For office use only	Team Control Number	For office use only
T1 ________________	**64548**	F1 ________________
T2 ________________		F2 ________________
T3 ________________	Problem Chosen	F3 ________________
T4 ________________	**A**	F4 ________________

2017
MCM/ICM
Summary Sheet

Where should the Kariba Dam go?

Summary

In this paper, we provide a brief assessment of the three options offered by the Zambezi River Authority and a detailed analysis of option III - replace the Kariba Dam with multiple dam system.

On the basis of considering the possible costs (permanent construction investment, reservoir area resettlement, annual running cost of hydropower station, basic depreciation expense and demolition fee), and potential gains (shipping, power generation, tourism, etc.), we establish the Cost-Benefit Analysis model,which is a comprehensive evaluation model taking the maximum total return of the dam area as the evaluation criterion.The results of the model help us rank the three options and naturally come to an assessment report.

Next, we choose the reasonable locations and number of small dams. Taking into account the altitude, slope, population density, precipitation, economic development level, we use Analytic Hierarchy Process to build the weight between the factors. Then, using the GIS spatial modeling idea, the weight of each factor is input into the model for spatial matching modeling. And we obtain the area suitable for the dam site selection. Using Lingo software, the optimal number of small dams is 10. According to the indicators and Google Earth and the data from other tools, we find 20 possible locations that meet the constraints. Finally, a comprehensive evaluation model of TOPSIS is established. According to the level of the comprehensive evaluation scores in 20 possible areas, the optimal 10 dam sites are selected and expressed in Google Earth.For the decision support system of the multiple dam system, we build the Harmony Search Model, which takes the benefit maximization of power generation and irrigation as the objective function, and gets the optimal release trajectories and storage trajectories of each dam. We assume extreme conditions to be floods and droughts at different locations,then calculate the optimal release trajectories and storage trajectories in extreme cases and provide the corresponding measures.

Contents

1 The Assessment Report

We choose two indices to measure the three options :1)rebuilding the dam; 2) repair the dam; 3) replace the dam with a series of ten to twenty smaller dams

Net Present Value (NPV):NPV is defined as the total present value (PV) of a time series of cash flows. It is a standard method for using the time value of money to appraise long-term project. The NPV has been the most frequently used of all economic measures of efficiency. NPV can be defined as:

$$NPV = \sum_{t=0}^{N} \frac{(B_t - C_t)}{(1+i)^t}$$

Where B_t = Benefit at time t; C_t = Cost at time t; i = Discount rate; n =Number of years.

A project is acceptable to the government when the NPV is larger than zero. If the NPV of a project is larger than the other, then the former one is better.

Internal Rate of Return (IRR). The IRR is the discount rate at which the net present value is equal to zero. It can be defined as r:

$$NPV = \sum_{t=0}^{N} \frac{(B_t - C_t)}{(1+i)^t} = 0$$

WhereB_t = Benefit at time t; C_t = Cost at time t; i =Discount rate; n =Number of years.

A project is acceptable if its IRR exceeds some specified interest or discount rate. In terms of two mutually exclusive projects, this criterion indicates that the project with the highest IRR should be selected[4].

Because The Republic of Zambia is a developing country and its high inflation rate, we use the discount rate at 8% . According to the metrics mentioned above, we calculate the NPV and IRR of three options, the present values of benefits and costs at a 8% discount rate are shown in Table 1.

The NPV of three options are **$115845, $105,773.12, $106,388.00** .The IRR of three options are **14.49%, 7.23%, 9.17%**. It is obvious that NPV and IRR of the first option is the largest

As a consequence,the best solution is to repair the dam. And the second best solution is to replace the Kariba Dam with a series of smaller dams. The worst solution is to rebuild the dam[19].

Items	Option Ⅰ PV at 8% Discount Rate (Million USD)	Option Ⅱ PV at 8% Discount Rate (Million USD)	Option Ⅲ PV at 8% Discount Rate (Million USD)
Benefits			
1. Sale of Water	$128,443.70	$129,194.60	$135,583.80
2. Sale of Power	$83,294.30	$84,785.60	$73,216.90
3. Saving from Buying Drinking Water	$233.10	$433.40	$374.10
4. Benefits forgone for constructing the new dam	$540.00	$509.40	$524.30
5. New tourism value created by the reservoir	$151.40	$142.80	$147.00
Costs			
1. Land acquired and Resettlement costs	$1,388.90	$1,310.30	$1,348.40
2. Direct Construction Cost for Dam	$17,701.30	$13,502.30	$15,413.60
3. Indirect Construction Cost	$2,655.20	$2,025.30	$2,312.00
4. Direct Construction Cost for Generation System	$2,265.20	$1,857.70	$2,047.90
5. Indirect Construction Cost	$339.80	$278.70	$307.20
6. Power Delivery Cables	$38.70	$30.60	$34.30
7. Preparation Fee for Dam Construction	$4,349.10	$3,191.80	$3,711.60
8. Preparation Fee for Generation System	$528.70	$343.30	$424.60
9. Maintenance Costs	$20,486.20	$47,950.10	$38,523.30
10. Annual Personnel Expenditure	$14,700.00	$9,440.80	$6,115.90
11. Basic water treatment cost	$2,839.50	$1,488.20	$1,026.70
12. Replacement Costs	$337.90	$303.50	$319.90
13. NPV (W/O considering the ecosystem, cultural and tourism loss)	$169,082.80	$150,245.40	$146,465
14. NPV	$115845	$105,773.12	$106,388.00
IRR	**14.49%**	**7.23%**	**9.17%**

Table1 NPV of the three options.

2 Introduction

2.1 Background

The **Kariba Dam** is a double curvature concrete arch dam in the Kariba Gorge of the Zambezi river basin between Zambia and Zimbabwe. Italian constructed the dam between 1955 and 1959 at a cost of $135,000,000 for the first stage with only the Kariba South power cavern. The overall impacts of the dam are displayed in Table 2. Although the construction of the dam was controversial, the Kariba Dam undoubtedly stimulated the local economic development through hydro-electric stations and specifically increased the performance of the agricultural, manufacturing and tourism sectors. [8] Unfortunately, the Institute of Risk Management of South Africa warned that the dam needed the maintenance. There are three options for us to choose: **1) rebuilding the dam; 2) repair the dam; 3) replace the dam with a series of ten to twenty smaller dams**.

	Positive Impact	Negative Impacts
Social Aspect	·Provide water and power	·Displace and Resettle indigenous people
	·Prevent flood	·Destroy domestic culture and reduce the recreation value
	·Create tourism value	·Prevent access to the river by indigenous people
		·Damage the grazing industries and fishery
Environmental Aspect	·Replace the thermal power plant and reduce the emission of carbon dioxide	·Destroy the habitats of animal
		·Clear the land
		·Change the temperature and nutrient contents of the stream
		·Block the movement offish
		·Emit methane due to the decomposition of bacteria in reservoir
		·Erode the river bank

Source: WCD, 2000

Table 2 Positive and Negative Impacts of Dams

2.2 Restatement of the problem

The problems we need to solve in this paper are:

- A brief assessment of the three options
- Specify the number and the placement of smaller dams while maintaining existing capabilities of the water management, abilities of the protection and levels of management options
- Design a decision support system for multiple dam system for modulating the water flow under regular and extreme conditions and address the restrictions for smaller dams

2.3 Our work

We apply a **Cost-Benefit Analysis(CBA)** to these options respectively with two common measures: **Net Present Value (NPV), Internal Rate of Return**. We compare the results of options under two measures and come to a brief assessment.

Next, we selected the five indicators of **altitude, slope, population density, precipitation, and economic development level**, using the **Analytic Hierarchy Process(AHP)** to determine the weight of each indicator. And then use **ARCGIS** to establish the model, and get the region with the highest comprehensive evaluation value. In these areas, we have selected ten sites for the construction of small dams[17].

3 General Assumptions

In order to simplified the problem, we suppose that all the benefits and costs associated with the Kariba dam on the Zambezi River are measurable and can be measured using current market values based on the following assumptions.

- Linear additive. The total cost and total revenue of the three solutions to the Kariba dam can be divided into the various costs and benefits associated with them, and these costs and benefits are independent of each other, linearly additive .
- Measurable. In addition to the transformation from the direct costs and benefits of dams to the market value of the factors, the potential costs and potential benefits can also be measured using market value. Revenue, such as the amount and value of bottled water saved as a result of dam establishment, can be reliably predicted, and the benefits associated with future new tourism projects can be predicted. Costs, such as land expropriation costs and occupation of land loss can be accurately measured, the existing related to the loss of tourist attractions can be measured. As far as possible to ensure that the requested data contains all the costs and benefits and can be measured in the same unit of measurement.
- Estimability. The inflation rate in the coming years can be accurately estimated within the useful life of the dam. From the inflation rate of future years, we can calculate the future price level and turn future proceeds and costs of each year into the present value.
- Predictability. Except for the costs and benefits incurred during the reconstruction of the dam, the costs and benefits of each year of future use can be measured.

4 The Analytic Hierarchy Process and ARCGIS Model

In this section, we focus on the number and location of small dams. We select five indicators, and use the analytic hierarchy process to calculate the weight of five indicators. The weight will be taken into the ARCGIS modeling. Finally, we got the suitable location to build the dams.

The analytic hierarchy process (AHP) is a structured technique for organizing and analyzing complex decisions, based on mathematics and psychology. It was developed by Thomas L. Saaty in the 1970s and has been extensively studied and refined since then. The AHP plays a significant role in deciding the weight of effective factors.

In order to determine the weight of effective factors in selecting an appropriate site, we conduct studies and list the common effective attributes (criteria). These attributes are shown in Figure1.

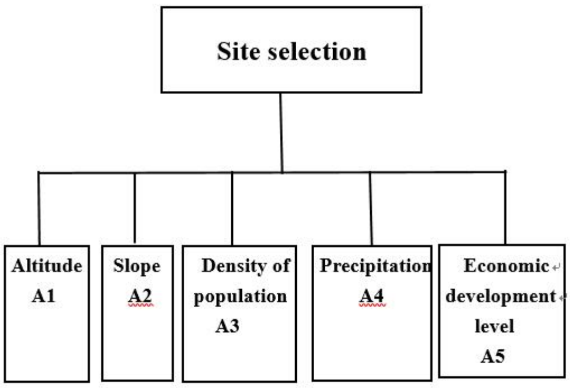


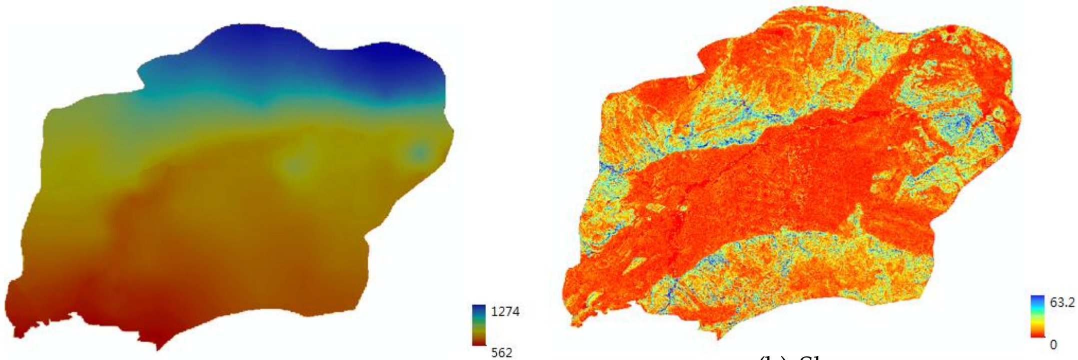
Figure 1: Five common effective attributes

4.1 A brief description of five indicators

Altitude: The high altitude is not conducive to building a dam because of the construction difficulty and high cost while gentle terrain is conducive to the construction of dams.

Slope: The geological conditions of steep place is unstable and prone to rubble, which means the larger security risk. Meanwhile, suitable slope can bring in enough potential energy to generate electricity.

Density of population: The higher the density, the greater the demand for water. If dams are closer to populated areas, then the length of Irrigation Pipe is shorter, and the cost is lower.



(a) Altitude (b) Slope

Figure 2: The altitude and slope of Zambezi River Basin

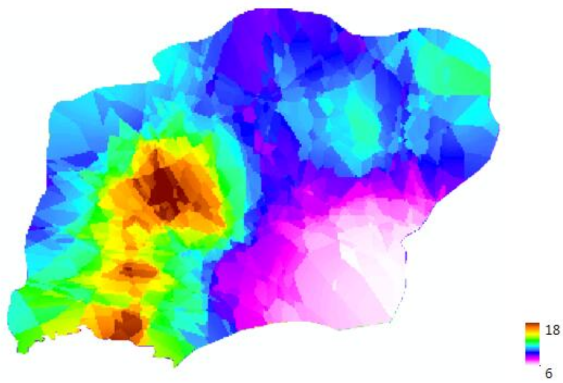


Figure 3: The density of population of Zambezi River Basin

Precipitation: The greater the precipitation, the abundant hydropower. Large rainfall is beneficial to irrigation, power generation.

Economic development level: The effect of dam construction on agriculture and industrial development, power generation, fishery, etc., which are related to economic development, are regarded as important attributes for selecting the dam site[6]

4.2 The Analytic Hierarchy Process

Using AHP, we construct five indicators comparison matrix as Table 3.

According to the mathematical formula $T_{ij} = \frac{A_{ij}}{\sum A_{ij}}$, we get a new T matrix. The sum of the rows of the T matrix yields its eigenvectors. Next, we normalize the eigenvectors according to the mathematical formula $W_i = \frac{B_j}{\sum B_j}$to obtain the weights of the five indexes as Table 4.

——	A1	A2	A3	A4	A5
A1	1	9	7	5	3
A2	1/9	1	1/3	1/5	1/7
A3	1/7	3	1	1/3	1/5
A4	1/5	5	3	1	1/3
A5	1/3	7	5	3	1
SUM	1.787	25	16.333	9.533	4.676

Table3 Five Indicators Comparison Matrix

	T1	T2	T3	T4	T5	SUM	W	W%
T1	0.56	0.36	0.429	0.524	0.642	2.515	0.503	50.30%
T2	0.062	0.04	0.02	0.021	0.031	0.174	0.035	3.50%
T3	0.08	0.12	0.061	0.035	0.043	0.339	0.068	6.80%
T4	0.112	0.2	0.184	0.105	0.071	0.672	0.134	13.40%
T5	0.187	0.28	0.306	0.315	0.214	1.302	0.26	26%
SUM	1.001	1	1	1	1.001	5.002	1	100%

Table4 The Weights of the Five Indicators

4.3 The ARCGIS Model

Based on the weights above,we then use ARCGIS to build a model and solve the possible area for site selection.The modeling process is shown in Figure 4.

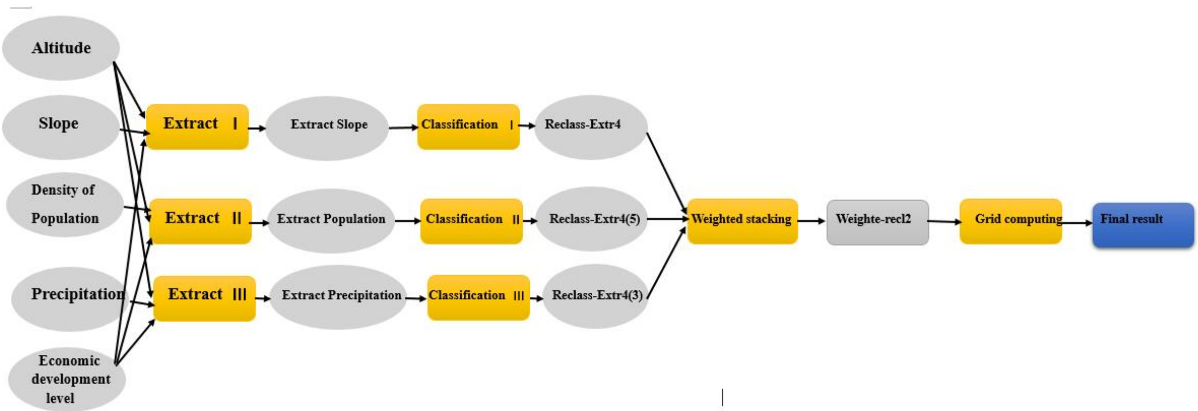


Figure 4: The process of ARCGIS Modeling

Generated GIS graphics tells us the suitable placement of dams. The blue area indicates where the dam is suitable for construction while the yellow area indicates the river network.

Using Lingo software, the optimal number of small dams is 10. According to the indicators and Google Earth and the data from other tools, we find 20

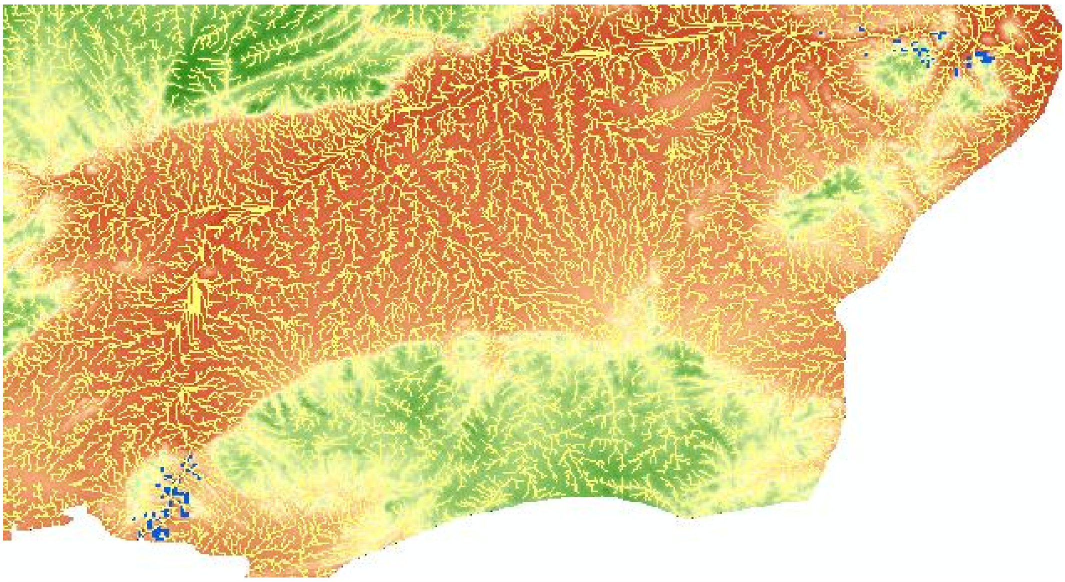


Figure 5: The GIS graphics of the placement

possible locations that meet the constraints. Next, we establish a comprehensive evaluation model of TOPSIS. According to the level of the comprehensive evaluation scores in 20 possible areas,we compare ARCGIS's blue area with the actual location in Google Maps,select the optimal 10 dam sites and express them in Google Earth.

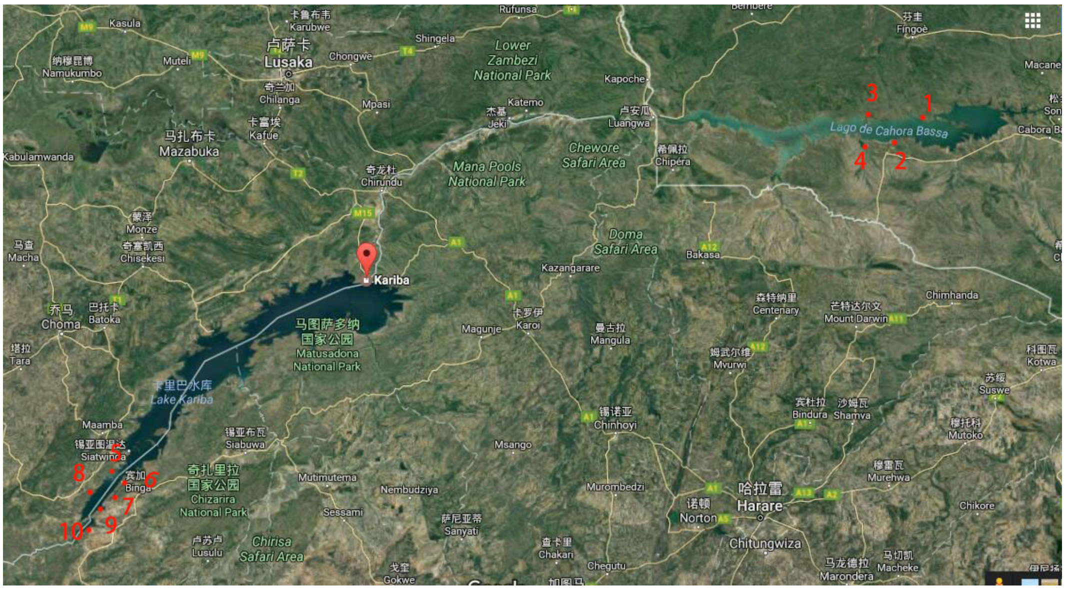


Figure 6: The 3D map of the placement

$$1: Maravia15.58S, 31.92E; \qquad 2: Maravia15.74S, 31.77E$$

$$3: Maravia15.60S, 31.68E; \qquad 4: Maravia15.75S, 31.66E$$

$$5: Siatwinda17.59S, 27.25E; \qquad 6: Binga17.63S, 27.33E$$

$$7 : Binga17.67S, 27.30E; \qquad 8 : Sinazongwe17.69S, 27.16E$$
$$9 : Binga17.74S, 27.25E; \qquad 10 : Binga17.91S, 27.11E$$

5 The Harmony Search Model

5.1 A brief introduction of the model

A dam is a barrier structure across flowing water, and the operation of a multiple dam system is a complex decision-making process with many variables and constraints.

Traditionally researchers have used mathematical optimization techniques with linear programming (LP) or dynamic programming formulation to find every schedule for each dam in a system.[10] However, most of the mathematical models are valid only for simplified dam systems. Accordingly, during the past decade, a metaheuristic technique-genetic algorithm (GA), has absorbed great attention among dam researchers.

Lately, another metaheuristic algorithm-harmony search (HS), has been developed and applied to various engineering problems such as water network design , offshore structure design , and hydrologic parameter estimation . The results of those applications showed that HS could be a competent alternative to existing metaheuristics such as GA. So we use HS to solve the multi-dam system operation problems.[15]

5.2 The establishment of the model

The HS algorithm is originally inspired from a music improvisation process . While it basically mimics behaviors of musicians such as memory consideration, pitch adjustment, and random consideration, the HS model also has problem-specific features in every different application.[9]

For the multiple dam system, the HS model has the following objective function:

$$MaxZ = \sum\sum P_i(t)R_i(t) + \sum\sum b_i(t)R_i(t)$$

where $R_i(t)$ = discrete water release in time t from dam i ;$p_i(t)$ =unit benefit from hydropower generation; $b_i(t)$ =unit benefit from irrigation.

The water release $R_i(t)$ should locate between lower and upper limits:

$$R_i^{MIN}(t) \leq R_i(t) \leq R_i^{MAX}(t)$$

Also, the model should satisfy continuity constraint as follows:

$$S_i(t+1) = S_i(t) + I_i(t) + MR_i(t)$$

where $S_i(t)$ = vector of dam storages; $I_i(t)$ =vector of inflows to each dam; M =dam connection matrix.

The dam storage $S_i(t)$should also locate between lower and upper limits:

$$S_i^{MIN}(t) \leq S_i(t) \leq S_i^{MAX}(t)$$

Once the optimal operation of the multiple dam system is formulated, HS begins to find the optimal solution. For the first step, HS randomly generates solution vectors as many as **HMS (harmony memory size)**, then store them in **HM (Harmony Memory)** as follows:

$$\begin{bmatrix} R_1^1 & R_2^1 & \cdots & a_N^1 & \vdots & Z(R^1) \\ R_2^1 & R_2^2 & \cdots & a_N^2 & \vdots & Z(R^2) \\ \vdots & \cdots & \cdots & \cdots & \vdots & \cdots \\ R_1^H MS & R_2^H MS & \cdots & a_N^H MS & \vdots & Z(R^N) \end{bmatrix}$$

where N =number of decision variables (= number of dams $\times$number of time steps).

Next,we use random selection, memory consideration, and pitch adjustment to generate **R** randomly.Then if the new solution violates the constraints,it still may be included in **Harmony Model** with penalty f_p. If the new solution is better than the worst solution in the original harmony,then the former one will replace the latter.And the computation will be terminated when the HS model reaches MaxImp (maximum number of improvisations).

5.3 The application of the model

5.3.1 The operation in the normal water cycle

We have 24 hours a day as an example, 24 hours will be divided into 12 time periods.The ten dams are divided into two parts and we first study the four dams in the east.The goal is to obtain optimal release trajectories and storage trajectories over twelve time periods in the normal water cycles.

The water storage capacity of the dam is 185 cubic kilometers, in order to maintain the original water storage capacity, we assume that the maximum storage capacity of each dam is not less than 18.5 cubic kilometers.

The releases from dams through turbines are as follows:

$$0.0 \leq R_1 \leq 3$$

$$0.0 \leq R_2, R_3 \leq 6$$
$$0.0 \leq R_4 \leq 7$$

The dam storages are as follows:

$$0.0 \leq S_1, S_2, S_3, S_4 \leq S_{MAX}(S_{MAX} \geq 18.5)$$

Based on the research of Wardlaw, R., Sharif, M.[18]on the enhanced GA,we apply the following algorithm parameters: $HMS = 30; HMCR = 0.95; PAR = 0.05$; and $MaxImp$ (= Number of Function Evaluations) = 35,000.

HS model gives us five satisfactory solutions.Table5 shows one (HS4) of five optimal water release schedules,table6 shows one (HS4) of five optimal water storage schedules and Figure8 shows corresponding release and storage trajectories in east four dams.As for the solutions for the six dams in the west,they can be obtained in the same way.So this paper omits the solutions for the sake of time.

Time	Dam1	Dam2	Dam3	Dam4
0	1.0	4.0	0.0	0.0
1	0.0	1.0	0.0	2.0
2	0.0	2.0	4.0	7.0
3	2.0	0.0	4.0	7.0
4	3.0	3.0	4.0	7.0
5	3.0	3.0	4.0	7.0
6	3.0	4.0	4.0	7.0
7	3.0	4.0	4.0	7.0
8	3.0	4.0	4.0	7.0
9	3.0	4.0	4.0	7.0
10	3.0	4.0	4.0	0.0
11	0.0	3.0	0.0	0.0

Table5 Optimal Water Release Schedule in HS4

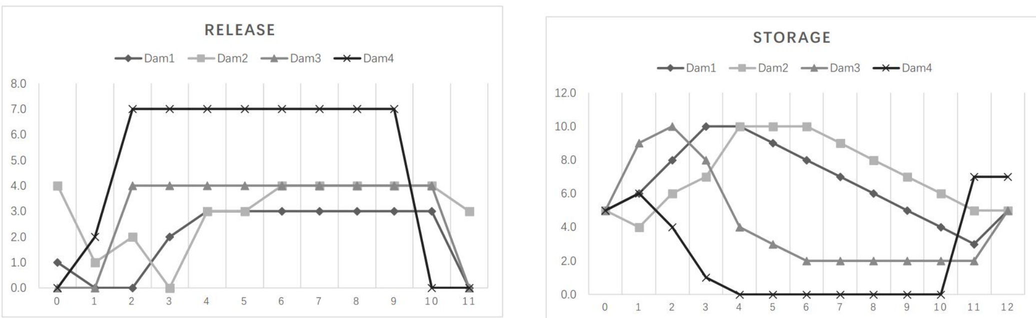
(a) 1

Time	Dam1	Dam2	Dam3	Dam4
0	5.0	5.0	5.0	5.0
1	6.0	4.0	9.0	6.0
2	8.0	6.0	10.0	4.0
3	10.0	7.0	8.0	1.0
4	10.0	10.0	4.0	0.0
5	9.0	10.0	3.0	0.0
6	8.0	10.0	2.0	0.0
7	7.0	9.0	2.0	0.0
8	6.0	8.0	2.0	0.0
9	5.0	7.0	2.0	0.0
10	4.0	6.0	2.0	0.0
11	3.0	5.0	2.0	7.0
12	5.0	5.0	5.0	7.0

Table 6 Optimal Water Storage Schedule in HS4

(b) 2

Figure 7: The optimal release trajectories and storage trajectories of HS4



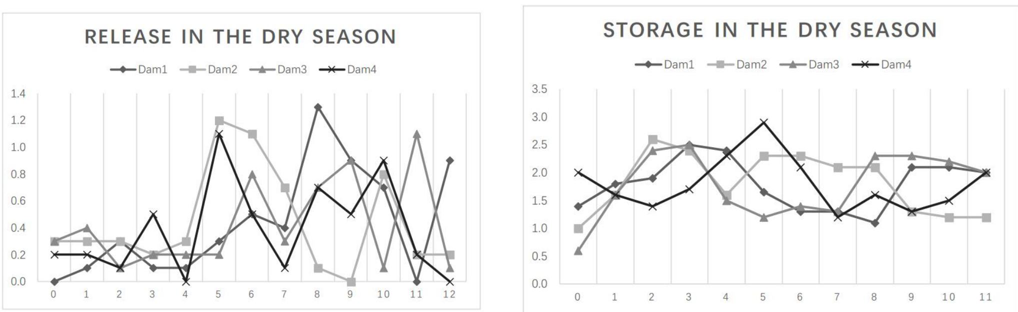
(a) Release (b) Storage

Figure 8: The optimal release trajectories and storage trajectories of HS4

5.3.2 The operation in the extreme condition

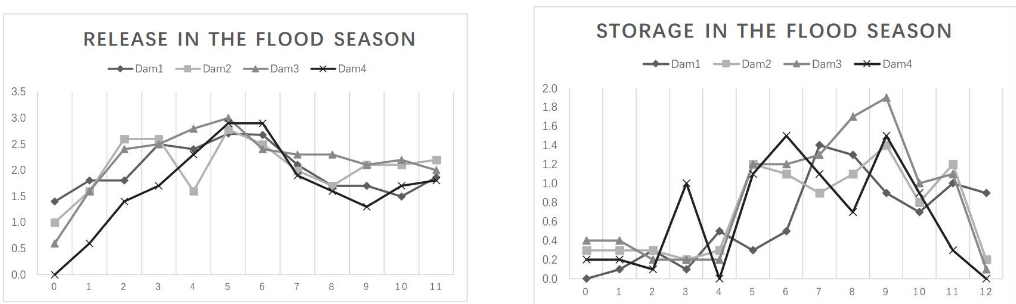
To address the restrictions of different dams in the extreme conditions.We first suppose the extreme conditions as the flood season and dry season.In flood season,emptying the reservoir,venting the sand,reinforce dams and transfer people around the dam are some of the common measures to avoid the risk of dikes. In the low water period, properly exploiting groundwater and restricting agricultural water are quite normal.

We use HS model mentioned above to calculate the specific of the four east dams.We select one day from the dry season and the flood period to represent the dry season and flood season.Similarly,we divided this day into 12 time periods.Finally we obtain the release trajectories and storage trajectories in the dry season and flood season as Figure9 and Figure10.



(a) Release (b) Storage

Figure 9: The optimal release trajectories and storage trajectories in the dry season



(a) Release (b) Storage

Figure 10: The optimal release trajectories and storage trajectories in the flood season

6 Conclusions

In this paper, we design the model to solve the problem of the Kariba Dam. We should choose to repair the dam according to the CBA model. The CBA model tells the net present value of three options are $\$115845, \$105, 773.12, \$106, 388.00$ .The IRR of three options are 14.49%, 7.23%, 9.17%.The first option-repairing the dam has the highest NPV and IRR.

Next, we deal with the location and number of multiple dam system. We adopt the GIS spatial matching modeling thought, integrate AHP method, get the suitable area of the site. With TOPSIS comprehensive evaluation model and the 3D map in the Google Earth, we mark out 10 optimal solutions. They are:

$$1 : Maravia 15.58S, 31.92E; \qquad 2 : Maravia 15.74S, 31.77E$$

$$3 : Maravia 15.60S, 31.68E; \qquad 4 : Maravia 15.75S, 31.66E$$

$$5 : Siatwinda 17.59S, 27.25E; \qquad 6 : Binga 17.63S, 27.33E$$

$$7 : Binga 17.67S, 27.30E; \qquad 8 : Sinazongwe 17.69S, 27.16E$$

$$9 : Binga 17.74S, 27.25E; \qquad 10 : Binga 17.91S, 27.11E$$

To follow next, we choose HS model to manage multiple dam system in the normal conditions to maximize their utility. The optimal storage and release in the normal water cycle are displayed in the Figure11

Time	Dam1	Dam2	Dam3	Dam4
0	1.0	4.0	0.0	0.0
1	0.0	1.0	0.0	2.0
2	0.0	2.0	4.0	7.0
3	2.0	0.0	4.0	7.0
4	3.0	3.0	4.0	7.0
5	3.0	3.0	4.0	7.0
6	3.0	4.0	4.0	7.0
7	3.0	4.0	4.0	7.0
8	3.0	4.0	4.0	7.0
9	3.0	4.0	4.0	7.0
10	3.0	4.0	4.0	0.0
11	0.0	3.0	0.0	0.0

Table5 Optimal Water Release Schedule in HS4

(a) 1

Time	Dam1	Dam2	Dam3	Dam4
0	5.0	5.0	5.0	5.0
1	6.0	4.0	9.0	6.0
2	8.0	6.0	10.0	4.0
3	10.0	7.0	8.0	1.0
4	10.0	10.0	4.0	0.0
5	9.0	10.0	3.0	0.0
6	8.0	10.0	2.0	0.0
7	7.0	9.0	2.0	0.0
8	6.0	8.0	2.0	0.0
9	5.0	7.0	2.0	0.0
10	4.0	6.0	2.0	0.0
11	3.0	5.0	2.0	7.0
12	5.0	5.0	5.0	7.0

Table 6 Optimal Water Storage Schedule in HS4

(b) 2

Figure 11: The optimal release trajectories and storage trajectories of HS4

The optimal release trajectories and storage trajectories in the dry season and flood season are shown in Figure9 and Figure10.

7 Strengths and weaknesses

Because of the time-rush and the distraction of energy, the model used in the paper has some unavoidable shortcomings. But at the same time, these models also have some unique glitter.

7.1 Strengths

- The CBA not only considers the direct benefit costs, but also considers potential costs and potential benefits, future costs and future benefits from a social and environmental perspective.
- The CBA choose a proper discount rate so that the benefits and costs in the future can be used in comparisons in present value.
- The ARCGIS is widely used, and computer simulation can be used to generate location map for smaller dams.
- The HS model analyzes how to adjust the water flow of the new multiple dam system to maximize the benefit.

7.2 Weaknesses

- Distortions of market are not taken into account. Due to the limited amount of information and time, the estimates of benefits and costs are directly from their market price instead of the real price which would include taxes as well as government preferential policies.
- A comparison between the real map and the GIS-generated images is used to find the location of the dam, so there are some inevitable errors.
- We apply the enhanced GA algorithm parameters into the HS, but we do not operate the sensitivity analysis,thus lacking comprehensive and detailed analysis of the HS.We choose the east four dams to represent our solutions for problem while omitting the west six dams.If we have enough time,we will provide a more comprehensive strategy.

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