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MULTI-CRITERIA DECISION ANALYSIS OF THE RECONSTRUCTION PLAN OF KARIBA DAM

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Abstract. In this paper, we provide the optimal renovation plan for the Kariba Dam based on information such as temperature and reservoir area. First, we select the most important factors from an environmental and economic perspective to formulate construction standards. Second, we use multi-criteria decision analysis (MCDA) and computational tools such as ArcGIS to determine the location of the dam. Finally, we present a comprehensive and comprehensive assessment of the Kariba Dam. The results of our research will help Africans improve their water systems and increase their resilience to climate extremes.

1. Introduction

Kariba Reservoir is a regulating lake across the Zambezi River Basin in southeastern Africa. With an area of 1.37×106 square kilometers, the Zambezi River Basin is the fifteenth largest river basin in the world and the fourth largest in Africa. The river is shared by 8 countries, with Zambia, Zimbabwe and Mozambique occupying nearly 70% of the entire basin [14]. Hydropower is the main source of electricity within the basin and is generated by four main regulating reservoirs. The total hydroelectric capacity is 5,145 MW, approximately 35% of the total capacity is installed on the Kariba Dam built in 1960.

In the future, extreme floods and droughts may be exacerbated by climate change [10]. Climate change coupled with high population growth rates will boost migration rates and increased energy and food demand in the region. These random exogenous factors will put additional pressure on already strained water resources [4, 13]. As a result, existing and planned reservoirs will have to face a wide range of future challenges, including water scarcity, increased frequency of extreme events such as floods and droughts, and the need to operate efficiently to meet growing resource conflicts. These threats will have a potentially huge impact on the Kariba Dam. More generally, a potentially large impact on existing water infrastructure, which was originally designed under the short-sighted assumption that they were only designed to maximize hydropower production under a fixed hydroclimatology [2].

Multi-criteria decision analysis (MCDA) usually involves criteria of different importance, therefore, the authors obtained the relative importance of the relevant criteria by assigning a weight to each criterion. There are many weighting techniques

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available in the literature [8] at the discretion of experts, stakeholders or policy-makers. For example, using direct weighting methods for standard arguments [1, 9], using Analytic Hierarchy Process (AHP) and direct weighting methods to model the suitability of managed aquifer recharge sites [11, 12], using AHP Weighting techniques to identify potential locations of RWH structures [6].

In addition, many authors introduced factor interaction method (FIM) as a weighting technique [7, 15]. The philosophy of FIM is that the importance of any physical factor cannot be assessed in isolation. These factors, when combined, can change the effect on the output. For sustainable planning of subsurface dams, their positioning needs to be based on scientific knowledge. If the collected information is not available, then expert judgment is required. In order to synthesize and apply existing scientific knowledge or expert judgment in decision-making problems, we need appropriate decision-making tools. Jamali et al. [5] used spatial multi-criteria analysis (SMCA) to locate suitable sites for construction of underground dams in northern Pakistan. In the study, the authors used two weighting techniques, Analytic Hierarchy Process (AHP) and Factor Interaction Method (FIM), for spatial data of geology, slope, land cover, soil depth, and terrain moisture index (TWI). In studying the sensitivity of model parameters, the analysis showed that AHP was a more robust weighting technique than FIM, and that land cover was the most sensitive factor. Their method shows promising results and can be used in early planning to find suitable sites to build underground dams.

The purpose of this paper is to provide possible reconstruction options for the Kariba Dam with the aid of a MCDA approach. We must not only consider natural ecological factors, but also social and economic factors. Natural ecological factors include factors such as the topography and geological structure of the site. Social economy includes factors such as dam construction cost, original inhabitant migration cost, and ecological cost. We will select the main factors among these factors to further determine the dam site. There are four main hydroelectric power stations on the Zambezi River, of which the Kariba Dam is located between the Batka Dam and the Cahora Bassa Dam. Therefore, the dam to replace the Kariba Dam should also be built between the Batka Dam and the Cahora Bassa Dam. The rest of the article is organized as follows. As a preparatory work, we introduce the geographic environment information, data resources and main computational analysis tools around Kariba Dam in Section 2. In Section 3, we use the MCDA method to select the five most critical factors among the factors that determine the dam site, in which the possibility of extreme weather will be fully considered. In Section 4, we present a comprehensive assessment of the Kariba Dam. Finally, we point out technical issues that need to be investigated in future work.

2. Basic settings

In the preparatory stage, we need to understand the geographical environment where the Kariba Dam is located, the data sources of the model and the indispensable computational analysis tools.

FIGURE 1. Location of the four dams.

2.1. **Geographical environment.** There are 4 dams along the Zambezi River (Figure 1). In addition to the Kariba Dam with a capacity of 185 cubic kilometers, there is a Cahora Bassa Lake Reservoir located downstream along the Zambezi River. To avoid affecting other dams, our goal is to build small dams in the channel between Lake Kariba and Lake Cahora Bassa. According to Figure 2, we simply divide the target channel into two parts upstream and downstream, using Kariba Dam as the dividing line. The upstream elevation is 475m to 380m and the downstream is 380m to 320m. The total elevation difference of the target river channel is 155m . With the MCDA approach, we decided to build 5 to 15 dams upstream and 5 to 10 dams downstream.

2.2. **Data resources.** The data for the model comes from two sources. One is Wikipedia (http://wikipedia.org/http://wikipedia.org/), which gives us information on the flow of the Zambezi River. The other is the Global Digital Elevation Model (GDEM), with data provided by the Ministry of Economy, Trade and Industry (METI) and the National Aeronautics and Space Administration (NASA). We utilize digital elevation models (DEMs) to implement limited terrain elevation data as a digital simulation of the ground.

2.3. **Calculation tools.** Our basic tools for working with data are ArcGIS and AutoCAD.

(1) ArcGIS10.2: ArcGIS is mainly used for spatial analysis and hydrological analysis, contour analysis of data, and information on water area, reservoir area and reservoir storage capacity. As a GIS platform, it can assist in collecting or calculating various forms of DEM information.

(2) AutoCAD: Calculate the length and area of the floor plan exported by ArcGIS.

FIGURE 2. Upstream and downstream of the target river.

3. DAM SITE SELECTION

We utilize FIM and consider the five most important factors in determining dam location, such as slope, capacity, construction cost, transportation cost, and ecological cost. First, the power generation capacity is determined by the slope of the river, and the capacity of the dam plays a crucial role in regulating the speed of the water flow. Second, construction costs and transportation costs affect the government's willingness and determination to build dams. Finally, ecological cost is also an important measure of planning.

3.1. Model.

Environmental factors, as well as economic factors, can influence dam siting. Environmental factors include site topography and valley shape, runoff velocity, geological structure, foundation conditions, earthquake disasters, climatic conditions, water level drop, reservoir storage capacity, etc. Economic factors include the construction cost of the dam, the migration cost of the original inhabitants, and the ecological cost. Considering the basic information of the river, we screened various influencing factors and listed them in Table 1.

According to the geographical environment information of the Zambia River, we determined that the height difference of a dam is 10 meters. For those candidate sites with appropriate elevation differences, we will further utilize the MCDA method to determine the best locations among them (Fig. 3).

3.2. Data processing.

Since the DEM grid map obtained from NASA is the WGS-1984 coordinate system, which belongs to the geocentric coordinate system, and

Environmental factor	Topography	The width of dams height of dams the slope of the river
	Hydrology	Runoff of river drop of river capacity of dams
Social and economic factor	The overall construction cost	The cost of transportation The cost of construction
	Location cost	The cost of removal The cost of ecology

TABLE 1. Influencing factors of dam construction.

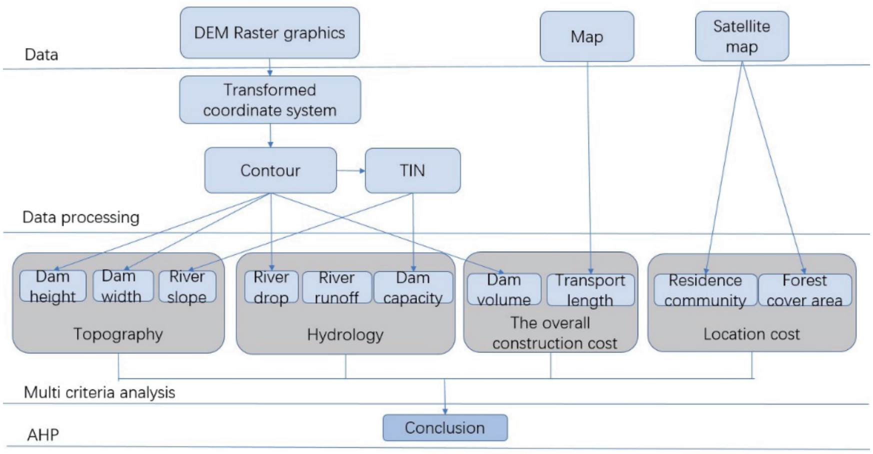

FIGURE 3. Detailed analysis of the MCDA model.

the units of the XY coordinates are minutes and seconds, the coordinate units must be converted to meters. Using ArcGIS, the coordinate system is converted to the African Mauritania UTM-1999 coordinate system. We use the "contour" communication to draw the contour lines and the "create" command to generate a contour data file, triangulating the irregular network (TIN) (Figure 4).

3.3. **Dam construction standards.** We use the generated profile data file to obtain the topography of the reservoir through the "Linear Interpolation / Contour " tool, and import the profile data into AutoCAD to calculate the height and width of the dam. We enter the command of [3D Analysis Tool]-[Grid Surface]-[Arc Toolbox] through [Arc Toolbox] to obtain the value of the slope. If the output of the slope is not intuitive, we can divide it into six degrees, where the larger the interval, the more suitable for building the dam. We use the [Arc Tool Box] in the ArcGIS software to enter the command [3D Analyst]-[Surface Analyst]-[Area and Volume] to obtain volume data.

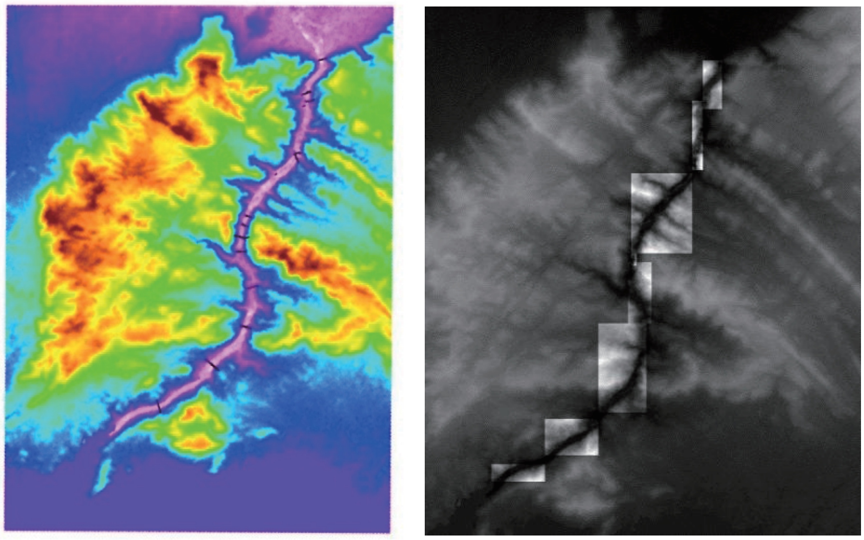

FIGURE 4. Topographic model of the Zambezi River.

We calculate construction costs by linearly fitting existing dams. We define transportation cost as the distance between the dam and the nearest road, as most transportation costs are between water and land transportation. Using remote sensing around the dam through Erdas software, we can get the area of settlements and forests with a fineness of 10 degrees.

3.4. **AHP for dam site selection.** We are going to build a 10 meter high dam. To make the selection as reasonable as possible, we will provide three or four possible locations at each height and use Analytic Hierarchy Process (AHP) to rank the possible dams to determine the best location.

Table 2 lists the details of three alternative dams, where the construction cost is proportional to the dam volume and the transportation cost is proportional to the distance from the site to the dam.

Num	Slope	Capacity ($*10^9 m^3$)	Construction cost (m^3)	Transportation cost (km)	Ecological cost
1	6	109.3	1328	8.1	3
2	5	111.3	9123	7.8	3
3	5	149.3	8986	7.7	4

TABLE 2. Information on three alternative dams.

In the model, we choose five factors for the best dam, including slope, capacity, construction cost, transportation cost, and ecological cost. These factors reflect

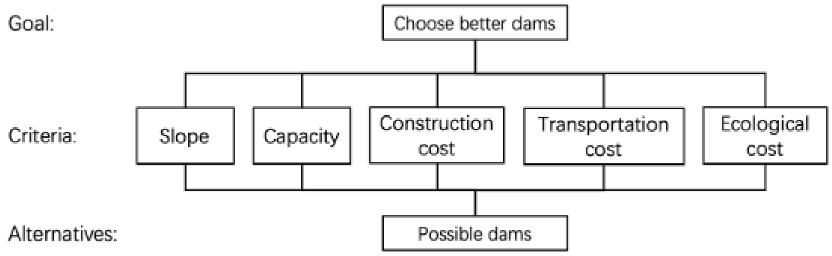

FIGURE 5. Hierarchical diagram of the analytic hierarchy process.

the most critical indicators for determining the location of replacement dams. The AHP hierarchy for decision-making is shown in Figure 5.

In AHP, we prioritize each decision based on its importance to the goal. Throughout the hierarchy, we combine these priorities to establish an overall prioritization for each alternative. The priority ratio of alternatives indicates their relative advantage in achieving the goal.

We set relative weights for the indicators and get the indicator matrix (Table 3).

Criteria	Slope	Capacity	Construction cost	Transportation cost	Ecological cost
Slope	1	1/2	2	5	4
Capacity	2	1	3	6	4
Construction cost	1/2	1/3	1	3	2
Transportation cost	1/5	1/6	1/3	1	1/2
Ecological cost	1/4	1/4	1/2	2	1

TABLE 3. The value of each factor indicator.

The calculation shows that the consistency factor is 0.014, and the priority of each indicator is 0.282, 0.421, 0.153, 0.055 and 0.089 respectively. Since the consistency factor is less than 0.1, we can consider this set of values and their resulting priorities to be reasonable. Now that we have weights for each indicator, the next step is to compare alternatives in terms of slope, capacity, construction cost, transportation cost, and ecological cost (Table 4).

We get the consistency factor, and all possible overall priorities, as shown in Table 5.

Since the consistency factor is less than 0.1, we can consider these matrices to be reasonable. After comparing priorities, we found that the third dam was the best option.

Similarly, we can select other dams from three or four possible dams, the details of the selected dams are listed in Table 6.

From the analysis of the existing data, we obtain that the capacities of the Kariba Dam and the new multi-dam system are 180,000 km^3 and 181,991 km^3, respectively.

Slope	1	2	3
1	1	2	2
2	1/2	1	1
3	1/2	1	1

Capacity	1	2	3
1	1	1/2	1/5
2	2	1	1/4
3	5	4	1

Construction const	1	2	3
1	1	9	8
2	1/9	1	1/2
3	1/8	2	1

Transportation const	1	2	3
1	1	1/2	1/2
2	2	1	1
3	2	1	1

Ecological cost	1	2	3
1	1	1	2
2	1	1	2
3	1/2	1/2	1

TABLE 4. Weights of the three alternatives for each indicator.

	1	2	3	CR
priorities	0.360	0.223	0.416	0.014

TABLE 5. The priority of the three alternatives.

The capacity of the new multi-dam system is approximately 1.1% higher than that of the Kariba dam, and the increased capacity will have a positive impact downstream.

Dams play a vital role in water regulation, especially during times of flooding. The multi-dam system increases water flow downstream without degrading Lake Kariba. In addition, the new dam addresses the dangerous situation at Kariba Dam. As floods come, part of Lake Kariba's water will be discharged to downstream dams to relieve its pressure, and orderly water regulation can ensure downstream safety.

During the dry season, daily water use and irrigation are critical. As multiple dams are introduced, the inflow of water downstream can be regulated through these dams, and the extra volume of water can prevent drought in the downstream catchment.

New dams do not increase their capacity too much, which means they do not disrupt the balance of the existing ecological environment. On the other hand,

NUM	E(°)	S(°)	Dam Height (m)	Water area(m^2)	Surface area(m^2)	Capacity(m^3)	Dam volume(m^3)
1	28.764	-16.521	128.000	5,503,685,108.000	5,648,390,257.012	180,568,308,146.000	749,112.000
2	28.785	-16.510	91.000	1,249,755.374	1,343,843.393	71,613,252.752	477,750.000
3	28.805	-16.493	87.100	1,742,432.622	1,864,022.054	91,811,024.109	317,997.000
4	28.823	-16.462	13.300	3,392,245.802	3,572,319.241	143,327,470.874	10,606.000
5	28.817	-16.449	12.200	1,262,710.616	1,317,008.731	30,642,025.058	4,743.000
6	28.841	-16.409	21.800	2,499,253.769	2,544,708.891	73,734,897.879	24,640.000
7	28.843	-16.388	15.000	639,047.269	661,917.169	8,932,285.710	9,562.500
8	28.850	-16.371	28.200	591,589.027	619,478.659	9,469,688.798	24,640.000
9	28.838	-16.050	10.800	60,620,258.497	61,867,957.766	694,705,141.531	5,518.000
10	29.057	-15.885	15.200	25,517,759.601	26,192,620.698	251,458,352.653	12,375.000
11	29.692	-15.645	15.500	3,642,667.609	3,737,535.920	24,979,103.348	23,625.000
12	30.362	-15.651	11.300	2,572,916.062	2,631,781.938	22,044,516.302	35,713.600
total	-	-	-	5,607,415,744.248	5,754,743,451.470	181,991,025,905.013	947,170.100

NUM	construction cost(10^8 $)	Other cost (10^8 $)	Removal cost (10^8 $)	runoff(m^3/s)	Generating capacity (*10e8kwh/year)	water level (m)
1	52.185	-	10.126	4,000.000	5.300	475.000
2	34.768	1.402	-	4,078.345	5.289	465.000
3	23.731	1.832	-	4,150.450	5.368	455.000
4	0.832	2.852	-	4,235.346	5.394	445.000
5	0.311	0.630	-	4,100.089	5.456	435.000
6	1.927	0.147	-	4,135.908	10.940	415.000
7	0.746	0.189	-	4,256.675	5.689	405.000
8	3.038	0.190	-	4,298.075	5.895	395.000
9	0.435	14.256	-	4,823.832	8.560	380.000
10	0.968	5.289	-	5,245.126	12.142	360.000
11	1.853	0.548	-	5,356.781	13.452	340.000
12	2.796	0.479	-	5,488.391	14.251	320.000
total	123.590	27.814	-	-	97.736	-

TABLE 6. Engineering Survey Data for Alternative Dams.

a multi-dam system can adjust the flow capacity and flexibly change the water storage.

We found that the surrounding residents are mainly engaged in agriculture, so optimized water management can guarantee agricultural irrigation. In addition, the multi-dam system provides natural conditions for fish farming, which will bring additional income to the residents.

According to reports, the current Kariba Dam may collapse at any time, which will cause huge damage to the economic life of the downstream residents. Neither repairing the dam nor rebuilding it in situ will fundamentally solve the problem. However, multi-dam systems can alleviate this problem to a greater extent. The water level will be lowered from 128 meters to 10 meters, which will improve the safety of the entire dam.

4. Evaluation report

In this section, we present a comprehensive assessment of the maintenance of the Kariba Dam project from an economic and ecological perspective.

4.1. **Indemnity.** In 2015, the South African Risk Management Institute reported that the dam was in severe condition and needed repairs. Considering the different opinions on how to deal with the dam, we have three options, namely repair the dam, rebuild the dam, and remove the dam and build 12 new small dams to replace it (the number of small dams is based on the model we established in Section 3.4).

To assess these options, we need a model to measure the economic and ecological impacts of dams. Economic impacts include hydropower generation, industrial benefits, sunk costs, and repair costs. Sunk costs refer to costs that have already occurred but cannot be recovered. Ecological impacts include positive and negative impacts on biodiversity, and impacts from harmful substances on the reservoir surface (Table 7). In addition, circular plots are used to characterize the impact of the dam. The graph includes eight separate "impacts," four of which represent economic impacts and the remaining four ecological impacts. Each impact is divided into five grades, which categorize the magnitude of the effect, from a grade of 0 for "no effect" to a grade of 5 for "extreme effect" [3]. To help decision makers better understand the differences and make decisions easier, we use the shading on the circles to show the degree of positive impact of each option.

Label	Impact	Each section refers to	Option 1	Option 2	Option 3
EN1	Power generation	5000/ 5000~10000/ 10000~20000/ 20000~40000/ 40000 (Gwh per year)	8000	8000	97736
EN2	Industry benefited	Very low/ Low/ Moderate/ High/ Very high	Very low	Very low	High
EN3	Safety	Very low/ Low/ Moderate/ High/ Very high	Low	Moderate	Very high
EN4	Total cost	8/4~8 /2~4 /1~2/ 1 (billion dollars)	0.294	6.231	15.140
EL1	Biodiversity (negative)	Very high/ High/ Moderate/ Low/ Very low	Moderate	Moderate	Low
EL2	Biodiversity (positive)	Very low/ Low/ Moderate/ High/ Very high	Moderate	Moderate	High
EL3	Reservoir surface	6000/ 4000~6000/ 2000~4000/ 2000 (square kilometers)	5120	5120	5754.743
EL4	Frequency and severity of contamination	240/ 180~240/ 120~180/ 60~120/ 120 (days/year)	180	180	110

TABLE 7. Three alternatives based on ecological and economic impacts.

4.2. **Evaluation.** We compare the impact of the Kariba dam and the multi-dam system. The total cost of Kariba Dam in its two construction phases is approximately \$480 million, which is a sunk cost for Option 2 and Option 3. In addition, construction costs include material costs, labor costs, and the like. Through quadratic fitting, it is concluded that the total power generation of the dam is 977,367 kWh. The reservoirs created by the dam construction can drive the development of surrounding industries such as fishery, planting, animal husbandry, and manufacturing.

On the ecological front, the construction of the multi-dam system will allow nearly 1,000 square kilometers of water to be cleared in preparation for gillnet fishing. The ecological environment of Lake Kariba is also conducive to the reproduction of species such as crocodiles and aquatic birds. For Kariba Dam, DDT is the most predominant pollutant and it was widely used during and after the construction of the dam to eliminate tsetse flies from the area [16]. However, a multi-dam system would avoid this. Instead, rotting vegetation will pollute the environment, which cannot be avoided. In the existing evaluation system, we show the evaluation results of the three options in the circle diagram (Figure 6-8).

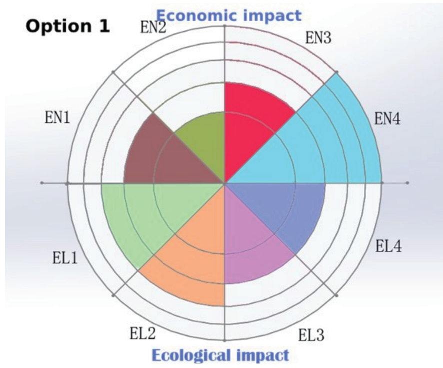

FIGURE 6. Option 1

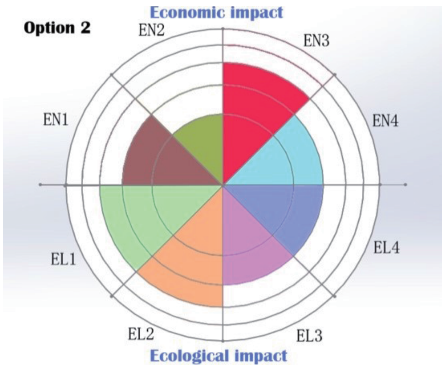

FIGURE 7. Option 2

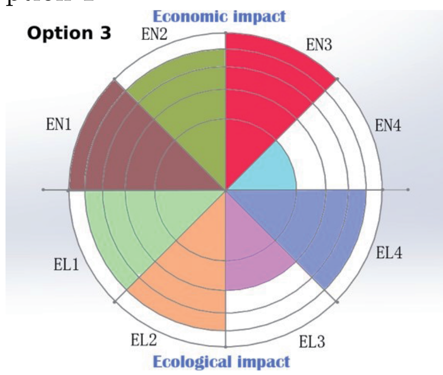

FIGURE 8. Option 3

4.3. **Conclusion.** First, the economic factor is the main factor. The cost of removing and rebuilding a dam is far greater than the cost of repairing a dam. However, local residents could benefit more from the electricity generated by the new multi-dam system, the prosperity of nearby industries, and the safety of the dams.

Second, multi-dam systems have both negative and positive impacts on ecology. Once the multi-dam system is built, the number of small reservoirs will increase. The air humidity around the reservoir will be regulated to be more suitable for plant growth. At the same time, the biodiversity in the reservoir will also increase, which will certainly improve the quality of the ecological environment around the multi-dam system.

The comparison results show that option 3 (Figure 8) has the largest shaded area, option 2 (Figure 7) has the least area, and option 1 (Figure 6) is between them. In other words, Option 3 is better than Option 1, and Option 1 is better than Option 2. Therefore, we believe that option 3, which has the most positive impact, is the best choice for policymakers.

5. FUTURE WORK

As a water conservancy hub, the main function of a dam is to retain water and prevent floods. Generally speaking, dams are divided into earth dams, gravity dams, concrete face rockfill dams, arch dams, etc. The powerhouses of some hydropower stations are also part of the dam. Hydropower dams act as barriers in streams, rivers, and estuaries to prevent and release floods, generate hydroelectric power, or store water sources for irrigation. In the 1990s, hydropower dams played an important role in flood control and release of large floods, reducing the huge risks brought by floods. More and more people pay attention to preventing floods from overflowing and breaking dams and realizing harmonious coexistence between man and nature. After the type of dam is selected according to the natural conditions of the dam site, building materials, construction site, diversion, construction period, cost and other factors, each dam must have clear flow construction standards. Therefore, designing and controlling the flow of each section of the dam will become an important technical issue for subsequent research.

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