Managing the Zambezi River

Qi Gao¹, Shaoxia Yang¹*
¹School of Renewable Energy, North China Electric Power University, Beijing, China yangshaoxia@ncepu.edu.cn

Abstract. The Kariba Dam is one of the larger dams in Africa, while it is also in dire need of maintenance. The evaluation model and related calculation methods are built to measure potential benefits and costs of three maintenance programs. Moreover, a detailed analysis is provided by the calculation method and the number and placement of the new dams along the Zambezi River are proposed.

1. Introduction
After more than 50 years, the Kariba Dam provides power for the Southern African Region, while it is found that its rehabilitation must be required to safe operation. Commonly, there are three particular options that Zambezi River Authority (ZRA) might choose:

- Repairing the existing Kariba Dam;
- Rebuilding the existing Kariba Dam;
- Removing the Kariba Dam and replacing it with a series of ten to twenty smaller dams along the Zambezi River.

To evaluate three options listed, it is very necessary to build mathematical models, provide a detailed analysis of Option 3 and analyze the extreme water flows.

2. Model One

2.1. Overview
The economic value system is built from the potential benefits and costs according to the impact of the dam on river ecosystem. Moreover, the market value method, opportunity cost method, shadow engineering method of direct market method and alternative market are applied to evaluate on this issue.

2.2. Detailed Design

2.2.1. The Brief Introduction. We adopted the cash flow model in engineering economics to visualize the relative benefits and costs flows over the life of the project[1]. By substituting reconstruction costs, construction time, useful life and other parameters into the model, annual net profit and average annual net profit can be calculated for three options.

2.2.2. The Potential Benefits

- The Economic Value of Power Generation: We choose the following norms with market value method:

  \[ V_e = Q_e P_e \]  

  \( V_e \) is the economic value of hydroelectricity of Kariba Dam; \( Q_e \) is the annual energy production of Kariba Dam; \( P_e \) is the marketing price of electricity in Kariba areas.
The Economic Value of Tourism: It is assumed that only the large dam could achieve tourism effect. According to this, only option 1 and Option 2 have the benefit.

The Benefit of Flood Storage: This is the most basic function for building a dam. The Kariba Dam can protect the cultivated land from submerged, which indirectly creates benefits. According to opportunity cost method, the formula is gotten as followed:

\[ V_f = S_{f1}P_{f1} + S_{f2}P_{f2} \]  \hspace{1cm} (2.2)

Namely \( V_f \) is the total economic value from regulation of floodwater; \( S_{f1} \) is the annual reduced flooded area; \( S_{f2} \) is the annual reduced the affected population; \( P_{f1} \) is the loss of unit flooded area; \( P_{f2} \) is the per-capita loss because of flood.

The Benefit of Reducing Harmful Gas: Replacing coal-fired power generation with hydroelectric power can effectively reduce emissions of harmful gases. The Shadow Engineering method is applied to assess these values and use the formula below:

\[ V_{cd} = Q_{cd}P_{cd} \]  \hspace{1cm} (2.3)

Namely \( V_{cd} \) is the economic value of reducing Carbon dioxide; \( Q_{cd} \) is the reduction of Carbon dioxide; \( P_{cd} \) is the afforestation cost.

Similarly, we could calculate economic value of reducing Sulfur dioxide and get the total value:

\[ V_{total} = V_{cd} + V_{sd} \]  \hspace{1cm} (2.4)

2.2.3. The Potential Costs

The Cost of the impact on River Ecosystem: We preliminary account for the impact on the river ecosystems services.

The Cost of Submergence: Complex ecosystems are destroyed because of the construction of the dams. Here we adopt the opportunity cost method to calculate the cost mentioned here:

\[ V_s = \sum \sum S_{sij}P_{sij} \]  \hspace{1cm} (2.5)

In the formula above, \( V_s \) is the loss value of reservoir submergence. \( S_{sij} \) is the forests, grasslands, wetlands and marshes and arable land areas flooded by the dam, respectively.

The Cost of Construction: The formulas are used according to our analysis:

\[ C_i(t) = \begin{cases} C_{\text{repair}} \cdot N_{\text{repair}} + C_{\text{maintenance}} \cdot t & i = 1 \\ C_{\text{newbigdam}} \cdot N_{\text{newbigdam}} + C_{\text{removal}} \cdot N_{\text{removal}} + C_{\text{maintenance}} \cdot t & i = 2 \\ C_{\text{newsmallerdam}} \cdot N_{\text{newsmallerdam}} + C_{\text{removal}} \cdot N_{\text{removal}} + C_{\text{maintenance}} \cdot t & i = 3 \end{cases} \]  \hspace{1cm} (2.6)

In the formula above, \( C_{ci}(t) \) devotes the cost of construction of option \( i \).

Considering the time value of money, we analyze the maintenance fee by using the Capital Equivalent Formula\(^{[2]}\):

\[ A = P(P/A, i, t) = P \times \frac{t(1+i)^t - 1}{(i+1)^t - 1} \]  \hspace{1cm} (2.7)

\( A \) is the annual value, \( P \) is the present value.

Cost of the decay of dam: We should assess the cost of the decay effect. Here are two models to describe the effect: Straight Line Depreciation and Exponential Depreciation\(^{[3]}\). The formulas are shown as below respectively:

\[ C_{\text{decay}}(t) = C_c^i - \left[ \frac{C_c^i - S}{L} \right] \cdot t \]  \hspace{1cm} (2.8)

\[ C_{\text{delay}}(t) = C_c^i \cdot \left[ \frac{(C_c^i)^2}{S} \right] \cdot t \]  \hspace{1cm} (2.9)

\( C_c^i \) is the cost of construction; \( L \) is the lifespan of a dam; \( S \) is salvage value.

2.2.4. Model Test of Model One. The values are calculated to compare select the potential benefits and costs used of three options shown in Tables.
### Table 1. Potential Costs of Three Options (108$/a)

| Potential Costs                  | Option1 | Option2 | Option3 |
|---------------------------------|---------|---------|---------|
| Cost of Construction            | 52.322  | 62.581  | 69.219  |
| Cost of impact on River Ecosystem | 2.174   | 3.185   | 3.639   |
| Cost of Submergence             | 1.249   | 1.526   | 1.806   |
| Cost of the Dam Loss            | 2.472   | 4.392   | 5.018   |
| Total Costs                     | 58.217  | 71.684  | 79.682  |

In Table 1, it is obvious that the construction fee of the dam occupies the main part of potential costs for all options. The construction fee in Option 3 is more than others.

### Table 2. Potential Benefits of Three Options (108$/a)

| Potential Benefits              | Option1 | Option2 | Option3 |
|---------------------------------|---------|---------|---------|
| Power Generation                | 5.824   | 6.471   | 10.381  |
| Tourism                         | 3.132   | 3.024   | 1.234   |
| Flood Storage                   | 2.954   | 3.583   | 4.321   |
| Reducing Harmful Gas            | 2.424   | 2.416   | 3.012   |
| Total Benefits                  | 14.334  | 15.494  | 18.948  |

In Table 2, it is found that total benefits of Option 3 are more than others. The benefit from Power Generation is far more than others, while the benefits from Tourism and Flood Storage of Option 3 are less than others.

### 3. Model Two

#### 3.1. Overview

The multiple-dam model is applied to discuss Option 3. The model includes three parts:
- Generating potential dam sites;
- Calculating suitability of generated site;
- Recommending the number of small dams.

#### 3.2. Detailed Design

**3.2.1 Multiple Dam System Model.** The derivative of height and width of the dam is calculated over length of the Zambezi River. The sites satisfying the equation, where derivative values are zero, is chosen as potential dam sites. 25 generated potential dam sites are obtained. Five criteria (soil type, land cover, degree of slope, resistance of geological layer and predicted precipitation) are considered as main factors.

**3.2.2 Analytical Hierarchy Process.** AHP provides an integrated measurement on tangible factors with different priority by pairwise comparison. We use a linear function assign preference value to different classes of all criteria to calculate the suitability of all the potential dam sites. With comparison, the weight of criteria $i$, which is used in later analysis for suitability analysis [4], could be calculated with the formula below.

$$W_i = \sum_{j=1}^{n} P_{ij} / \left( \sum_{i=1}^{n} \sum_{j=1}^{n} P_{ij} \right) \quad (3.1)$$

Where $P_{ij}$ is relative importance in pairwise comparison of criteria $i$ and $j$. Using the formula above, with the criteria judging matrix $A$ we could calculate the weight of criteria.
Then, the consistency is evaluated by using the equation shown below:

\[
CR = \frac{CI}{RI}
\]

Where CI could be calculated according to equation below:

\[
CI = \frac{\lambda_{\text{max}} - n}{n - 1}
\]  

### Table 3. Criteria identifier and weight

| Criteria No. | Criteria                | Score  |
|--------------|-------------------------|--------|
| C1           | Predicted precipitation | 0.343  |
| C2           | Slope                   | 0.254  |
| C3           | Resistance of geological| 0.177  |
| C4           | Soil type               | 0.116  |
| C5           | Land cover              | 0.110  |

And the coincidence indicator table is drawn:

### Table 4. Consistency index RI

| N  | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  |
|----|----|----|----|----|----|----|----|----|
| RI | 0  | 0  | 0.59 | 0.90 | 1.12 | 1.24 | 1.32 | 1.42 |

Suitability of dam sites is calculated as weighted summation of different criteria layers. Based on the result of AHP, 20 possible dam sites are selected with the higher suitability.

### 3.2.3 Recommend Number of Dam Sites.

According to Knapsack Problem\textsuperscript{[5]}, the formula is listed.

\[
C_T = \sum_{i=1}^{N} C_i \quad \text{s.t.} \quad \sum_{i=1}^{N} U_i = M, \\
10 \leq N \leq 20
\]

Where \( C_T \) is the total cost of \( N \) small dams. \( C_i \) is cost of \( i_{th} \) dam; \( M \) is water management capability of old Kariba Dam. \( U_i \) is capability of \( i_{th} \) dam. Result of the fitting equation is shown below.
Above the conditions, it is found that the optimal number of dams is 14. The number of selected dam site is 5, 6, 7, 9, 10, 11, 12, 14, 16, 17, 18, 19, 20 and 22.

4. Conclusions
To make the assessment of three options, the potential benefits and potential costs are chosen as criteria. Then the weight of each item is calculated. Three options are compared and the differences of them are found in Model One. In addition, the number and placement of small dams are discussed. The extreme points are regarded as the potential dam sites because these points are more flat so that they are more suitable to build dam here. Then 25 potential sites are generated. To compress the number into 20, AHP is adopted and the suitability of each site is discussed. Finally, the question is regarded as Knapsack Problem. It is calculated that the optimal number of small dams is 14.

References
[1] https://en.wikipedia.org/wiki/Zambezi
[2] Li Y, Cui Q, Li C, et al. An improved multi-objective optimization model for supporting reservoir operation of China's South-to-North Water Diversion Project[J]. Science of the Total Environment, 2016, 575:970.
[3] Tullos D, Brown P H, Kibler K, et al. Perspectives on the salience and magnitude of dam impacts for hydro development scenarios in China[J]. Water Alternatives, 2010, 3(2). 71-90
[4] Wong, Evelyn. “Damming The Dams”: A Study of Cost Benefit Analysis In Large Dams Through The Lens of India's Sardar Sarovar Project[J]. 2013.
[5] Richard Beilfuss 2010 Modelling trade-offs between hydropower generation and environmental flow scenarios: a case study of the Lower Zambezi River Basin, Mozambique International Journal of River Basin Management 8 (3): 331-347.