 17 pump, and 41 pipe options. First design alternative consists of 1.17 million, second design alternative consists of 28500, third design alternative consists of 48500 and fourth design alternative consists of 8.26 million different pipe and pump matches. Therefore implementing exhaustive enumeration is not practical in this problem. Optimization procedure is stopped by performing 14,000 design evaluations and the least total cost is obtained on the forth design alternative. The optimization ended up with 5.5 kW pump for pump1, Φ63 mm PVC pipe for pipe1, 5.5 kW pump for pump2, 11 kW pump for pump3 and Φ55 mm PE 100 PN8 polyethylene pipe for pipe2. Net present value of the total cost of the water distribution line is computed as 295,331 TL. In the analysis exchange rate for 1 US Dollar is taken as 3 TL.

4. CONCLUSION

In this study, an optimization procedure is proposed for the design of water distribution lines which minimizes the summation of the construction and operation costs. The proposed approach prevents the design of inefficient water distribution lines which does not take operating costs in to account. Results of the case study present that the proposed approach can provide significant savings in the long term. The savings will be enormously high if the design approach is implemented on the design of water distribution lines of highly populated cities.

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