Evaluation of the Three Gorges Dam project using multi-criteria analysis (MCA) based on a sustainable perspective

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Abstract. The Three Gorges dam of China is one of the largest and expensive hydropower projects of the world. The four main purposes of the project are flood control, energy production, improved navigation and fresh water supply. The dam project has been completed and running successfully with the potential benefits. However, this project is still a controversial issue among many environmentalists and socialists due to various impacts. This study focuses on the benefit and the impacts of the project, and also evaluates the performance of the project using multi-criteria analysis (MCA) approach from a sustainable perspective. Different sustainability criteria related with the dam project have been identified and used for the ranking and rating process. The final result of MCA comes with this scoring process and pairwise comparison, which evaluates the performance of the project considering different positive and negative aspects.

1. Introduction
The Three Gorges Dam (TGD) of China is considered as the largest hydropower project of the world until now. The dam has been fully operated from the end of 2008 and its construction took 17 years [1]. The main purpose of this large project includes flood control and protection (to more than 10 million downstream floodplain residents), energy production (generation of more than 20,000 MW), improved navigation of the Yangtze River (primarily along the stretch of 660 km that separates Yichang from Chongqing), and access to fresh water mainly in the northern China plains (more water available for irrigation, industrial uses, and human consumption) [2, 3].

Some of the environmental and social benefits that the TGD has had during the period 2004-2008 are: the project has reduced the transportation and the use of coal for energy production, with the consequent reduction of CO₂, SO₂ and NOₓ emissions [1, 3, 4]. Besides of the project’s potential benefits, the project is still a controversial topic as it is regarded as a model of disaster by many environmentalists. The TGD has important environmental effects. For instance, Tullos [2] and Zhang et al. [3] mention that it affects a wide range of river-related ecosystem components: hydrology, water quality, sediment regime, terrestrial and aquatic flora and fauna, and human activities. Since 2007, the government authorities and scientists have become more conscious about social and economic impacts that have become evident. For example, the capacity to produce energy is not as anticipated and thus criticized by some parts of the Chinese society [4]; the project sets more than 1.2 million people displaced and flooded many villages, towns and cities [5].

This study summarizes the environmental, social, and economic benefits and impact of the project and efforts to sustainable development, evaluates the implementation phase of the project through
multi-criteria analysis (MCA), compares different sustainability criteria related with the TGD project, and identifies the main positive and negative aspects that MCA has for the evaluation of a hydropower project.

2. Methodology

Multi-criteria analysis (MCA) is chosen to evaluate the Three Gorges Dam project during its implementation phase from a sustainability perspective, which helps to address problems and cases involving a variety of attributes or criteria [6]. Different criteria and indicators related with the project were identified and evaluated by an expert group. The evaluation process is based on two main phases. The first one counted on a ranking/rating process, and the second one on a pairwise comparison known as Analytic Hierarchy Process (AHP).

For ranking/rating process, the MCA manual published by the Center for International Forestry Research (CIFOR) in 2009 has provided a guide to implement this decision-making tool and to evaluate the relative importance of all the criteria that are involved [7]. Seven steps were considered:

- Step 1: Establish a set of principles, criteria and indicators;
- Step 2: Individual judgment on each of the principles;
- Step 3: Individual judgments for all the criteria under each principle;
- Step 4: Prioritize principles and criteria, according to their relative weights;
- Step 5: Calculate the relative weights of each indicator;
- Step 6: Prioritize the indicators according to their relative weights;
- Step 7: Score the indicators based on the selected set.

For the second phase, Analytic Hierarchy Process is a widely used MCA tool proposed by Saaty [8]. The AHP method consists of six steps as follows:

- Step 1: Establish a numerical scale for comparative judgment of indicators;
- Step 2: Individual comparative judgments on the relative importance of each pair of indicators in terms of the criterion they measure;
- Step 3: For each individual judgment, calculate the relative weights of each indicator (calculate the sum of each column, and normalize the elements);
- Step 4: Calculate relative weights for the indicators;
- Step 5: Calculate the final score for each criterion;
- Step 6: Calculate the consistency index.

In Step 6, the consistency index (C.I.) is used to verify whether the experts’ judgments are consistent for each comparison, by calculating the largest eigenvalue of the matrix formed by pairwise comparisons of indicators [9]. Consistency ratio (C.R.) is adopted to interpret the C.I. values which are divided by a random index (R.I.). R.I. value is 0.58 for criteria with three indicators, and 0.90 for criteria with four indicators, as for this specific case. If C.R. value is larger than 0.1, the certain comparison is not consistent and judgments should be revised. Different criteria and indicators related with the project were identified and evaluated by an expert group composed of four experienced engineers from State Grid Shandong Electric Power Research Institute and one professor from Shandong University.

3. Results

3.1. Identification of principles, criteria and indicators

Based on the fact that the TGD project should provide an equitable and sustainable development of water and energy resources for Chinese community, this analysis tries to include a sustainable perspective following four main principles concerning environmental, social, and economic aspects, according to the recommendation of International Hydropower Association (IHA) [10]. Each one of the principles, criteria and indicators are identified and listed in Table 1.
Table 1. Principles, criteria and indicators used on the analysis.

| Principle | Criterion | Description |
|-----------|-----------|-------------|
| 1         | The project considers policy and planning aspects and establishes the essential institutional framework that is necessary to pursue a sustainable hydropower project. |
| 1.1       | There are corporate business structures, policies and practices. |
| 1.1.1     | Transparency, integrity and accountability issues are addressed. |
| 1.1.2     | External governance issues (e.g. institutional capacity shortfalls, political risks including transboundary issues, public sector corruption risks) are managed. |
| 1.1.3     | Compliance are properly solved. |
| 1.1.4     | Transparency, integrity and accountability issues are addressed. |
| 1.2       | Plans and processes are established to manage environmental and social aspects. |
| 1.2.1     | Negative environmental and social impacts associated with the facility are identified and managed. |
| 1.2.2     | Avoidance, minimization, mitigation, compensation and enhancement measures are implemented. |
| 1.2.3     | Environmental and social commitments are fulfilled. |
| 1.3       | The project provides safe infrastructure which is properly managed. |
| 1.3.1     | Life, property and the environment are protected from the consequences of dam failure and other infrastructure safety risks. |
| 2         | The project management maintains or improves the derived economic and social benefits. |
| 2.1       | The financial system includes measures that ensure the project sustainability. |
| 2.1.1     | Project costs and revenue streams are fully detailed. |
| 2.1.2     | Monitoring of the financial situation during implementation is being undertaken on a regular basis. |
| 2.1.3     | The project manage financial issues under a range of scenarios, can service its debt, and can pay for all plans and commitments including social and environmental considerations. |
| 2.2       | The project generates the expected hydropower levels. |
| 2.2.1     | The project improves the energy balance, reducing electricity deficit and peak power deficit. |
| 2.2.2     | The project benefits the economic growth by increased power supply. |
| 2.2.3     | The project generates the quantity of electricity that was expected. |
| 2.2.4     | The project is able to compete with other hydropower plants in China. |
| 2.3       | The project generates clean energy. |
| 2.3.1     | The benefits from replacing coal use are clearly identified and quantified. |
| 2.3.2     | The annual decreased of CO₂ level is clearly identified and quantified. |
| 2.3.3     | The annual decreased SO₂ level is clearly identified and quantified. |
| 2.4       | The project improves the flood control and navigation. |
| 2.4.1     | The benefit from flood control are clearly identified and quantified. |
| 2.4.2     | The annual rate of decline in power generation as a result of sedimentation is considered. |
| 2.4.3     | The benefit from navigation improvement is clearly identified and quantified. |
| 2.4.4     | The changes in transportation costs are clearly identified and quantified. |
| 3         | The project management maintains or improves the intergenerational access to resources, and integrates the stakeholder’s interest. |
| 3.1       | The physical displacement arising from the hydropower project has been fulfilled. |
| 3.1.1     | The dignity and human rights of those physically displaced are respected. |
| 3.1.2     | Livelihoods and standards of living for resettlees and host communities are improved. |
| 3.1.3     | Commitments made to resettlees are fully delivered. |
| 3.2       | The project improves labor and working conditions, including employee and contractor opportunity, equity, diversity, health and safety. |
| 3.2.1     | Workers are treated fairly and protected. |
| 3.2.2     | Permanent works and temporary works that are generated with the project. |
| 3.3       | Cultural resources and tourism activities associated with the hydropower facility are protected. |
| 3.3.1     | Physical cultural resources are identified, their importance is understood, and measures are in place to address those identified to be of high importance. |
| 3.3.2     | The aesthetics impact on tourism is identified and measures have been developed. |
| 3.3.3     | Tourist visit Three Gorges as an attraction. |
3.2. AHP process
All criteria and indicators were judged through ranking/rating and pairwise comparison. Relative weights were calculated by the percentage estimation of each indicator. Then, the average weight was calculated with the results from the relative weight which was obtained by ranking and rating, respectively. This number was multiplied by the score that was discussed by the expert group for each indicator, to obtain final scores. The scoring scale is shown in Table 2.

| Scoring scale | Description |
|---------------|-------------|
| 0             | Not an applicable Criteria or Indicator |
| 1             | Extremely weak performance or strongly unfavorable |
| 2             | Poor performance, unfavorable, may be the norm for the region, but major improvement needed |
| 3             | Acceptable, at or above the norm for good operations in the region |
| 4             | Very favorable performance, well above the norm for the region, but still needing improvement to be state of the art |
| 5             | ‘State of the art’ in region, clearly outstanding performance which is way above the norm for the region |

Table 2. Scoring scale.

| Principle | Criterion | Description |
|-----------|-----------|-------------|
| 3.4       | Public health issues associated with the hydropower project. |
| 3.4.1     | The project does not create or exacerbate any public health issue. |
| 3.5       | The project has established a communications and consultation mechanism that allow its engagement with project stakeholders (within the company and between the company and external stakeholders). |
| 3.5.1     | A communications and consultation mechanism has been established. |
| 3.5.2     | The stakeholders are identified. |
| 3.5.3     | The stakeholders are engaged in the issues of interest to them. |

4. The project protects the ecosystem integrity, and all the ecosystem-services are maintained in time and space.

4.1 The project are identified ecosystem services, habitat, threatened species, fish passage in the catchment, reservoir and downstream areas, and potential impacts arising from pest and invasive species.

4.1.1 There are healthy, functional and viable aquatic and terrestrial ecosystems in the project-affected area that are sustainable over the long-term.

4.1.2 Biodiversity impacts arising from project activities are managed responsibly.

4.1.3 Commitments to managed invasive species are fulfilled.

4.2 Erosion and sedimentation issues associated with the project are managed.

4.2.1 Erosion and sedimentation caused by the project is managed responsibly and does not present problems with respect to other social, environmental and economic objectives.

4.3 Water quality issues associated with the project are managed.

4.3.1 Water quality in the vicinity of the project is not adversely impacted by project activities.

4.3.2 Water quality issues are monitored and addressed as required.

4.3.3 Commitments to implement measures to address water quality are fulfilled.

4.4 Waste, noise and air quality issues associated with the project are managed.

4.4.1 Noise and air quality in the vicinity of the project are of a high quality and not adversely impacted by project activities.

4.4.2 The project wastes are responsibly managed.

4.5 Flow regimes downstream of project infrastructure during the project implementation stage are considered.

4.5.1 Flow regimes downstream of project infrastructure are planned and delivered with an awareness of and measures incorporated to address environmental, social and economic objectives affected by those flows.
For the AHP process, one-on-one comparisons were done between each of the indicators. Through pairwise comparison and normalization, relative weights for each indicator were obtained. The average results from each expert were calculated and thereafter multiplied by the same score that was given by the ranking/rating process. The consistency index was calculated in the final step, with the highest C.R. to be 0.065. This demonstrates a low degree of inconsistency amongst the judgments.

All the criteria scores obtained from the two methods are organized in a final column chart, seen in Figure 1. Certain criteria are not applicable for pairwise comparison since there is only one indicator

**Figure 1.** Final results of scores for each criterion.

4. Discussion

Final results display very similar outcomes using ranking/rating and pairwise comparison methods respectively. There are four criteria- 3.2, 3.1, 1.1, and 4.4- with lower values than 3 points, which indicates poor performance and needs major improvement. Criteria 3.4, 4.1, and 4.2 get exactly 3 points presenting acceptable performance but not good enough. The rest get values higher than 3 points, and four of them- 2.2, 2.4, 1.3, and 4.5- stand out as clearly prominent performance.

Simply drawn from the values, the TGD project seems satisfactory. Only 4 out of the total 17 criteria are identified as poor performance, and others are all favorable, at least acceptable. However, as the world’s largest dam project, with so much capital input, obvious impacts, and great public concerns and controversies, the TGD should provide an equitable and sustainable development of water and energy resources for Chinese community, and is supposed to render favorable features rather than so many aspects to improve. Therefore, these results are slightly beyond satisfaction for the evaluation of TGD. For the specific analysis, the four main objectives of the TGD should be considered and discussed in particular, in order to obtain a comprehensive and objective evaluation.

4.1. Flood control and protection

Referring to Criterion 2.4 which gets rather high values (4.60 and 4.80 respectively), flood control performance is identified as very favorable. This is not surprising, as flood control is in fact the primary and determinant reason for the TGD project [11]. However, there are two major aspects to consider, which may to some extent impair the performance of the dam’s flood control. One is related with the location of TGD- at the end of the upper reaches of Yangtze River. Concerns never cease on the actual dam performance, as TGD can control only 55% of the Yangtze River watershed [3]. If the flood happens downstream, the dam will not give any effective control over it, just like in the year 1954 and 1998 when the floods were caused by heavy downstream precipitations [12]. Another is about sedimentation. The Yangtze River has large amount of silt in water, which may influence the dam capacity. As the time goes by, silt and industrial pollutant from upstream will be accumulated in the reservoir, causing serious sedimentation problem. Besides, there are potential risks that erosion would occur within the reservoir bank as well as downstream rivers, which causes landslides and further leads to sedimentation. This situation can be drawn from Criterion 4.2 which gets 3.00. The TGD will sustain a long time given that erosion and sedimentation problems are satisfactorily solved.
4.2. Hydro power generation

Hydro power generation issue refers to Criterion 2.2 and 2.3, which, however, receive rather different values. For Criterion 2.2, only 3.22 and 3.09 are obtained, indicating that it is not a very favorable performance. The reason mostly lies in the fact that the TGD will probably not provide the expected quantity of electricity. There are so many critics on this issue. Some mentioned that it is not worthy of constructing such a costly and influential dam project without reaching the expected power generation; it is better to use those funds to build a series of small scale power plants, which could also satisfy the nation’s energy needs [13]. These critics are in a degree not convincing, as they simply focus on short-term benefit. Building a series of power plants is of course a feasible means of solving the energy shortage very quickly, but considering the fuel consumption and development trends of those districts in the long run, the TGD is an optimal choice and have long-lasting positive effects in terms of power supply and economic growth.

Criterion 2.3 receives 4.35 and 4.18, showing rather favorable performance. It is obvious that hydro power is a cleaner energy source and implies fewer emissions of CO₂, SO₂, NOₓ, or other pollutants. But just as stated before, concerns have arisen about the breakdown of the bottom of reservoir leading to considerable greenhouse gases emissions.

4.3. Navigation

Navigation issue is assessed together with flood control included in Criterion 2.4, which renders a rather favorable performance. The navigation depth were raised to 175m after 2008, and the tonnage of sailing ship were enhanced from 1000 tons to 3000-5000 tons [5]. Shipping to the inner districts will increase trade, and more closely links between the east and west will be established, further improving the economy growth of those areas. Still, there is sedimentation problem that may hinder the performance of navigation in the future. Channel dredging should be conducted every year in order to maintain a good performance of navigation, e.g. navigation of 10,000-tonnage vessels [14].

In addition to the decrease of navigation costs, another major benefit is tourism boost. Government expects an income rise in tourism, and get ready for the tourism boost thanks to convenient water transport that is much easier to get those dispersed scenic sites. Official claimed that the TGD would not damage the scenery of the Three Gorges; most of the sites within the district were higher than the water level, and the flooded sites were protected and moved. The combination of natural beauty, ancient relics, and modern miracles of the TGD would continuously attract tourists from all over the world. However, the fact seems unconvincing to some extent [15]. It is still unknown how tourism will be affected; whether there is a boost or a fall still remains to be anticipated.

4.4. Water availability

Due to the impounded water in the reservoir and better control of the river flow, more water will be available for agricultural and industrial use, as well as for human consumption. Fresh water is not only supplied in the vicinity of the TGD, but also transferred from the Yangtze Basin to north of China where there’s a deficiency of water resources [16]. Indeed, the water availability is practical and has long-lasting positive effects to both Yangtze Basin and north of China. However, pollution poses a great threat to the promising situation. Large amount of municipal waste and industrial waste have been dumped or landfilled along the river bank since decades ago. Within the reservoir area there are large numbers of factories, mines, hospitals, graveyards and garbage dumping sites, before the water impoundment [17]. Besides, widely used fertilizers in Yangtze Basin agricultural areas may cause eutrophication problem which is harmful to fisheries and aquatic ecosystems [3]. To solve these problems, better handling of all kinds of waste should be conducted; more waste treatment plants should be built to deal with the pollution; ecological farming should be promoted to reduce consumption of fertilizers; cleaner production measures should be taken by industries in order to mitigate their impacts. And most importantly, effective legislation and supervision mechanism should be established to prevent the problems from the cradle.
5. Conclusions
Although the TGD project is a controversial issue among many of the environmentalists because of its environmental effects, the project is still operating successfully and has achieved its primary goal. Flood control, energy production, smooth navigation and fresh water supply were the main objectives of the project which achieved more or less favorable performance.

The MCA result from this study also reflects that achievement. Only four of the total seventeen project performance criteria are identified as poor performance according to MCA pair wise comparison and scoring results, whereas the rest of them are either acceptable or favorable. This result reveals the projects satisfactory. Moreover, the project reduced the fossil based energy production and consequently provides reduction of CO₂, SO₂, and NOₓ emissions; thus promoting clean energy utilization brings the environmental sustainability. However, the long term environmental effects due to the TGD project are still on the way of minimization by implementing different measuring plans. Concrete mitigation and proper efforts should have continued to control environmental impact and ecological balance to achieve the best performance of the project.

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