Advances in Engineering Research, volume 138
2nd International Conference on Machinery, Electronics and Control Simulation (MECS 2017)

Study on Removal and Replacement of the Kariba Dam

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Keywords: Kariba Dam Kriging Interpolation principal component analysis genetic algorithm

Abstract. The Kariba Dam on the Zambezi River is in dire need of maintenance. This paper is intended to study the strategy of removing and replacing the Kariba Dam.The elevation map of the watershed of Zambezi River is made and rasterized by using Kriging Interpolation. Combining the precipitation and geological condition of the basin, this paper identifies 21 points as candidate points and ranks them with the method of principal component analysis. Then the lowest cost is regarded as the objective function, simultaneously capabilities of water resource utilization and levels of protection for Lake Kariba regarded as the restriction. Eventually, this paper determines the specific number, 18, of dams through the genetic algorithm.

1. Introduction

The Kariba Dam, completed in the year of 1963 and built to generate hydropower basically, is one of the larger dams in Africa. Recently, a 2015 report by the Institute of Risk Management of South Africa warned that the dam is in dire need of maintenance. This paper provides a solution for one of the options of interest to ZRA, removing the Kariba Dam and replacing it with a series of smaller dams along the Zambezi River.

2. Locations of new dams

First of all, the elevation map of the Zambezi River is made and rasterized by using Kriging Interpolation with the purpose of dividing the watershed into small regions as shown in **Figure 1**; each region is likely to be the site of the dam. Since the primary objective of the Kariba Dam is power generation and flood control, while replacing the Kariba Dam, the hydroelectric energy should be considered primarily. By consulting the literature [1], after analyzing the elevation map and combining the precipitation of the basin, we identified nearly 30 sites with large drop and rich hydroelectric energy. Taking into account another indispensable condition - geological condition in the dam construction, we finally identify 21 points as candidate points.

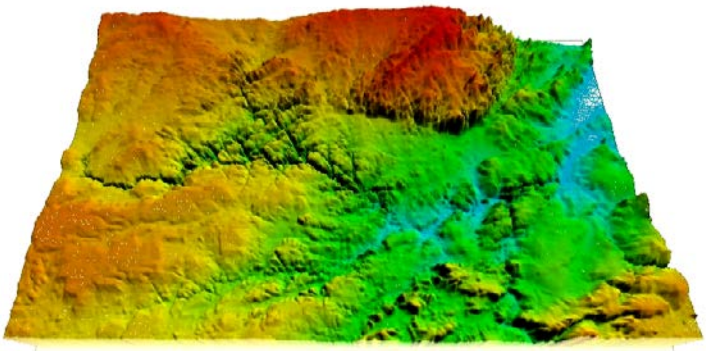

Figure 1 Elevation map

Because each candidate's location and situation are different, we take method of principal component analysis to evaluate and rank these 21 points. The top-ranking represents that it is more conducive to the construction of the dam, that is, it should be given priority. The main factors involved in the assessment and the assessment method are shown in **Table 1**. The results of principal component analysis are shown in **Table 2**.

Table 1 Main factors and assessment method

Main factors	Assessment method
Forest restraint factor	Whether there is forest nearby and how far
Hydroelectric factor	Amount of water resource
Urban distance factor	Whether there is city nearby and how far
Dam scale factor	Size of the dam
Farmland irrigation factor	Whether there is farmland nearby and how much area

Table 2 The results of principal component analysis

Number	Characteristic root	Contribution rate	Cumulative contribution rate
1	1.6204	32.41	32.41
2	1.3933	27.8659	60.28
3	1.0052	20.1036	80.38
4	0.7109	14.2185	94.60
5	0.2702	5.4038	100.00

After analysis, we get the sort order on the candidate points, as shown in **Table 3.**

Table 3 The sort order on the candidate points

Dam site									
south latitude	east longitude	Width (m)	Height (m)	City	Forest	Farmland	No.	Ranking	Evaluation value
17.98	26.07	300	40	∞	∞	60	1	1	0.9067
17.92	26.27	450	80	∞	∞	0	2	14	0.1883
17.99	26.87	600	90	∞	∞	0	3	5	0.5957
16.82	28.76	600	90	∞	∞	20	4	6	0.5172
16.49	28.8	450	70	5	∞	0	5	16	-0.3002
15.9	28.59	300	50	∞	∞	0	6	15	-0.2827
15.64	30.02	300	50	∞	∞	0	7	10	-0.0472
14.45	30.45	250	40	∞	∞	0	8	14	-0.2471
16.61	34.02	550	80	∞	5	30	9	3	0.6411
15.85	34.74	250	35	5	∞	0	10	20	-0.9001
15.82	34.7337	150	30	9	∞	0	11	21	-1.1
15.68	34.74	400	30	∞	3	0	12	11	-0.0859
15.87	29.09	600	80	∞	5	0	13	4	0.6056
15.94	28.91	300	45	∞	∞	80	14	2	0.7799
17.73	34.76	300	50	∞	∞	0	15	17	-0.5256
15.59	34.75	300	30	∞	∞	0	16	18	-0.5256
17.87	27.21	300	40	∞	∞	0	17	12	-0.2042
17.58	27.1	300	40	∞	∞	0	18	13	-0.2042
17.11	28.03	600	80	∞	1	0	19	7	0.4486
16.5	28.124	200	30	2	1	50	20	19	-0.7089
17.95	27.07	600	90	∞	2	0	21	8	0.4486

Note that the red numbers in the table indicate the parameters of the Shire River. The positive sign of the evaluation value indicates that the benefit is greater than the cost.

3. Number of new dams

Because the dam is a project with large scale and large investment, the greater the number of dams is, the greater the ability to modulate water is, the lower the cost of hydropower generation is [2]. However, the corresponding costs of overall construction and operation management will increase instead. So there must be an optimal number of dams that can make the total cost of the dam-system minimized. In view of the economic situation in Africa, we propose to use the lowest cost as the objective function, to use the subject of 'the same overall water management capabilities as the existing Kariba Dam while providing the same or greater levels of protection and water management options for Lake Kariba' as the restriction. Eventually, we are able to determine the specific number of dams.

Model Building

$$\begin{cases} minF(m) = \sum_{i=1}^{m} Q_i \left(X_1, X_2, X_3, X_4 \right) - \sum_{i=1}^{m} (B_i - C_i) \cdot n \\ \sum_{i=1}^{m} N_i(X_1) \geq N \\ \sum_{i=1}^{m} M_i(X_1) \geq M \\ 0 \leq m \leq 20 \end{cases}$$

Parameter Description

In this model, the first term in the objective function represents the construction cost; the second term represents net income in the run-time. Constraint 1 indicates that the amount of electricity generated is greater than that of current Kariba Dam; Constraint 2 indicates that the sum of new dam capacity is greater than or equal to the capacity of Kariba Dam; Constraint 3 indicates that the number of dams is between 10 and 20.

Parameter Determination:

- Determination of Q_i: Q_i is a regression equation related to dam length, height, installed capacity and construction time. See the specific regression expression :

$$Y = -7.0419 + 0.0143X_1 + 0.0560X_2 + 0.0048X_3 + 0.2467X_4$$

- Determination of B_i and C_i: *Bi* and C_i are the comprehensive evaluation indexes of three major aspects (27 small aspects). It is emphasized that B_i and C_i represent very comprehensive costs and benefits, so it is reasonable to assume that the difference between *B* and *C* is sufficient to represent the water management capacity of Lake Kariba.
- Determination of *n*: It is known that for small and medium-sized dams, *n* is usually 10 years.
- Determination of N_i: The amount of electricity generated is an amount related to the width and height of the dam, according to the literature [3].

Estimation formula is $N = 9.81 \times X_1 \times 5 \times X_2^2$

- Determination of M_i: $M_i = 330 X_2^{1.55}$.

The model above is a constrained nonlinear programming model. The objective function is a convex function and the feasible region is a nonconvex set. Therefore, it is difficult to achieve the optimal solution by using the general constrained nonlinear programming model (taking SUMT method for example). However, when *fmincon ()* function in Matlab optimization toolbox is used to solve the constrained nonlinear programming model, it may lead to no optimal solution when the value of R-r is small. In order to solve the above constraint nonlinear programming model, the **genetic algorithm** is adopted. The specific algorithm parameters are shown as follows:

Table 4 The specific algorithm parameters of genetic algorithm

Name of parameter	Symbol	Numerical value
population size	*M*	100
Maximum algebra	*G*	5000
crossing-over rate	*pc*	1
aberration rate	P_m	0.1

4. Conclusions

The result indicates that the optimal number of dams is 18, in which case the cost is the lowest. Therefore, the first 18 locations above (shown in **Table 3**) can be selected as the location of the new dam system.

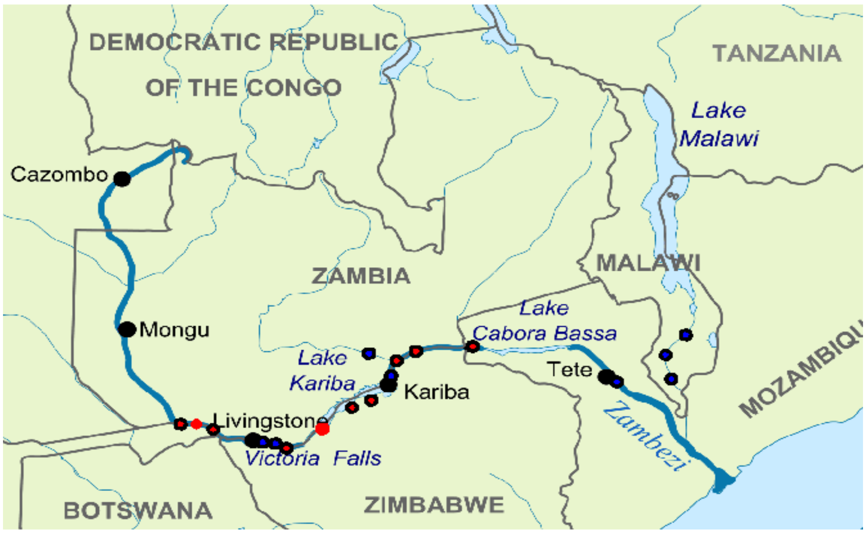

Figure 2 The selected 18 locations

Blue dots indicate dam sites where hydroelectric energy potential is high. Red dots indicate dam sites where hydroelectric energy potential is low. The evaluation of costs of new dam system is shown as **Table 5.**

Table 5 The evaluation of costs of new dam system

ranking	southern latitude	east longitude	cost(billion)	Duration of recovery cost(year)
1	17.98	26.07	0.08346112	0.556407467
2	15.94	28.91	0.11446298	0.763086533
3	16.61	34.02	0.73653488	4.910232533
4	15.87	29.09	0.81556896	5.4371264
5	17.99	26.87	0.89558384	5.970558933
6	16.82	28.76	0.89558384	5.970558933
7	17.11	28.03	0.81556896	5.4371264
8	17.95	27.07	0.89558384	5.970558933
9	17.92	26.27	0.57846672	3.8564448
10	15.64	30.02	0.145818	0.97212
11	15.68	34.74	0.16763584	1.117572267
12	17.87	27.21	0.08346112	0.556407467
13	17.58	27.1	0.08346112	0.556407467
14	14.45	30.45	0.0100776	0.067184
15	15.9	28.59	0.145818	0.97212
16	16.49	28.8	0.50657452	3.377163467
17	17.73	34.76	0.145818	0.97212
18	15.59	34.75	0.02251688	0.150112533

5. References

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[3]. WC Study . Kariba Dam Zambia and Zimbabwe.