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Optimal Design and Benefit/Cost Analysis of Reservoir Dams by Genetic Algorithms Case Study: Sonateh Dam, Kordistan Province, Iran

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A B S T R A C T

This paper presents a method concerning the integration of the benefit/cost analysis and the real genetic algorithm with various elements of reservoir dam design. The version 4.0 of HEC-RAS software and Hydro-Rout models have been used to simulate the region and flood routing in the reservoir of the dam, respectively. A mathematical programming has been prepared in MATLAB software and linked with the optimal programming then employed to maximize the benefit/cost ratio of the reservoir dam construction. After a sensitivity analysis, mutation and crossover probability are assumed to be 0.05 and 0.7, respectively. The objective function of the study is benefit/cost ratio. The combined methodology has been provided to help to compute the optimal normal water level, length of spillway and downstream levee height of a reservoir dam considering flood control and cost of construction. This is the first attempt to optimize these important parameters, in the construction of a reservoir dam, together considering flood control and economical aspects. It has been displayed that the proposed method provides strong and suitable solutions to determine these parameters. The results showed that there is potential for application of genetic algorithms to such optimization problems, where the objective function is nonlinear and other optimization techniques may be troublesome to apply and find the global optimum.

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1. INTRODUCTION

This paper deals with the optimal design of reservoir dams. World commission on dams mention that the construction of dams has denoted to quick human development by providing credible sources of drinking water, crop irrigation, hydro power, recreation, navigation income, in addition to a number of other significant benefits [1]. Although, construction of dam in addition has destructive ecological results on the constructions, procedures, and operating of ecosystems [2], involving deforestation, loss of fauna and flora species, and the desolation of historical remain [3].

Determining normal water level (NWL) and length of spillway (LS) are taken into account to be the most meaningful proper values of a dam construction project. These parameters can have direct effects on the aim of the project and environmental ecology, likewise other factors, like capacity efficiency, flow controlling, and extensive employment benefit. Moreover, land of reservoir and recreational amounts are contingent upon water levels staying at serviceable levels. Therefore, extensive attentions of economic, engineering and eco-environmental factors by measurable tools are needed to optimize NWL and SL. Recently several mathematical and optimal programming methods have been increasingly used for optimizing NWL and SL for example, Lu [4] presented a novel technique to select NWL using grey layers analysis, in which the weighted constant factor of every indicator was concluded using analyzing, examining and containing the depth data in a derivative procedure of the indicators. Zhan and Qu [5] presented a novel technique for optimization of NWL dependent upon obscure relation analysis that demonstrated trust worthy in practical implementation. Zeng et al. [6] supplied a multi-objective decision-making method using grey correlation lysis for the

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selection of NWL of Three Gorges dam. In order to extensive appraisal of NWL plans, Jin et al. [7] presented an objective weight technique dependent upon the projection search in accordance with the example series of water criterion and enhanced analytical hierarchy procedure on the basis of an accelerating genetic algorithm.

In a study, Yanmaz and Gunindi [8] investigated the relationship between reservoir capacity and the weight of concrete dams, RCC dams and their benefit and cost. Xie and Qian [9] employed the grey fuzzy extensive estimation technique to choose a NWL to determine quantity of qualitative indicators using the fuzzy number and the relationship of indicators being taken into account. Hou [10] displayed the application of the multi-principle assessment technique in the selection of NWL, using a real hydropower plant as an example. A four-step method for optimizing the NWL of reservoirs on the basis of a mathematical programming model involving various parameters that affect the economic viability, engineering characteristics, environmental and urban ecology was proposed by Shijun et al. [11]. Shafiei et al. [12] showed that GAs supply strong and satisfactory solutions to the levees encroachment optimization problem. Their results indicate that GA is suitable to levees optimization problems. Marcos et al. [13], presented a process to optimize the construction of mass concrete structures using GAs and their results demonstrated that the process can be employed in the design of enormous concrete structures. A comprehensive overview on the cost optimization of concrete structures given by Sarma and Adeli [14], demonstrated that most papers face up to structural optimization interested of weight minimization. A few papers on cost optimization mainly were devoted to simple elements like beams and girders, and extremely few employed costs functions that took into account the costs of placement and construction. Sharif and Wardlaw [15] developed a GA approach for the optimization of multi-reservoir systems. Salmasi [16] determined the optimal top width of gravity dam by a GA in which the top width is taken as a function of water depth. In a study, Varaei and Ahmadi Nadooshan [17] optimized the dimensions of concrete gravity dams using GA and particle swarm algorithm and then compared and evaluated the accuracy and speed of access to response. They mentioned the large impact of amounts of particle swarm algorithm in convergence. Bozorg Haddad et al. [18] addressed a possible decrease in flood damages using structural methods and determined proper locations (layout) to construct protective levees and height of levees (design of levees) in high-risk areas using GAs. Zhao Wanli et al. [19] focused on the problem of optimization method for selection of NWL of hydropower station reservoir. The results demonstrated that the method is simple and can decrease computational attempt of extensive evaluation, extremely and so can precisely optimize the rational NWL plan of the reservoir. The objective of this study is to find and develop a new optimization method using an improved real genetic algorithm (RGA), also known as continues genetic algorithm (CGA), and a benefit/cost analysis considering flood control and cost of downstream levee construction that is especially designed and suitable for NWL, LS and levee height (LH) decision making.

2. MATERIALS AND METHODS

Today, the economic consideration is an important factor in the selection of water resources projects, hence the attempt to minimize the economic costs of the project is essential. An economic water system is very broad and complex usually, and this process requires environmental, economic, engineering and social considerations. Although it is unnecessary to combine all the parameters which have impact on the system in a mathematical programming model. Every decision-making procedure begins with problem diagnosis, perused by data research, problem examination, further appraisal, and eventually the determination [11]. To design a reservoir dam, the first step is to determine the normal water level (NWL). As the NWL grows in amount, the dam height and the volume of reservoir rise and consequently the benefits and costs of the dam construction increases as well. Furthermore, considering flood control during an overflowing, as SL goes up, the height of overflowing water goes down, causes the height of dam to be smaller and as a result, the benefits and costs of the dam construction will decrease. And also the cost of downstream levee system construction is considered as an additional cost item to flood control in downstream of the reservoir dam. Therefore, determination of the optimum normal water level (ONWL), optimum length of spillway (OLS) and optimum levee height (OLH) to maximize the benefit/cost ratio of the project is crucial. So in this study, by using the benefit/cost analysis and RGA, these important parameters have been calculated to achieve the maximum benefit/cost ratio.

2. 1. Problem Definition

This study includes three main steps as follow.

- Step 1: Determination of the benefits and costs of the dam construction for various scenarios (14 different scenarios).
- Step 2: Application of the benefit/cost analysis for various scenarios (14 different scenarios).
- Step 3: Application of the RGA to optimize the benefit/cost ratio as the objective function.

2. 1. 1. Benefits and Costs of Dam Construction

The main cost regarding dam construction are related to construct dam's body, reservoir damage, spillway and downstream levee system construction, which is calculated for fourteen different scenarios. The total cost and benefit are calculated according to Equations (1) and (2) as below:

$$C_T = C_1+C_2+C_3+C_4 \quad (1)$$

where C_T is the total cost (main cost) of dam construction, C_1 denotes cost of dam body construction, C_2 is reservoir damage, C_3 represents cost of spillway construction and C_4 is cost of downstream levee system construction.Also the most important benefits of the dam construction including crop irrigation and downstream protection during flood occurring is calculated by Equation (2) as below:

$$B_T=B_i + B_p \quad (2)$$

where B_T is total benefit of the dam construction, B_i is benefits of the crop irrigation according to the crop pattern and B_p represents benefits of protecting downstream area of the dam.

To calculate the benefits and costs, it is necessary to have the properties and data of both the dam and dam site including topography maps of the reservoir, amount of the upstream and downstream area, shape and material of the dam, crop pattern and shape and material of the levee system. In the study, we used the final report of the Sonateh dam construction prepared by DEZAB consulting engineering company to calculate all of the benefits and costs of the dam project then based on these data the total benefits and costs have been calculated according to Figure 3.

2. 2. Benefit/Cost Analysis Benefit-Cost analysis (BCA) is a methodical technique to appraise the powers and debilities of choices that satate negotiations, actions or functional necessities for a business. It is a method which is employed to determine alternatives that supply the best method for the assumption and exercise regarding benefits in work, time and cost savings etc. [20]. Efficient design of a hydraulic structure is an optimization problem including an analysis of the hydraulic performance of the structure to convey flow across or through the structure and a determination of the most economical design alternative [21]. The minimization of sum of fund finance cost and maximization of sum of benefit are the objectives of each hydraulic structure project. Therefore, in the great hydraulic structure projects, such as reservoir dam construction, economic considerations are necessary. Consider now a reservoir dam and system benefits and costs, what they are and how they depend on reservoir dam parameters. A reservoir dam will have a number of factors reflecting the input and output or costs and benefits derived from the project. So, there are some economical parameters such as the interest rate, the inflation rate, the discount rate, the internal rate of return (IRR), the present value (PV), the future value (FV) and etc. These parameters will be used in the rest of the paper in Equations (5)- (8).

2. 2. Real Genetic Algorithms (RGA) Charles Darwin first inspired the process of natural evaluation and adaptation to environmental variation. Further, this idea simulated numerically by Holland as an optimization tool referred to as GA. Since then, GA has been realized as an efficient method for stochastic global search and has been used in various aspects of civil engineering [22, 23].

In the conventional GA (discrete version) each solution point is coded as a binary string. But RGA directly uses the variables themselves which is so better for optimization problems with continuous variables. Coding and decoding process is not needed in RGA which saves much computational time. Generally in GA, every individual is called chromosome and each variable is called gene. CGA is consisting of five main steps as follows:

1. Initialization: In this part, a set of primitive solutions as initial population is randomly created in the feasible region of the search space. For damage detection problems, the first generation can be obtained by generating a set of random damage vectors.

2. Fitness evaluation: In this part, the objective function for the individuals of current population is calculated. Here, benefit/cost is selected as the objective functions.

3. Selection: The selection is the process that chromosomes are selected for involvement in the procreation procedure. A famous method is fitness commensurate selection [24] that the probability P of an individual k being chosen is calculate by:

$$p_k = \frac{f_k}{\sum f_j} \quad (3)$$

where f is fitness of individuals.

Several rank selection plans are in service that care to ensure that good chromosomes have higher chance of being selected for the subsequent generation [25]. Ranking plans act by classifying the population based on fitness amounts and then apportioning a probability of selection based on the rank. The roulette wheel method is one of ranking plans of selection.

4. Reproduction: The reproduction process simulates the biological creation of a new generation. Reproduction process is usually consisting of two main stages: 1) cross over and 2) mutation.

Cross over is simulating marriage and generation of offspring by combining two individuals (chromosomes). Assume that $Chrom1=(x_1, x_2, \dots, x_n)$ and $Chrom2=(y_1, y_2, \dots, y_n)$ are two individuals from the current population, then one can gain the offspring, $Chrom\ 1' =(x'_1, x'_2, \dots, x'_n)$ and $Chrom2'=(y'_1, y'_2, \dots, y'_n)$ by cross over operation from Equation (4) as below.

$$x'_i = \alpha_i x_i + (1-\alpha_i) y_i \& y'_i = \alpha_i y_i + (1-\alpha_i) x_i \quad (4)$$

where α_i is a random real number between 0 and 1.

Mutation is an additional operator executed after cross over in some of the individuals. A certain number of genes are randomly selected to change their values. This process is simulating biological genetic mutation. This is a preventive operation form trapping of the solution in local minimums.

In addition, the elitist strategy, in which the best solution of each generation is copied to the next generation, is applied to insure improvement of the best individual generation by generation.

5. Termination: The algorithm is stopped based on the maximum number of generations. A flowchart of a real genetic algorithm is shown in Figure 1.

3. RESULTS AND DISCUSSIONS

3. 1. Case Study The above described methodology has been applied to Sonateh dam in Kordistan province in Iran. Sonateh dam was constructed on the Khor-Khore Chay River with Northern 994350 m and Eastern 434450 m in the UTM coordinate system and longitude and latitude 36°, 05', 14" and 36°, 29', 38", respectively. Sonateh dam is located in the unsymmetrical U shape valley near Saqez city. This dam was constructed for crop irrigation of 8800 ha of agricultural earth in downstream. We assumed a 20 kilometers levee system in the downstream of the dam to protect downstream earths against flood damages. General location and properties of Sonateh dam are shown in Figure 2, and Table 1, respectively.

3. 2. Applications

3. 2. 1. Application of the Benefit/Cost Analysis As mentioned before in this study our objective function is benefit/cost function. Using the benefit/cost analysis the benefits and costs of the reservoir dam construction are calculated and then objective function is formed. To do this, 14 different scenarios are considered for the project. The construction time and lifetime of this project are 5 and 50 years, respectively. Therefore, in Equations (5)-(8), n is equal to 55 (n=55) and also we considered i=0.07 and those equations can be rewrite as below:

$$B_{FV} = B_{PV} \times (1+0.07)^{55} \quad (5)$$

$$B_{PV} = B_{FV} \times (1+0.07)^{-55} \quad (6)$$

where, B_{FV} represents future value of benefit and B_{PV} is present value of benefit.

$$C_{FV} = C_{PV} \times (1+0.07)^{55} \quad (7)$$

$$C_{PV} = C_{FV} \times (1+0.07)^{-55} \quad (8)$$

where, C_{FV} is future value of cost and C_{PV} denotes present value of cost.

It is necessary to note that the amount of maintenance service costs is considered 5% of the total cost of dam construction during the lifetime of the dam and during 5 years of implementations of the dam construction that is divided into 5 parts as Table 6.

In Figure 2 the E-E axis shows the location of Sonateh dam. Then, considering Table 2 and the amount of maintenance service cost, the table of cash flows has been formed for 55 years to calculate the internal rate of return (IRR) using Excel by trial and error method and it is obtained 8.5%.

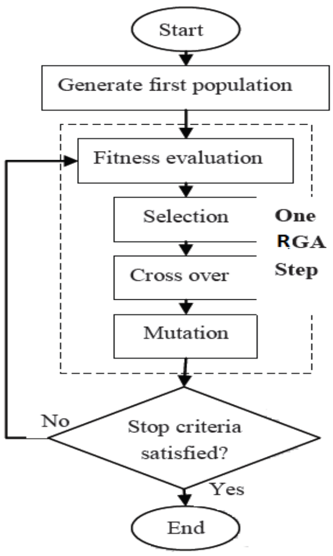

Figure 1. Flowchart of real genetic algorithm

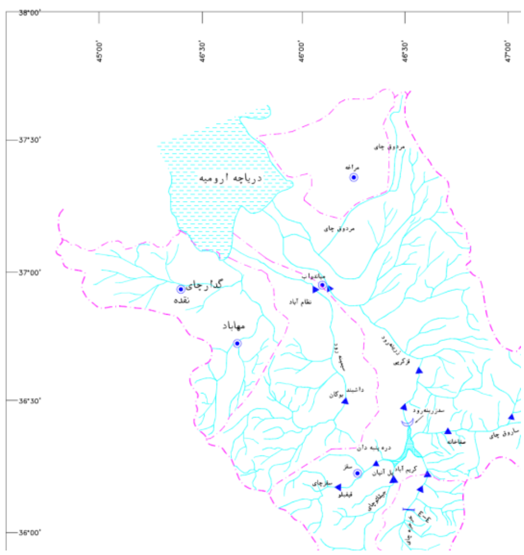

Figure 2. General Location of Sonateh dam

TABLE 1. Properties of sonateh dam

Body type	**Earth dam with vertical clay core**
Normal water level (NWL)	**Changeable** (m)
Bed river elevation	1514 m
Type of spillway	Overflow spillway
Length of spillway (SL)	**Changeable** (m)
Length of crest	505 m
Width of crest	20 m
Slope of upstream side	1:2.2
Slope of downstream side	1:2
Minimum beneficiary level (50 years sediment)	1525 m
Total volume of reservoir	**Changeable** (Mm^3)
50 years sediment volume	2.68 Mm^3
Length of reservoir in direction of main channel (length of fetch)	9250 m
Maximum velocity of wind	90 km/h

TABLE 2. The percent of total cost during the construction period

Years	**2015**	**2016**	**2017**	**2018**	**2019**
Percent of total cost	10	20	25	25	20

TABLE 3. Properties of the used RGA

No. of variables	**No. of population**	**Crossover probability (%)**	**Mutation probability (%)**	**Mutation rate**
2	20	70	5	0.1

TABLE 4. The optimum benefit/cost ratio for the present values of the project

Optimum B/C	**B_T (MR)**	**C_T (MR)**	**B-C (MR)**	**ONWL (m)**	**OLS(m)**
1.782	1.7113×10^6	9.6036×10^5	7.5094×10^5	1578.43	11.32

TABLE 5. The optimum benefit/cost ratio by applying 10% inflation rate to both benefits and costs

Optimum B/C	**B_T (MR)**	**C_T (MR)**	**B-C (MR)**	**ONWL (m)**	**OLS(m)**
1.782	1.8824×10^6	1.0564×10^6	8.2590×10^5	1578.43	11.32

This means the project for the discount rate greater that 8.5% is non-economic and the amount of the benefit/cost ratio becomes smaller than 1, when the discount rate is equal to 8.5% the amount of the benefit/cost ratio is equal to 1.01, So, in this study to calculate the present values of the benefits and costs we considered the discount rate equal to 7% and used Equations (5) and (7). Because the interest and inflation rates are not clear exactly in future, so, in each project by considering a few rates of interest and inflation benefits and costs have been calculated. In the present project we considered three inflation rates, 10, 20 and 30%, and applied those to the benefits and costs of the project and then using the RGA the optimal benefit/cost ratio is calculated and the results are shown in Tables 8 to 11.

3. 2. 2. Application of the Real Genetic Algorithm (RGA)

After preparing a mathematical programing to calculate the objective function an improved RGA is used in MATLAB to maximize the objective function. Because the objective function is benefit/cost ratio so the problem is a maximization problem and to convert it to minimization the objective function is multiplied by a minus sign. The prepared mathematical programing can calculate each benefit and cost, and then benefit/cost ratio of the dam construction for each scenario. The properties of used RGA in this study are listed in Table 3.

3. 2. 3. Application of the Combined RGA and Benefit/Cost Analysis

The framework of the proposed methodology and the results are shown in Figure 3, and Tables 4 to 13, respectively. All costs and benefits of dam construction have been calculated using Equations (1) and (2), respectively. The results according to the present values of the project are listed in Table 4 and in Tables 5 to 7, 10, 20 and 30% inflation rates are applied to the both benefits and costs of the project, respectively, and as it is clear from these Tables the amount of the optimum benefit/cost ratio and NWL and LS are constant for all inflation rates and just the amount of the total benefit and cost have been changed. In Tables 8 to 10, 10, 20 and 30% inflation rates were applied just to the benefits, respectively, and the costs were constant, and as it is clear from these Tables the optimum benefit/cost ratio and NWL increased and the amount of the optimum SL decreased by increasing the inflation rates, because by increasing the amount of the benefits while the costs are constant the project becomes more economic and we can construct a higher dam but on the other hand by increasing dam height, length of spillway decreases as we can see it in Tables. Finally in Tables 11 to 13, 10, 20 and 30% inflation rates were applied just to the costs, respectively, and the benefits were constant, and as we can see in these Tables the amount of the optimum benefit/cost ratio and NWL decreased and the optimum SL increased by increasing in the inflation rates, and the reason is that by increasing the amount of the costs in the event that the benefits remain constant the project is not economic and we should construct a dam with smaller height and since the relationship between dam height and length of spillway is inverse the amount of SL becomes greater than before.

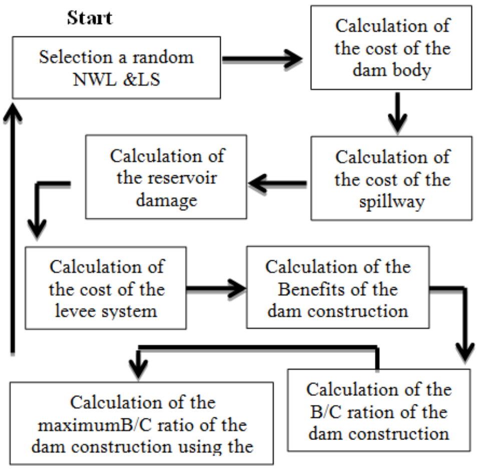

Figure 3. Framework of the proposed method

TABLE 6. The optimum benefit/cost ratio by applying 20% inflation rate to both benefits and costs

Optimum B/C	B_T (MR)	C_T (MR)	B-C (MR)	ONWL (m)	OLS(m)
1.782	2.0535×10^{6}	1.1524×10^{6}	9.0110×10^{5}	1578.43	11.32

TABLE 7. The optimum benefit/cost ratio by applying 30% inflation rate to both benefits and costs

Optimum B/C	B_T (MR)	C_T (MR)	B-C (MR)	ONWL (m)	OLS(m)
1.782	2.2247×10^{6}	1.2484×10^{6}	9.7630×10^{5}	1578.43	11.32

TABLE 8. The optimum benefit/cost ratio by applying 10% inflation rate just to the benefits

Optimum B/C	B_T (MR)	C_T (MR)	B-C (MR)	ONWL (m)	OLS(m)
1.960	1.8824×10^{6}	9.6014×10^{5}	9.2226×10^{5}	1579.00	11.15

TABLE 9. The optimum benefit/cost ratio by applying 20% inflation rate just to the benefits

Optimum B/C	B_T (MR)	C_T (MR)	B-C (MR)	ONWL (m)	OLS(m)
2.140	2.0535×10^{6}	9.6014×10^{5}	1.0934×10^{6}	1579.60	11.03

TABLE 10. The optimum benefit/cost ratio by applying 30% inflation rate just to the benefits

Optimum B/C	B_T (MR)	C_T (MR)	B-C (MR)	ONWL (m)	OLS(m)
2.317	2.2247×10^{6}	9.6014×10^{5}	1.2646×10^{6}	1579.85	10.87

TABLE 11. The optimum benefit/cost ratio by applying 10% inflation rate just to the costs

Optimum B/C	B_T (MR)	C_T (MR)	B-C (MR)	ONWL (m)	OLS(m)
1.620	1.7113×10^{6}	1.0564×10^{6}	6.5500×10^{5}	1578.50	12.88

TABLE 12. The optimum benefit/cost ratio by applying 20% inflation rate just to the costs

Optimum B/C	B_T (MR)	C_T (MR)	B-C (MR)	ONWL (m)	OLS(m)
1.485	1.7113×10^{6}	1.1524×10^{6}	5.5890×10^{5}	1577.37	13.41

TABLE 13. The optimum benefit/cost ratio by applying 30% inflation rate just to the costs

Optimum B/C	B_T (MR)	C_T (MR)	B-C (MR)	ONWL (m)	OLS(m)
1.370	1.7113×10^{6}	1.2484×10^{6}	4.6290×10^{5}	1577.03	13.94

The amount of the levee height in downstream of the reservoir dam for the present values is obtained and it is equal to 1.37 m.

The shortcoming of others' approaches is that they considered just one of the proposed parameter as a variable and assumed the others constant. Also the protection of the downstream area was not considered in the past researches.

4. CONCLUSION

In the paper, a new integrated methodology based on the RGA and benefit/cost analysis (BCA) is presented to calculate Optimum Normal Water Level (ONWL), Optimum Length of Spillway (OLS) and Optimum Levee Height (OLH) in reservoir dams. The objective function is benefit/cost ratio of dam construction. The aim of this study was considering flood control and cost of levee construction in downstream as additional items in a dam project and it is very helpful for decision making in dam construction projects. Also in this study, the first attempt was made to optimize NWL, SL and together through the advancement of mathematical and optimal modeling considering economic aspects of reservoir dams. The proposed methodology was applied for the Sonateh dam, as a case study, and the results can be remarked as follows:

1. The optimum benefit/cost ratio calculated considering three different inflation rates and they applied to the benefits and costs of dam construction, separately, and the results were listed in Tables 9 to 17.
2. By increasing the amount of inflation to the benefits, as it is expected, the amount of the optimum benefit/cost ratio increased, and for the cost it is vice versa.
3. The optimum benefit/cost ratio, NWL, LS and LH have been calculated by considering the present values of the dam construction, and the results are according to Table 8 and the last paragraph of the pervious section.
4. The proposed method is very rapid for running, in comparison with the present methods that need more time consuming and computational effort of comprehensive evaluation for running especially when the parameters are more than one for optimization, which shows it is more efficient for this problem. However, for a problem with spread search space or more variables this method may not be rapid and some amendments are needed to improve its performance.
5. The numerical model proposed here may also be combined with other techniques to further improve its data processing and evaluation capacity.

More additional items, such as encroachment; material and shape of the dam body and levee; upstream and downstream slopes of dam body; side slops of levee and etc., they all may be considered as decision variables to find the best benefit/cost ratio of reservoir dam construction as future works.

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Optimal Design and Benefit/Cost Analysis of Reservoir Dams by Genetic Algorithms Case Study: Sonateh Dam, Kordistan Province, Iran

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چکیده

در این مقاله از یک روش که در آن تحلیل سود بر هزینه و الگوریتم ژنتیک پیوسته با هم ترکیب شده‌اند برای طراحی سد مخزنی استفاده شده است. برای شبیه‌سازی محدوده مورد نظر و روندیابی سیلاب در مخرن سد به ترتیب از نرم افزار 4.0 HEC-RAS و Hydro-Rout استفاده شده است. برای یافتن حداکثر مقدار نسبت سود به هزینه ساخت سد یک برنامه کامپیوتری در نرم‌افزار MATLAB نوشته شده و با برنامه بهینه‌سازی پیوند داده شده است. پس از تحلیل حساسیت برنامه بهینه‌سازی، مقادیر جهش و تولید مثل به ترتیب برابر با ۰/۰۵ و ۰/۷ به دست آمدند. در تحقیق حاضر تابع هدف نسبت سود به هزینه ساخت سد مخزنی است. برنامه یاد شده امکان محاسبه مقادیر بهینه رقوم نرمال، طول سرریز و ارتفاع خاکریزپایین‌دست سد مخزنی، با در نظر گرفتن کنترل سیلاب و هزینه ساخت سد مخزنی، را فراهم می‌سازد. روش معرفی شده در این مقاله اولین تلاش برای به دست آوردن مقادیر بهینه پارامترهای یاد شده با در نظر گرفتن موضوع کنترل سیلاب و جنبه‌های اقتصادی سد مخزنی و همچنین روشی قدرتمند برای محاسبه مقادیر پارامترهای یاد شده است. نتایج به دست آمده نشان می‌دهد که برای چنین مسائلی که تابع هدف غیرخطی بوده و استفاده از روش‌های دیگر بهینه‌سازی با مشکلاتی روبه‌رو خواهند بود، الگوریتم ژنتیک ابزاری دقیق و قدرتمند خواهد بود.

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