PARTIAL SOCIAL COST BENEFIT ANALYSIS OF THREE GORGES DAM: IMPACT ASSESSMENT UPDATE AND A GREENHOUSE GAS EXTERNALITY COMPONENT STUDY

by

Qian Sun

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To Ruth

Without her help and support I could never have finished this thesis

To April and Aaron

For everything we shared, every chance we had to grow, and the countless hours we spent together in the lab

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ABSTRACT

This study reviews the literature and updates qualitative and quantitative impacts based on new research and applies a partial greenhouse gas (GHG) emissions cost benefit analysis to the Three Gorges Dam Project (TGDP) in China. The results of CBA suggested a 22.305 billion dollars net present value (using Nordhaus's 2007 optimal carbon price trajectory with assumed average social discount rate (SDR) of 4% assumptions) and a 440.324 billion dollars net present value (based on Nordhaus's Model using Stern's assumption with 1% SDR). This sensitivity analysis indicates that social discount rates highly affect the final results. This study extends the GHG emissions impact component by updating carbon prices and calculation methods, thereby updating the GHG component of Morimoto and Hope's 2004 study. Although the CBA is limited to the GHG component, a review of recent literature and preliminary impact analysis provides the groundwork for a more comprehensive analysis for future study.

LIST OF ABBREVIATIONS USED

CBA	Social Cost- Benefit Analysis
CIDA	Canadian International Development Agency
GESAMP	Group of Experts on the Scientific Aspects of Marine Environmental Protection
GHG	Greenhouse Gas
PBL	Planbureau voor de Leefomgeving (Netherlands Environmental Assessment Agency)
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
Mt	Megatons
NPV	Net Present Value
PRC	People's Republic of China
SDR	Social Discount Rate
TGD	Three Gorges Dam
TGDP	Three Gorges Dam Project
WCD	World Commission of Dams
TWh	Terawatt-hours

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CHAPTER 1. INTRODUCTION

The idea of the Three Gorges Dam was first conceived of in 1919. Since then it has been a very controversial topic among scientists, economists, environmentalists, and journalists. Preliminary work on the dam was interrupted several times due to the successive years of warfare among warlords (1919-1930), the anti-Japanese War (1937-1945), and the KMT-CPC civil war (1945-1950). In 1954, the TGDP captured the attention of Mao Tse-tung after 30,000 people died in one of the worst floods of the century. Due to the massive scale of this project, the "to build or not to build" debate has lasted for almost four decades.

Many people have supported this project. They said the TGDP would be a great way to achieve both economic and environmental goals simultaneously; Benefits they have cited include hydro power generation, flood control, improved navigation, and increases in the water supply. Baruch Boxer[1] has written that "It will be the ultimate statement of old-fashioned steel and concrete engineering, a permanent monument to the dominance of man over nature" and that it would also serve to "symbolize China's modernization dreams", to demonstrate the level of China's industrialization (Boxer, 1988).

The original plan for the Three Gorges Dam was to generate 84.7 TWh per year, which was expected to account for 10% of China's total energy needs and expected to save 50 million tonnes of coal each year (Stone, 2008). However, in 2011, the Three Gorges Dam generated 78.293 TWh, which only accounted for 1.67% of the total electricity supply for the whole country (National Bureau of Statistics of China, 2013). Even though the share of energy created by the dam was overestimated, since China's energy supply growth was

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[1] Rutgers University. He is a visiting scholar at Stanford University and mainly working on China issues.

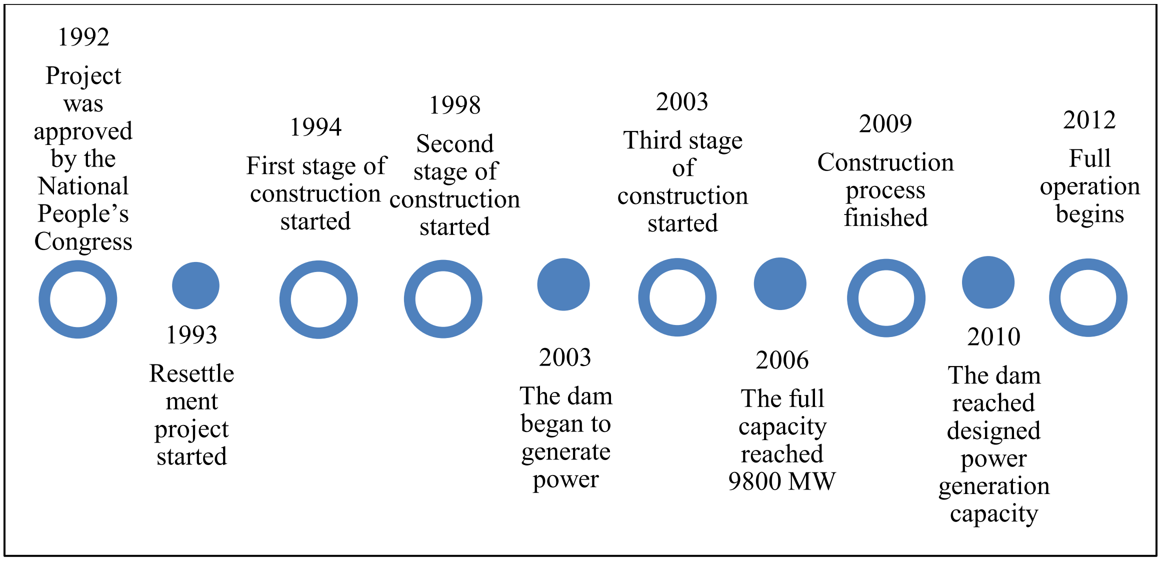
much higher than the estimation, we still cannot ignore the energy benefits brought by the project.

There is a significant unexpected benefit from the project. At the time of the approval of the TGDP (1992), the GHG benefits were not part of the rationale for the plan. However, as humanity became aware of the problem of global warming due to the GHGs which are produced as a byproduct from fossil fuel combustion, this unexpected benefit was to become appreciated. A Study suggested that the dam would potentially reduce China's CO_2 emissions by 100 Mt/year if the electricity generated by the dam was not produced by coal (Morimoto and Hope, 2004).

However, many people have fought against this project. Some have called the Three Gorges Dam "the great leap backward" for China (Adam and Ryder, 1998). Newspaper headlines like "Scientists lined up against the Three Gorges Dam" have remained on the front pages of scientific magazines continuously since the project's inception (Edmonds, 1991; Perkin, 2003; Li, 2009). Some have questioned the social impacts, and particularly, the environmental damages caused by construction of the dam. Such concerns have continued even after the Chinese National People's Congress approved the project in 1992. Many scientists have worried that the project would cause irreparable ecological damages to the whole region (Edmonds, 1991; Reeves and Leatherwood, 1994; Schmidt, 2002; Wu *et al*., 2004; Shen and Xie, 2004) and eventually would put the country under significant economic risk.

After Chinese government approved the TGDP in 1992, the resettlement project started in 1993. The resettlement plan was to displace over 1.2 million people away from the reservoir area. The construction process began in 1994. The first stage construction included building the open channel diversion and temporary ship locks to maintain the navigation. The second stage commenced in 1998 during which the construction work focused on the spillway sections, the left bank, the left power plant, and the permanent ship locks. During the third stage, started in 2003, the construction of the right bank, the right power plant, and the underground power plant were finished. The construction process was finished in 2009 and full operation began in 2012. The project process is illustrated in Figure 1.

Figure 1: Timeline of Three Gorges Dam Project



Both prior to and during construction, the Three Gorges Dam has continued to be a controversial project; Many scholars have tried to assess its social desirability via different methods. This has included two social cost benefit analyses, one CBA by the Canadian International Development Institution (CIDA) in 1988, and, most recently, a study by Morimoto and Hope (M&H), two professors at Cambridge University in 2004.

M&H applied a “comprehensive probabilistic CBA methodology to evaluate the Three Gorges Dam. Their study was “comprehensive” in the sense that they took into account a broader spectrum of impacts than previous CBAs. This included estimating the greenhouse gas due to replacing coal-generated electricity with a low GHG energy source. Their study was “probabilistic” in the sense that they used estimates of probabilities of various impacts to estimate the net present values (NPV)[2] of the project under various scenarios.

H&M’s results suggested a high positive net present value of the project with a mean value of 51 billion Yuan in 1992 prices, a 5% probability that the NPV was greater than 159 billion Yuan and a 5 % probability that the NPV was less than – 14 billion Yuan[3]. In conclusion, M&H emphasized that in spite of the high expected positive NPV, there still existed plenty of uncertainty surrounding the nature and magnitude of the benefits and costs. With respect to this “uncertainty”, they noted that missing and uncertain figures had limited their results and that if accurate data had existed, better results could have been obtained using their model.

Since Morimoto and Hope’s study was an *In medias res* CBA (that is it was carried out after the project had commenced but before all the capital costs were sunk), it is meaningful to redo the TGDP CBA since the construction costs were completed in 2009. An *Ex poste* CBA, a CBA conducted after initial capital costs have been sunk, can include actual values for benefits and costs in comparison with the projections used in

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[2] Net present value at time t = present value of benefit at time t – present value of cost at time t.

[3] This corresponding to a mean NPV of 68.497 billion Yuan and 11.134 billion US dollar; a 213.549 billion Yuan and 35.69 billion US dollar for 95th percentile; and a -18.803 billion Yuan and -3.113 billion US dollar 5th percentile in 2013’s present value.

H&M’s study. Also, the impact analysis on costs and benefits has been updated and hence can be incorporated into the *Ex poste* study.

Given the large scope of a full comprehensive probabilistic CBA in the manner of H&M, instead of undertaking a full CBA, this study is limited to updating the impact analysis done by Morimoto and Hope (2004) and to add a CBA of the GHG component of impacts.

This paper will cover following sections: We will provide an overview of the CBA methodology in chapter 2 and give a literature review of previous CBAs of the Three Gorges Dam Project in chapter 3. We will specify the counterfactual, standing, and identify impacts in chapter 4. We will provide the updated impact analysis and discuss the detailed data of the GHG components of impacts in chapter 5. Chapter 6 will include impact analysis of the GHG components of benefits (dam’s power generation, GHG saving due to reduced coal transport, and improvement of navigation) and costs (the construction of the dam and the resettlement costs). At the end of this chapter, we will monetize all the impacts using Nordhaus’s 2007 optimal carbon price under Nordhaus’s dynamic integrated climate economy (DICE) model. Sensitivity analysis will be introduced in chapter 7, we will monetize impacts using Stern’s carbon price under Nordhaus’s model and apply various discount rates to each assumption. We will include a comparison to discuss the difference between our study and H&M study. And finally we will discuss limitations about this study in Chapter 9.

Our impact analysis and partial CBA of the GHG component of the TGDP provides an important step towards a full comprehensive *Ex poste* CBA of the TGDP and provides a better look for this project.

CHAPTER 2. SOCIAL COST BENEFIT ANALYSIS OVERVIEW

Social cost-benefit analysis is an analytical tool used to evaluate projects to determine whether they are socially desirable. It can provide a systematic and potentially objective method of analysis for policy makers to help them make decisions wisely.

In a CBA to determine the social desirability for projects we use the net present value (NPV). The NPV is calculated by summing the discounted total social surplus over the time period of our project. Following paragraphs will introduce how to get NPV step by step.

First, we have to calculate the total social surplus. We have to identify every impact of the project and quantify them if possible. Then for each time period, the total social surplus of the project includes the private surplus[4] from consumers, producers, and external benefits and costs to third parties for every impact. For the TGDP, the change in total consumer surplus associated with the lower price of electricity and higher output level is the consumer net benefit (the change in their total consumer willingness to pay minus their expenditure); the construction cost for the dam would be considered as the producer cost; and GHG emission benefits would be considered as external benefits to everyone.

Second, we have to monetize each impact such that we will be able to put them into common units. We can get the total social surplus for each time period by subtracting monetized costs from benefits. Considering the fact that people value things differently in

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[4] Private surplus = private benefits – private costs.

different time periods, we weight each time period using discount factors in order to put net benefits in each time period into common units of real value.

Finally, we can get our estimation of NPV by summing the estimates of discounted total social surplus and comparing with that of counterfactuals. If the NPV of the project is positive and higher than the counterfactual alternatives, it means that the project is estimated to be socially efficient to carry out and the method of CBA suggests that (based on the efficiency criterion) the project is a net benefit to “society as a whole” (Boardman *et al.*, 2011).

Also, CBA analysis attempts to account for uncertainty by running trials using different values for uncertain parameters; Such process is called sensitivity analysis. To take into account uncertainty, we have to use the probabilities of various impacts (if available). The simplest way to do this is to estimate the mean values, low estimates, and high estimates (with the most common case being to estimate the impacts for the mean and for probabilities at 5% and 95% confidence level). A more complex way to conduct a sensitivity analysis is to use Monte Carlo Method, which allows CBA analysis to estimate a distribution of the NPV of the project. This is the method that M&H applied in their study. However, we will only cover the simpler method in this study.

Cost-benefit analysis is commonly used because the method within it is quite easy to understand for the majority of people, and at the same time, it can give people a direct look at deciding whether, from the perspective of society as a whole, a project’s benefits outweigh its costs (Boardman *et al.*, 2011).

In general, there are three types of CBA: *Ex ante, In medias res,* and *Ex post*. Almost half of CBA studies are *Ex ante* analysis; decision makers use such processes to choose the best alternatives before the project is undertaken. *In medias res* analysis is used while the project is ongoing, and it can aid in decisions regarding whether to switch to another project before the project is completed. The *Ex post* analysis studies the actual costs and benefits after the project has been completed; it cannot change the final decision but it can provide valuable information for future projects (Boardman *et al.*, 2011). The CBA to be conducted here is an *Ex poste* CBA.

There are nine main steps in CBA according to Boardman (Boardman *et al*, 2011). These are:

1) "Specify the set of alternative projects",

2) "Decide whose benefits and costs count (standing)",

3) "Identify the impact categories, catalogue them, and select measurement indicators",

4) "Predict the impacts quantitatively over the life of the project",

5) "Monetize (attach dollar values to) all impacts",

6) "Discount benefits and costs to obtain present values",

7) "Compute the net present value of each other alternative",

8) "Perform sensitivity analysis", and

9) "Make a recommendation". After those nine steps, CBA might be able to provide a "rational voice for decision making."

This partial CBA study of the TGDP will proceed according to the above steps. The recommendation will include a discussion of the limitations of the study and will outline steps for future work (chapter 9). In the next chapter, we review the literature on CBA's of the TGDP to date.

CHAPTER 3. LITERATURE REVIEW OF CBAS OF THREE GORGES DAM

The scale, complexity and lack of availability of both qualitative and quantitative impacts have made it extremely difficult to apply a comprehensive CBA on the Three Gorges Dam. Nevertheless, there have been several studies that using CBA model to determine the project's social desirability.

The earliest systematic CBA was conducted in 1988 by the Canadian International Development Agency (CIDA). They did a comprehensive feasibility study and then evaluated the project by 10 major impacts: construction planning, scheduling and estimating, economic and financial, design, sediment, environment, resettlement, navigation, flood control, power benefits, and regional economic impacts (CIDA, 1988). This study included monthly data such as construction workers salaries to make its results more precise. The corresponding counterfactual project considered in this study was mixed hydro-thermal.

The CIDA study's result suggested a median net benefit of 0.635 billion Yuan (1988 price), given 17.238 billion Yuan total costs and 17.873 billion Yuan total benefits. This corresponds to a NPV of 3.093 billion Yuan (0.507 billion US dollars) in 2013's present value. Based on sensitivity analysis, this study estimated a 10% possibility that the project would yield net costs (which means there is 10% possibility the net present value of the project would be negative such that, based on the CBA, the project should not have been approved based on the CBA social surplus criteria).

Although this study was the most exhaustive study at that time, since it was done 25 years ago, there were certain limitations, which suggest that the CIDA study underestimated the net benefits of the project. For example, the authors did not take into account the GHG external benefits and did not include costs such as the loss of archaeological sites and flood impacts upon downstream residents. Moreover, some crucial numbers were incorrect. For example, the CIDA study estimated that 22 turbines would be used to generate power but after extended construction, the number of turbines increased to 26 and eventually to 32 (CIDA, 1988; Morimoto & Hope, 2004; Executive Office of Three Gorges Project Construction Committee State Council of the PRC).

Another influential study, which is also our main resource, was conducted by Morimoto and Hope in 2004. They used a comprehensive probabilistic CBA model[5] to take into account the possible impacts by calculating the net present value. In the benefit category, they estimated five impacts including economic growth, power generation, clean power[6], flood control, and navigational improvement. In the cost category they estimated nine impacts including construction, archaeological loss, resettlement, operation and maintenance, accidents, downstream effects, fishery loss, tourism loss, and land inundation loss

In H&M's study, the authors took coal-fried electricity as the counterfactual based on the fact that 75% of electricity in China was coal-fried. In their assumption, considering that coal-fired electricity is unable to meet demand of the country for some proportion of the

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[5] Probabilistic CBA model is a CBA model that applies the assumption of Monte Carlo Simulation as discussed in chapter 2.

[6] In Morimoto and Hope's paper, they considered hydropower as the clean power due to its low GHG emissions because their counterfactual was coal-fired power generation, which releases GHGs during the power generation process.

time (P_o), then if the electricity the dam is used to meet the excess demand, then there is no GHG benefit since coal is not replaced. If this is the case, then the amount of electricity generated by the dam will be addition to the electricity supply. In order to model this, H&M considered the parameters P_0 (the "initial proportion of time during when alternative power is not available"), φ("the annual rate of decrease in P"), E_0 (the "initial expected increase in economic output caused by increased power supply"), A (the annual power generation decreased rate) and GC (the generation capacity).

In this study, the most influential benefits were power generation (PG), economic growth (EG), and clean power (CP); the most influential costs were construction costs (CC), resettlement costs (RE), and the value of lost archaeological sites (AS). Here we will only introduce impacts that also considered in our study for future comparison[7].

The income from power generation for year t (PG_t) was calculated by multiplying the quantity of electricity generated in each year (QE_t) by the price of electricity at the same time (PE_t).

$$PG_t = [(QE_t) * PE_t]$$

The clean power (CP_t) was calculated by multiplying the annual decreased CO_2 or SO_2 caused by the Three Gorges Dam in gigatons (CL_i) by the benefits of CO_2 or SO_2 reduction in Yuan per ton of CO_2 or SO_2 (CM_i)[8] and then multiplying by the proportion of the time that the dam was generating power $(1 - P_t)$.

$$CP_t = (1 - P_t) \sum_{i=1,2} [CL_i * CM_i]$$

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[7] Others are discussed in Appendix B: Equations.

[8] CM_1 is for CO_2, CM_2 is for SO_2.

$$CL_i = (C_i * QE_t)/10^9$$

$$P_t = P_0 * e^{[-\varphi t]}$$

They calculated the construction costs (CC_t) and the resettlement costs (RE_t) in similar way and details will be discussed in the Appendix.

Results also suggested that the sedimentation would be expected to limit power generation ability, the operation and maintenance work would be costly, and the loss of archaeological sites would be irreversible. Sensitivity analysis suggested that parameters P_0 and φ have most significant impact on NPV and the chosen discount rate is crucial for the NPV result.

This H&M's study covered many impacts to increase the accuracy of the estimation. However, some of the data they used has not been updated. For example, they used the assumption that the total power generated by the dam would be equivalent to firing 50 million tonnes of coal (1996), however this assumption was made eight years before this study and they did not have the data to take into account the technology change to the energy production efficiency as is done in our study.

Considering the fact that both of the studies discussed have certain limitations restricted by the time they were done, applying a CBA after the dam's construction could reduce uncertainty in the CBA. Our study will include an updated impact analysis and apply a partial CBA on GHG component using updated data and modified calculation methods to be discussed shortly.

CHAPTER 4. SPECIFYING THE COUNTERFACTUAL, STANDING, AND QUALITATIVE IDENTIFICATION OF IMPACTS

4.1 “SPECIFY THE SET OF ALTERNATIVE PROJECTS”

We assume that coal is the alternative energy resource. China is number one in coal production, 4th in oil, and 6th in natural gas worldwide. Yet, its huge and growing population base causes a constant energy shortage for China. What makes it worse is that, limited by uneven regional resource distribution and incomplete industrialization, energy storage is more severe in the coastal area and south of China.

This dependency on coal has also caused a large GHG intensity of electricity in China (Liu *et al*., 2012). Historically, China’s industry has heavily relied on coal production; it is one the cheapest and most common resources in China. It has been used for centuries, and this is still the case. In 2007, 94.83% of the coal went to the industrial sector, of which 50% went to the electricity sector (Lin and Liu, 2010); around 75% of power was coal-fired and it supported half of the railway transportation (National Bureau of Statistics of China, 2013). Studies suggest that the global coal production peak will be reached around 2030. For China, the peak is predicted to happen during late 2020s and the early 2030s, and coal imports have been increasing since 2008 (Lin and Liu, 2010).

These factors may lead to increases in coal prices and hence increases in the cost of coal-fired electricity generation. Suggestions have been suggest that, given such circumstances, developing renewable energy is one of the best alternatives for China. But before renewable energy becomes the main energy resource, coal is expected to continue to be the main energy resource.

However, by assuming that coal is the alternative energy resource, we have also assumed that any energy displaced by the dam would have been produced from coal and not from lower GHG energy sources such as renewable energies or natural gas. As a result, we may have overestimated the benefits of the project. Such uncertainty will be discussed in the conclusion.

4.2 "DECIDE WHOSE BENEFITS AND COSTS COUNT (STANDING)"

Our study considered the costs and benefits of the following groups: First, Chinese people (who, for example, experience benefits from lower electricity price and lower navigation costs, as well as costs due to paying the government tax revenue to support the TGD instead of other sector); and, second the costs and benefits for international people for example, global benefits due to reduced GHG emissions for current and for future generations up to 2092).

There are groups that could have be given standing but whom we did not include in our study. Examples include: non-Chinese companies who benefit by providing equipment and materials for construction, people in other countries and future generations, who's happiness might be affected by knowing that dolphins and other animals in the Yangtze River area have gone extinct.

4.3 "IDENTIFY THE IMPACT CATEGORIES"

In this study, we have identified 15 impacts, these are: power generation, flood control, navigation, greenhouse gas benefits, ecosystem, biodiversity and extinction, architectural heritage, resettlement, geological hazards, greenhouse gases released by reservoir, fishery, flood effects, water pollution, national security, international impacts, and others. We did not catalogue every impact by benefits or costs because some of them contain both costs and benefits. Details for each impact will be introduced in the next chapter.

CHAPTER 5. QUANTITATIVE & QUALITATIVE IMPACT ANALYSIS

5.1 POWER GENERATION

The designed goal of the Three Gorges Dam is to generate 84.7 TWh (billion kilowatt-hours) per year of electricity. That amount of electricity will be equivalent to burning 50 million tons of coal (Stone, 2008), which is as much as 10% of China's energy demand (Allin, 2004). Hydropower is one way to generate low GHG emissions and the largest source of renewable energy in the electricity sector (IPCC, 2011). Yet some scientists have argued it is not the most efficient way to provide low GHG energy. First, hydropower projects require a high capital investment cost and yield a long-period, low level return in the future. Second, a large hydro dam such as the Three Gorges Dam generates the most power in spring (glaciers melting) at which time the demand for power is comparably lower than summer and winter.

The power generating ability of TDG is affected by three factors: rainfall caused by temperate monsoon climate, spring water flow caused by the glaciers' melting, and sedimentation. Studies suggested precipitation reduction and sedimentation condition of the reservoir might be the biggest factors to affect power generation ability which will create huge uncertainty for future power generation ability estimation (Boxer, 1988; Lei, 1998; Lu *et al.*, 2003; Morimoto and Hope, 2004). Uncertainty regarding climate change impacts and their timing is, according to Adam and Ryder (1998), the biggest uncertainty of the dam's power generation. Records show that from the 1960s, precipitation decreased constantly in the upper Yangtze River and the temperature increased 0.88 Celsius at the glaciers' area for the past 50 years causing the glaciers'' to shrink by 1%

per (IPCC, 2007). Studies showed around 0.5 to 1 % of water storage capacity will be lost because of the sedimentation (Mahmood, 1987; The World Commission on Dams, 2000) and that after 30 to 50 years, 30% to 40% of sediments will be discharged such that equalization[9] will happen after 80 years (Lei, 1998). Water and sediment discharge mostly happens during the summer with 50% of the annual water discharge occurring in the period July – September. During the dry seasons, water discharge and sediment load decrease at the same time.

Another concern surrounding the hydropower project is whether it would be able to fulfill the promise on its energy generating ability (Boxer, 1988). Historical records suggest that the energy generating ability is not the problem for now. By the end of 2006, the Three Gorges Dam had reached its full capacity of 9800 MW. A year later, its total capacity had reached 14800 MW, and the dam generated approximately 62 TWh of electricity that year. At the end of 2010, the total capacity exceeded 22000 MW and generated 84.37 TWh of electricity (Gleick, 2009; National Bureau of Statistics of China, 2010). By 2011, power generation only reached 78.293 TWh due to precipitation reduction (National Bureau of Statistics of China, 2011). However, it is still too early to say whether the dam's future generation ability will be able to maintain the current level due to the reasons we discussed above.

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[9] Equalization of sedimentation means silting at the reservoir area won't be increasing over time after 80 years.

5.2 FLOOD CONTROL

Due to the unique natural landscape and monsoon climate, the Yangtze River valley is one of the most flood prone areas in China while the middle-lower Yangtze River plain has one of the highest population densities in China. It is also the most important agricultural base. These factors make flood damage more severe compared with other places. As such, one of the major purposes of the Three Gorges Dam is to prevent floods the size of the one in a hundred year frequency thus protecting hundreds of million peoples' lives and properties of those who live downstream. But unlike the other designed purposes of the dam, the actual flood control ability can only be tested when the flood occurs.

During the first construction period (1998), the Yangtze River experienced a flood that was second only to the one that happened in 1954. Since the construction was in progress, the dam did not have full ability to control the flood. The flood cost 255 billion Yuan (1998 Yuan value, corresponding to 347.394 billion Yuan and 57.525 billion dollars in 2013's present value) in direct losses. In 2010, the dam played its role as the flood control operator by successfully preventing the "ChuanJiang" flood. However, the flood control ability has not been fully tested since the stored floodwater did not exceed the maximum level of flood storage limit when the flood peak reached the Three Gorges Dam. In a nutshell, the flood control ability functioned as well as we expected.

5.3 NAVIGATION

The lower Yangtze River was and continues to be one of the busiest waterways in China. It directly connects five provinces, has dozens of tributary rivers, and meets with the Grand Canal (the longest canal in the world, built during the Sui Dynasty, 581-618 AD, which also connects Beijing and Hangzhou), which makes its radiation region extend to Beijing. However the navigational situation for the middle and upper Yangtze River is not that ideal; the mountainous landscape has been the biggest impediment for those areas. For centuries, those natural barriers disconnected the community from mainland to coast.

An important initial goal of the dam was to improve the transportation capacity and reduce the transportation cost by using both the Three Gorges Dam and the Gezhouba Dam (38km downstream of the Three Gorges Dam) to reduce the gap between the upper and middle Yangtze River. One study estimated the total transportation among the Three Gorges area would increase five times and the transportation cost will decrease 35-37% compared to previous level (Allin, 2004). A government report showed that the total cargo by river for the Chongqing area was 14.7 million tons in 2009, which counted for 87.2% of whole country. The waterway transportation is comparably clean, cheap but slow. Its passenger transportation share in the market was affected by the development of aviation, railway, and speedway industries. The total volume of passenger transport for the Three Gorges Dam only reached 0.9 million people in 2010. Early this year, the water level of the Three Gorges' reservoir fell to 160 meters, yet there is no information about how that will affect the navigation.

Navigation improvement provides other benefits. Studies suggested river transport yields lower GHG intensity than land transport (Xu *et al.*, 2010). Hence the increased river traffic would reduce the land transport pressure, thus reducing the carbon dioxide released by public transportation. Additionally, increased river transport is predicted to provide more job positions and create new markets (Allin, 2004).

The most basic factor that will help Three Gorges to maintain its navigation capacity is to keep water flow at a steady level. However, this is hard to guarantee because the water level is under the influence of monsoon climate. Sedimentation conditions also can limit river's navigation ability (Lu *et la.*, 2003). A research report which studied the sedimentation conditions for the Yangtze River in June 2003 also pointed out that during the dry season, the water level was even lower than 38 meters (Chu and Zhai, 2008).

5.4 GREENHOUSE GAS BENEFIT

Chinese industrialization, as in other developing countries, has highly relied upon its labor input and natural resources. The incomplete industrial system and lack of techniques has made China the biggest greenhouse gas polluter in the world (in total GHG emissions, not per capita). By 2006, China's CO_2 emissions from fossil fuel used and industrial processes became larger than those of the United State (Planbureau voor de Leefomgeving, 2006).

China's greenhouse gas growth rate is faster than expected (Inman, 2008). In 2008, China's annual CO_2 emissions accounted for 23.33% of the global total annual CO_2 emissions (International Energy Agency, 2009). Theoretically speaking, the Three

Gorges Dam will help to relieve such emission pressure for the country by providing hydropower. Studies have indicated this amount of power will be equivalent to firing 50 million tonnes of coal which would have created 100 million metric tonnes of CO_2 (Morimoto and Hope, 2004). However, the power generation ability for the Three Gorges Dam is affected by many factors and coal-fired power generation rate varies with time. As a result, it is difficult to calculate greenhouse gas benefits for the project. However, we will use updated data (up to 2011) to compute it as best as we can, methods and results will be carefully discussed in chapter 6.

5.5 ECOSYSTEM, BIODIVERSITY AND EXTINCTION

Most scientists think, based on studies around the world, that the construction work will cause irreversible effects on the ecosystem for both the reservoir area and downstream of the Yangtze River (Shen and Xie, 2004). For example, the level of reservoir increased, leaving hundreds of islands upstream, and the sudden loss and fragmentation of habitat and change of humidity caused more competition among terrestrial animals (Perkin, 2003; Wu *et al.*, 2004).

The Yangtze River Valley has the largest number of wild fauna and flora compared with other valleys in China. Among 361 fish species, 177 are endemic, and 25 of them were categorized as endangered as of 2003 because of the construction of the dam (Xie, 2003). Rare species like the panda, Rhinopithecus, snub-nosed monkey, tiger, Chinese sturgeon, white-flag dolphin, and the Yangtze alligator only exist in the Yangtze River valley. In 1998, the Three Gorges Dam Ecological and Environmental Monitoring Center found white-flag dolphin 7 times. In 2003, they only found it once, and after that they no longer have record of the wild white-flag dolphin. They kept finding Chinese sturgeons but their number decreases every year.

Dam construction not only affected the diversity and biomass of species, it also affected their reproductive process. Take the Chinese sturgeon for example; after 2005, the Monitoring Center found no evidence that Chinese sturgeons were breeding downstream of the dam (Three Gorges Dam Ecological and Environmental Monitoring Information Bulletin, 1997-2011).

Table 1: Biodiversity in the Three Gorges Reservoir Region (number of species by different taxonomic groups)

	1996	1997	1999	2003	2004	2005	2006	2007	2008	2009	2010
Higher plants		6088	6088	6088	6088	6088	6088	-	-	1314	1222
Terrestrial vertabrates	369	367	552	561	561	-	575	-	-	692	692
Mammals	85	81	118	-	103	194		-	-	112	112
Birds	237	236	342	-	390	-	-	-	-	485	485
Reptiles	27	23	51	-	36	-	-	-	-	51	51
Amphibian species	20	27	41	-	32	-	-	-	-	44	44
Fish		105	107	91	100	117	127	118	118	118	119

Source: 1997-2011 Three Gorges Dam Ecological and Environmental Monitoring Information Bulletin

- : No record for given category in corresponding year.

In Table 1, we can see that the numbers of species of terrestrial vertebrates and fish has increased since 1996. Such increases should be considered as the result of the *Ex situ* conservation program. Up to 2001, 75 % of the rare flora have been safely removed to protection zones (Southern slope of Shennongjia). However, the number of higher plants has decreased rapidly since most of them were submerged under the water (see Table 1). Moreover, the huge reservoir will affect the downstream ecosystem and the biodiversity. The temperature and the oxygen level downstream are predicted to decrease, which will affect fisheries, bird species and other animals (Allin, 2004).

5.6 ARCHITECTURAL HERITAGE

The Yangtze River valley is one of the cradles of Chinese civilization. Besides the thousands of cultural antiquities situated around the riverside, there are many sites, tombs, and stone implements under the river water. All these precious historical relics can be traced back from the Paleolithic period to the Qing Dynasty (Tang, 2012).

The construction of the dam caused significant damage to the cultural antiquities in the reservoir area. The dam construction has created a huge reservoir that has covered lots of architectural sites under the water. To reduce the damage to cultural antiquities, scientists suggested several actions to protect them. Above all, the first thing they did was to figure out how many sites there were and their conditions. Including the architectural sites, there were 1282 priority-level cultural antiquities in the Three Gorges Area. Among those there was 1 officially approved national-level site and 5 provincial-level sites (Xinhua net, 2005).

To reduce damages towards cultural antiquities, preservation work such as removing antiquities to high altitude areas has taken place. In theory, the preservation work should be finished before the construction begins. Unfortunately, protection of these cultural antiquities was limited at the beginning of the preservation process, with a lack of financial support being the biggest problem. Preservation work officially started at 1997, at the time the first stage of construction work was almost finished. As a result, many cultural antiquities were damaged or destroyed. Up until 2002, total fund for preservation work were 0.3 billion Yuan which corresponds to 0.413 billion Yuan (0.068 billion dollars) in 2013's present value and the estimated cost for the project was 1 billion Yuan which corresponds to 1.377 billion Yuan (0.228 billion dollars) in 2013's present value (State Administration of Cultural Heritage, 2003)[10].

Planning and regulations for preservation work were quickly put into place. The State Council published the Regulations on Residents-Resettlement for the Yangtze River Three Gorges Project Construction, which set principles for conservation of historic landmarks and sites for reservoir areas in 1992. Also, the National Heritage Board published the Planning Framework for Conservation of Historic Landmarks and Sites for Reservoir Region in 1991. In the planning framework, they recorded 455 under-water sites and 383 surface relics. Among those, one National-level unit of cultural relics and 4 Provincial-level units of cultural relics have been submerged. Another has been removed followed by a protection program, with the first stage of removal from 1995-2000 when 75% of the relics were moved out of the reservoir before the water level reached 155 meters. The second stage begun in 2001and aimed to finish the rest of the removal work. The most famous sites such as Zhang Fei Temple (Zhang Fei, the military general who served under the Liu Bei ,who proclaimed himself emperor in A.D. 221, in the early

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[10] Above figures are from government report. Instead of yearly data only the final number was provided. Numbers were converted to current value, but we do not have information about whether the number they posted was discounted or not.

Three Kingdoms Period, around A.D. 208 to A.D. 220) has been removed to a higher latitude in order to maintain the original landscape (Duan and Zhao, 1999).

5.7 RESETTLEMENT

The dam construction of massive dams usually leads to resettlement, yet there is no other project which has such a large number of migrants as the Three Gorges Dam. In the short term, among all consequences that are caused by the Three Gorges Dam, the one that affected peoples' lives most directly was the reservoir resettlement program. Dam construction caused 2 cities, 11 country towns, 114 townships, and 1353 villages to be permanently flooded by the rising water (Jackson and Sleigh, 2000; Li *et al.*, 2001).The original resettlement number was 1.2 million individuals, however a statistical survey showed that the total number of migrants is 1.39 million (Zhang, 2010). Among the millions of migrants, 86 % were relocated within the same province and others were moved to 25 different provinces (Figure 2). Of the 1629 enterprises in the Three Gorges Dam area, 617 of them were merged into 407 different companies while the other 1012 were closed (Chongqing Migration Bureau, 2011).

Figure 2: Migrant Receiving Provinces

Source: Edited based on Provinces map, In *Wikipedia*, Retrieved October 28, 2013, from http://en.wikipedia.org/wiki/File:Hunan_in_China_(%2Ball_claims_hatched).svg. Copyright 2011 by TUBS, free to transmit under *GNU Free Documentation License*

In order to put the resettlement program into force, the Chinese government has made large efforts. For example, it has continued to give subsidies to out-moving migrants as well as the resettlement places that will receive those migrants (Li and Jiang, 2003). The resettlement project cost 39 billion Yuan (1993 price value) by the end of 2007 (Chongqing Migration Bureau)[11]. The Chinese government allotted additional 22 billion Yuan (2008 RMB) for the resettlement program for the next 12 years in total (Stone, 2008)[12].

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[11] This corresponds to 111.06 billion Yuan (18.39 billion dollars) in 2013's current price.
[12] This corresponds to 26.702 billion Yuan (4.421 billion dollars) in 2013's current price.

The most common consequences of reservoir resettlement are: economic impoverishment, social instability and environmental degradation (Li *et al.*, 2001)[13]. For those people who were relocated within their original province, the biggest problem is poverty. Less than half of those displaced migrants can keep their original occupations while others had to change their career plans to fit into their the new community. This may make it harder to maintain their previous living standards. Out of the 1.2 million migrants, 25% of them worked in the agricultural sector (Heggelund, 2006). For those migrants who stayed in the agricultural sector, the loss of farmland has caused lots of problems.

The resettlement center came up with one of the major development strategies in a relocation scheme-the "land for land". The basic idea of this scheme is that government will provide a certain amount of land to migrants who choose to stay in the agricultural sector such that they can continue their previous production process. This strategy seems to resolve the land issue but it has failed to guarantee high land quality. In the mountainous Three Gorges area, woodlands and shrub lands cover most areas, such that only 25.4% of the land is used for farming. Reservoir inundation submerged the best farmlands in riverside valley, which makes the land issue more severe (Jim *et al*., 2003).

The land issue was not the only problem for the resettlement program. The World Commission of Dams (WCD) report (2000) also has criticized the resettlement program. In particular, they argued that the local governments lack accountability, which has led to

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[13] Two other important definitions that have been raised in the meantime are carrying capacity and environmental capacity. The first defines "the maximum number of organisms of a particular species that can be supported indefinitely in a given environment". In this case, carrying capacity refers to "the maximum number of people that a given land area will maintain in perpetuity under a given system of usage without land degradation setting in" (Allan, 1949). Environmental capacity is "a property of the environment and can be defined as its ability to accommodate a particular activity or rate of activity (e.g. volume of discharge per unit time, quantity of dredging dumped per unit time, quantity of minerals extracted per unit time) without unacceptable impact" (GESAMP, 1986, Page 8)

corruption, embezzlement and inequality of benefits (WCD, 2000). It seems that the Chinese government has a long way to go in order to achieve social justice (Li *et al.*, 2001).

The resettlement program faced many problems as the process carried on. Since the construction has changed the whole ecological system, and since extreme weather happens more frequently than before, landslides, triggered by heavy rains, are threatening those who live near the reservoir area. One anonymous Chongqing official revealed that another 4 million people might have to be resettled in the next decade (Stone, 2008).

5.8 GEOLOGICAL HAZARDS

Geological hazards are one of the most frequent impacts caused by dam construction. Previous experiences suggested that during and after construction, earthquakes, landslides and mud rock flows are the main types of geological hazards for dam areas. Considering the scale of the Three Gorges Dam, scientists have predicted that the situation for the reservoir area will only become worse. Some scientists even believe that the geological hazards will become so severe that they will eventually affect the functions of the dam. Others have argued that since construction increases the height difference between upstream and downstream of the dam, this will put the middle-lower Yangtze Plain in great danger. For example, if precipitation increases in the TGD area cause the water level to increase in the reservoir, the dam’s tolerance may be exceeded such that the people living downstream may have to face a potential flood caused by the dam.

The earthquake records provided by the Three Gorges Dam Ecological and Environmental Monitoring Information Centre showed very detailed information for the reservoir area. Before 2000 (during the second period of the construction), earthquakes happened so rarely that it cannot be confirmed whether the dam construction caused any (Table 2). However, during 2001 to 2002, there were obvious increases in earthquake frequency (Table 2). After 2003, as the third construction period began, the whole area experienced more earthquakes than before (Table 3). The earthquake frequency increased 500% in 2004 compared with 2003 and the maximum magnitude increased. The worst period was during 2008 and 2009, during which earthquakes happened 2121 times in 2008 and 1964 times in 2009. On May 12, 2008, the Sichuan Earthquake happened 79 kilometers northwest of Chengdu, killing 69,227 people, with 18,392 missing. It was the worst earthquake China has experienced since 1949. It was clear that the dam construction made the geological situation worse for the reservoir area. Several studies suggested that if the magnitude range stayed at a certain level, this would not cause fatal effects (Liu and Huang, 2009; Chen *et al*., 2010; Wu *et al*., 2010).

Table 2: Three Gorges Area Earthquake Record (1997-2002)

Year	1997	1998	1999	2000	2001	2002
Frequency	7	12	4	16	175	66
Magnitude Range	M0.0-3.9	M1.0-2.8	M0.3-1.7	M0.0-3.0	M0.0-3.6	M0.0-3.7

Source: 1997-2011 Three Gorges Dam Ecological and Environmental Monitoring Information Bulletin

Table 3: Three Gorges Area Earthquake Record (2003-2010)

Year		2003	2004	2005	2006	2007	2008	2009	2010
Total number		235	1062	905	1019	1402	2121	1964	510
Frequency Magnitude Range	M0.0-0.9	165	625	431	510	551	1112	1144	416
	M1.0-1.9	66	378	405	448	751	880	721	83
	M2.0-2.9	4	56	67	57	96	105	92	11
	M3.0-3.9	*	3	2	4	4	14	7	*
	M4.0-4.9	*	*	*	*	*	1	*	*

Source: 1997-2011 Three Gorges Dam Ecological and Environmental Monitoring Information Bulletin

*: no earthquake happened at the corresponding magnitude

5.9 GREENHOUSE GASES RELEASED BY RESERVOIR

The whole idea of a hydropower program is to obtain energy, which incidentally as it turns out might slow down global warming by releasing less greenhouse gases if the electricity would otherwise have been produced using coal-fired generators. However, reservoirs, created by dams, have been found to contribute a large part of the global warming potential of GHG emissions.

Estimating the GHG emissions released from the reservoir is complicated for many reasons. In general, the emissions released depends upon decomposition rates[14], water residence time[15], reservoir's age and latitude (Steinhurst *et al.*, 2012) with decomposition being the main source. Decomposition rates will mainly depend on temperature, reservoir shape, volume and depth, the amount and type of vegetation flooded, geographic location,

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[14] The rate of decomposition for organisms that have been covered under water.

[15] The time that the water has been stored in the reservoir.

the reservoir's age and latitude. High biodegradation level causes reservoirs located at low latitudes to produce higher GHG emissions. In fact, studies suggest that compared with boreal regions, reservoirs in tropical regions can produce 20 times more GHG emissions (Steinhurst *et al.*, 2012). Water residence time and GHG emissions have a negative relationship. The relationship between GHG emissions, reservoir age and latitude are negatively correlated as well (Barros *et al.*, 2011). As the study shows, in the first ten years the hydropower reservoir may emit a higher level of GHG emissions than are saved by the dam, such levels of GHG emissions may be higher than the annual emission for certain fossil fuel sources. Yet, as the reservoir age increases and the decomposition are completed, the GHG emissions from the reservoir decrease.

There are only a few studies that have thus far investigated GHG emissions releases from hydro reservoirs. A study indicated that hydroelectric reservoirs release GHG such as CO_2, CH_4, and N_2O, which account for 4 % of global carbon emissions from fresh water (Liu *et al.*, 2011). It also stated that reservoirs and lakes behave in many similar ways, such that reservoirs play the same part as lakes in the water cycle with similar net GHG emissions releases. One study that focuses on daily and seasonal variation of CH_4 and CO_2 fluxes at the Three Gorges Dam area suggests some interesting results, namely, that CO_2 fluxes are positively related with surface water temperature and water flow, and have a negative relationship with air pressure and the surface water pH. Compared with CO_2, CH_4 changes more between seasons, however the total fluxes for CH_4 are tens to hundreds of times less than CO_2 in different seasons (Xiao *et al.*, 2013). This is why in various studies we found the numbers of CO_2 emissions and GHG emissions were so close. In this study, 2010-2011 data showed that when compared with other reservoirs and natural lakes, the amount of CH_4 fluxes in the Three Gorges Dam reservoir were actually lower (Xiao *et al.*, 2013).

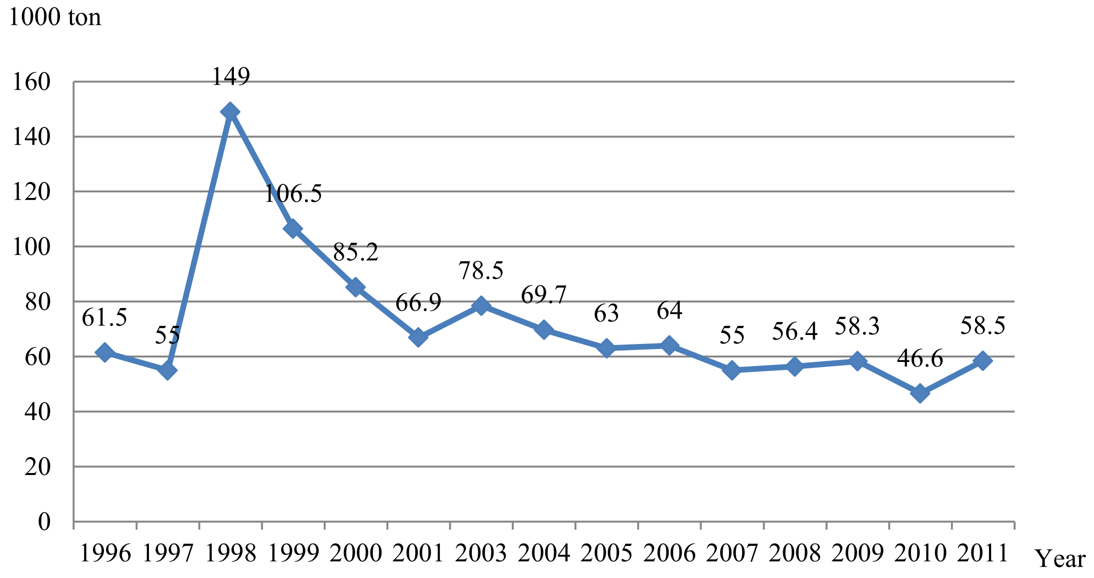
We are interested in how many extra GHG emissions have been and will be released from the Three Gorges Dam reservoir. Several studies suggested that GHG emissions of the Three Gorges Dam reservoir, especially for CH_4 emissions and N_2O emissions, were much lower than other reservoirs and natural lakes at the same latitude (Chen *et al.*, 2009; Chen *et al.*, 2011; Lu *et al.*, 2011; Zhu *et al.*, 2013). Moreover, one result indicated that latitude, which affects temperature, may not be a main determinant of the reservoir's GHG emissions (Chen *et al.*, 2011). Also, recent studies have shown that CH_4 emissions have decreased annually (Chen *et al.*, 2009; Chen *et al.*, 2011), suggesting that GHG emissions for the reservoir will decrease as the reservoir's age increases as addressed in Steinhurst *et al.*'s study (2012).

Opinions have been made that GHG emissions from reservoir should not be taken as the major impact for global carbon studies (Barros *et al.,* 2011). But for our TGD study it matters a lot. Unfortunately, most research on reservoir GHG emissions focuses on tropical and boreal regions (Liu *et al.*, 2011) and only few studies can advance our study. Also, given the fact that there is no consensus scientific model to support reservoir GHG emission analysis (Steinhurst *et al.*, 2012; Goldenfum, 2012), we are unable to calculate the GHG emissions for the past and for the future, causing considerable uncertainty to our analysis. Preliminary studies suggest that the Three Gorges Dam reservoir is not GHG neutral and its emissions are lower than other reservoirs and natural lakes at the same latitude.

5.10 FISHERY

The Yangtze River basin used to be one of the richest areas of fish species diversity (Xie, 2003). A considerable reduction in species diversity and fishery productivity was expected after construction began. As we have seen in Figure 3, the total production of fish declined rapidly after 1999 and consistently decreased after that at a decreasing rate. Another information resource reported that carp production decreased by nearly half from 2003 to 2008, and this same result was also confirmed by the Institute of Hydrobiology surveys (Stone, 2008). The wastewater from the upstream city, Chongqing, and the oil containing residuals coming from transportation boats and accidental release became two main water pollution resources. The pollution condition of the Yangtze River is grim, such that the fish contained a certain amount of metal residuals, but the toxic substances did not exceed the national food hygienic standard. After 1998, copper, oil, volatile phenol, non-iron ammonia, total phosphorus, and total zinc became the source of pollution one after another. According to the reports, pollution conditions like eutrophication were not severe enough to affect the fish reproduction; however, it caused eutrophication downstream (Wu *et al*, 2004).

Figure 3: Natural Fishing Amount in the Reservoir Area and Downstream of Yangtze River (1996 to 2011)



Source: 1997-2011 Three Gorges Dam Ecological and Environmental Monitoring Information Bulletin

5.11 DOWNSTREAM WATER FLOW AND FERTILITY CHANGES

Complex impacts on the downstream area are hard to measure. At the beginning part of this section, we examined the Three Gorges Dam's economic impacts upon power generation, flood control, and navigation improvements. While the Three Gorges Dam is controlling the flooding, the downstream area has experienced and continues to experience water flow reduction and fertility losses (Xie, 2003; WCD, 2000). The Three Gorges Dam will control the floodwaters during the natural flood period such that there will be a discontinuation of the natural river system.[16] The valley area will not get the annual nutrient replenishment as usual, which will lead to productivity decreases in agriculture and may affect fisheries, bird species, and forests (WCD, 2000). Also considering the fertility losses, downstream peasants will have to use synthetic fertilizers to maintain land fertility, which will cause environmental damages due to synthetic fertilizer production process and will cause greenhouse gas emissions due to the energy input during the fertilizer production process.

5.12 WATER POLLUTION

After the construction, the water quality changed completely for the downstream of the dam. Chongqing, as one of the biggest cities and an important industrial center of China, contains more than 30 million permanent residents. Located 600 kilometers upstream of the reservoir area, Chongqing's industrial sector produces around 1400 million m^3 of wastewater every year, with all of these pollutants flowing into the Three Gorges Dam reservoir (Okadera *et al.*, 2006). The dam has increased the transportation capacity of the river and has caused river pollution to increase according to the 1997-2011 Three Gorges Dam Ecological and Environmental Monitoring Information Bulletin. Water pollution not only endangers people who live downstream of the Yangtze River, but also endangers species that live in the river region. A study showed rare species like the Chinese sturgeon, river sturgeon, and paddlefish all contain high levels of toxins (Allin, 2004). However, economic growth was one of the reasons for downstream water quality

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[16] "Natural river system" means water flow of rivers will depend on complex impacts such as temperature and precipitation, and can be predicted given historical data. Since the water flows for downstream of the Yangtze River is controlled by the dam it's no longer natural.

decreasing. It is hard to determine how much damage was caused by the dam construction and operation.

5.13 NATIONAL SECURITY

Large projects such as nuclear power plants, hydro projects, landmarks, and government organizations have on occasion been targets of terrorism or military operations. Examples are the Mohne and Eder dams during WWII (Germany) and the Yellow River dikes during the anti-Japanese War (China). Several studies suggest that there is a possibility that the Three Gorges Dam will become a target and the 75 million people who live directly downstream of the Three Gorges will be threatened (Stone, 2008; Gleick, 2009). The U.S. Pentagon 2004 Annual Report mentioned that Taiwanese leaders once considered the Three Gorges Dam to be the deterrent against potential military action of the Chinese against Taiwanese (Gleick, 2009).

5.14 INTERNATIONAL IMPACTS

In addition to these impacts addressed above, the influences brought by the Three Gorges Dam are not only for the residents of China. Studies show that the Three Gorges Dam not only affects climatic variables (such as temperature, humidity) due to reduced GHG emissions, but also affects climate on a regional scale (Gleick, 2009). One particular point that has been made is that the ocean currents in the Japan Sea could be disturbed (Perkin, 2001). This is because the dam will reduce 41% of the water discharge for downstream Yangtze River (Lu *et al.*, 2003) while agricultural water usage will also reduce the remaining water flow. This reduction is predicted to lower the ocean salinity such that less saline water will follow the North Pacific gyre, in turn, causing the Japan Sea more easily to freeze during the winter. Also, the instigated convection is predicted to affect the temperature for this area, which is expected to warm Japan by several degrees Celsius (Perkin, 2001). Another thing that should be mentioned is that there might be unknown impact on ocean life.

5.15 OTHER IMPACTS

In the qualitative analysis, we have only discussed the most influential impacts. There are other impacts we did not discuss due to a lack of information. These include: island ecological systems created by the dam, air condition and noise pollution at the reservoir area, people's living conditions at the reservoir, the ecological system changes for downstream wetlands, and changes in the environmental conditions in the Yangtze River delta.

CHAPTER 6. GHG COMPONENTS OF COST-BENEFIT ANALYSIS

Given the available data, we do an *Ex post* cost benefit analysis for the Three Gorges Dam project which focuses on GHG components. This study differs from previous works is that: a) it takes into account the increase in efficiency of coal-fired generation when we calculate the benefits of clean power (GHG benefits); b) it estimates the fixed GHG costs of the construction and the resettlement project and the variable GHG costs; and c) it estimates some of the variable fixed GHG external benefits of the dam by using actual data on energy produced and the projections of energy that would be produced based on silting studies; and then we use this to update the GHG emissions for the construction period and to make prediction of future GHG emissions. Moreover, to monetize the GHG emissions benefits and costs, instead of using very low flat constant carbon price and the 5 % social discount rate as was used in Morimoto and Hope's study, we use a rising carbon price trajectory based on Nordhaus's (2007) Dynamic Integrated Climate Economy Model under two sets of assumptions. These were: 1) Nordhaus's optimal base case and 2) Stern's assumptions. For discounting, we used the average social discount rate generated by each of these models (4% and 1% respectively)[17].

In this framework, we first introduce two beneficial impacts (hydropower generation and navigation). Second, we look at three cost impacts (construction costs and resettlement costs) (details are shown in Table 4).

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[17] Ideally, the social discount rate should be changing during different time period such that to be more accurate, it should be decreasing over time. Due to time constraints and lack of availability of information, we only used the average social discount rate. When we used the average social discount rate, we put relatively more weight on earlier benefits and costs.

Table 4: Costs and Benefits

BENEFITS	COSTS
Hydropower generation • GHG emissions emitted by coal GHG emissions emitted by transporting coal • Reduction in expenditure on coal	Construction • GHG emissions released during construction work
Navigation • GHG emissions emitted by ground transportation	Resettlement • GHG emissions released by resettlement process

6.1 BENEFITS

6.1.1 Hydropower Generation

The benefits from hydropower generation can be divided into two parts: 1) the GHG emission benefits of hydropower, which includes the amount of GHG emissions released if the amount of hydropower had instead been generated by firing coal and the amount of GHG emissions released for transporting the required amount of coal; 2) reduced expenditure on coal.

6.1.1.1 The GHG Emission Benefits by Hydropower

Using 2003 data, the following steps indicate how to calculate the GHG emissions for power generation.

First, we find the coal used to make a unit of electricity by dividing the total coal used to make electricity in China (Table 5) by the total electricity generated from coal (Table 5). For 2003, we have

$$Coal\ usage\ per\ unit\ of\ electricity (Mt/\ TWh)$$

$$= \frac{\text{Coal Consumption by Energy Generation (Mt)}}{\text{Electricity Production from Coal (TWh)}}$$

$$= \frac{832.222}{1518.7} = 0.548\ (Mt/TWh)$$

Table 5: Coal Consumption and Corresponding CO_2 Emissions

Year	Coal Consumption by Energy Generation (Mt)	Electricity Production from Coal Sources (TWh)	CO2 Emissions from Coal Consumption (Mt)
2003	832.222	1518.7	1457.95
2004	950.598	1717.47	1742.63
2005	1062.867	1971.772	1967.26
2006	1210.597	2301.896	2207.31
2007	1336.52	2659.62	2383.8
2008	1367.25	2744.15	2471.15
2009	1448.774	2940.869	2614.941
2010	1511.631	3250.39	2772.584
2011	1707.441	3723.244	NA

Data Source: EIA (International Energy Statistics); The World Bank (World Development Indicators

Then to calculate the amount of coal required to achieve the Three Gorges Dam's power generation ability, we use the annual power generation by the Three Gorges Dam (Figure 4) multiplied by the coal usage per unit of electricity. For 2003, we have

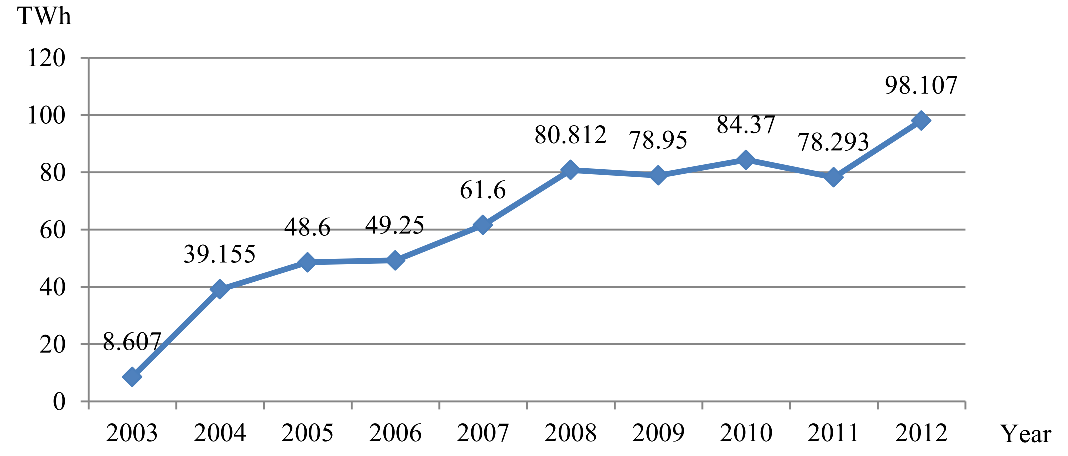
$$Corresponding\ Coal\ Required\ (Mt)$$

$$= \text{Power Generation by the Dam}$$

$$* \text{ Coal usage per unit of electricity} = 8.607 * 0.548$$

$$= 4.716636\ (Mt)$$

Figure 4: Total Annual Power Generation by Three Gorges Dam (in TWh)



Data Source: National Bureau of Statistics of China (Annual Report)

Next, we divide the total CO_2 emissions from coal consumption (Table 5) by the total coal used to generate electricity (Table 5) to get the CO_2 emissions per unit of coal consumption. For 2003, we have

$$CO_2\ Emissions\ per\ Unit\ of\ Coal\ Consumption\ \left(\frac{Mt}{Mt}\right)$$

$$= \frac{\mathrm{CO_2\ Emissions\ from\ Coal\ Consumption\ (Mt)}}{\mathrm{Coal\ Consumption\ by\ Energy\ Generation\ (Mt)}}$$

$$= \frac{1457.95}{832.222} = 1.752(Mt\ CO_2/Mt\ Coal)$$

Finally, we can use the amount of coal we would have needed to make the same amount of energy as the dam multiplied by average CO_2 emissions per unit of coal consumption to get the total CO_2 emissions external benefits for the dam’s power generation. For 2003, we have

$$Total\ CO_2\ Emissions\ Benefits\ (Mt)$$

$$= \text{Corresponding Coal Required (Mt)}$$

$$* \ \text{CO}_2 \text{ Emissions per Unit of Coal Consumption (Mt/Mt)}$$

$$= \ 4.716 \ * 1.752 = 8.263(Mt/y)$$

Using the same method for each year, by the end of 2011, the total amount of CO_2 emissions benefits from the Three Gorges Dam is 476.2206 Mt. The results of the calculations for the other years are indicated in the following table (Table 6).

Table 6: CO_2 Emission Benefits from TGD by Power Generation

Year	Power Generation (TWh)	Consumption of coal for a unit of electricity (Mt/TWh)	Equivalent Coal Consumption to Achieve Corresponding Generated Power (Mt)	CO_2 Emission by Firing Coal (Mt CO_2/Mt)	Total CO_2 Emission Benefits (Mt)
2003	8.607	0.548	4.716	1.752	8.263
2004	39.155	0.553	21.672	1.833	39.729
2005	48.6	0.539	26.197	1.851	48.489
2006	49.25	0.526	25.901	1.823	47.226
2007	61.6	0.503	30.955	1.784	55.212
2008	80.812	0.498	40.264	1.807	72.773
2009	78.95	0.493	38.894	1.805	70.2
2010	84.37	0.465	39.237	1.834	71.968
2011	78.293	0.459	35.904	1.737	62.362

Data Source: EIA (International Energy Statistics) ; The World Bank (World Development Indicators) ; National Bureau of Statistics of China (Annual Report)

One interesting fact is that during 2012, the total electricity generated by Three Gorges Dam was 98.107TWh, which is 15.8% higher than the designed ability. Yet that amount of electricity is equivalent to firing 40 million tonnes of coal, which is 20% lower than the number predicted at beginning of the project such that the GHG emissions benefits are lower than corresponding predication. Results in Table 6 shown that coal usage per unit of electricity has been decreasing for the past 10 years which means less coal has successively been needed to generate 1 unit of electricity and hence less GHGs been successively released. Thus, equivalent coal needed was less than the expectation and this can be explained by technological changes during the past two decades. Projections of future saving should be lower than estimated by H&M who assumed a fixed ratio of GHGs per unit electricity generated. We will take that into account when we predict the future GHG emissions benefits.

For the projection phase of the study (year 2013 to 2092), to calculate the GHG savings from the dam, we used the same method that was introduced above to estimate the benefits for future power generation. The power generation ability is expected to decrease considering that the water flow is projected to decrease by 1% per year and sedimentation by 0.5% to 1% per year. We used a fixed ratio of coal consumption per unit electricity (0.4 Mt/TWh) and a fixed CO_2 emissions factor for coal-fired electricity (1.8 Mt CO_2/Mt)[18]. According to the IPCC's Special Report on Renewable Energy, the normal life span for a hydropower plant is 40 to 80 years, which can be extended to 100 years if it is properly maintained (IPCC, 2011). We assume the life span of the Three Gorges Dam is 80 years thus our future estimation is from 2013 to 2092. Our estimated CO_2 emissions benefits are approximately 3077.471 to 3450.961 million metric tonnes.

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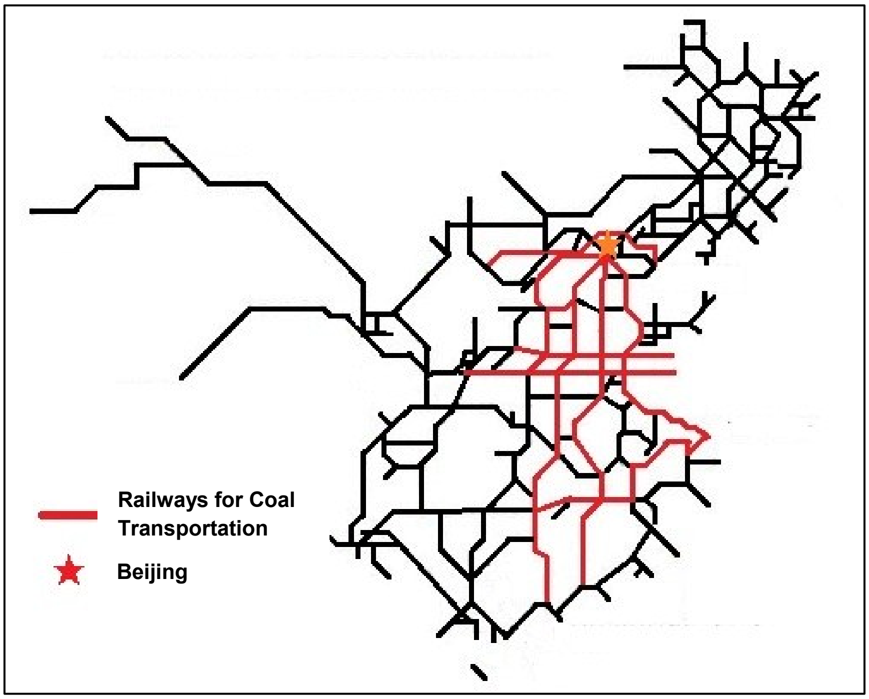
[18] Equations were introduced in Appendix B: Equation.

6.1.1.2 The GHG Emission Benefits by Transportation Saving

To calculate the transportation GHG emissions benefits, we have to first understand the transportation conditions for coal during the past 10 years, and then predict future changes. For the past 4 decades the major transportation type for coal was rail, which accounts for over 70% of the whole; water transport accounts for almost 20% and the rest of the coal has been highway transported (China Coal information). There are 12 railway lines carrying coal across the country (Figure 5). Three of them (Daqin line, Houyue line, Taijiao line) were designed to carry coal from Shanxi province (the major coal district in China) to other places. Three other lines, (Daqin line, Shenhuang line, Longhai line) carry coal to ports and then transfer it to the South by waterway while the rest connect the middle land to the coast and North to South.

Figure 5: China Rail Network Chart



*Source:*Edited based on China railway map, In *Wikipedia*, Retrieved November 3, 2013, from http://zh.wikipedia.org/wiki/File:Rail_map_of_China.svg Copyright 2013 by Howchou, free to transmit under *GNU Free Documentation License*

Different type of the railway yields different CO_2 emission factors. There are three types of railways in China: diesel locomotive, electric locomotive, and steam locomotive. A study has estimated that the CO_2 emissions for these three types of railways are, respectively, 1.51, 1.68, and 8.47 $kgCO_2$/100 ton kilometre (Xu *et al.*, 2010). However, after 2002, all steam locomotive railway lines have been replaced by diesel locomotives or electric locomotives. Thus, in this study, we will only consider diesel locomotives and electric locomotives for railway transfer. As of 2003, although electric locomotive railways only account 23% of the whole market, it carries 50% of the total tonnage shares of the market. Another study also indicates that in order to reduce CO_2 emissions from transportation, China plans to replace 45% of the diesel locomotive railway lines by electric locomotives. As a result, up until 2020, 60% of the railway lines will continue to be electric locomotives (He and Wu, 2011).

We also have to consider the coal lost during the transfer process. Considering the weather effects and possibility of accidents, Li's study suggested that the average coal loss rate during the storage and transfer is around 0.8% to 1% of total (Li, 2008).

The transmission project for the Three Gorges Dam is complicated and ambitious. The plan was to transmit electricity to eight provinces (Hubei, Hunan, Henan, Jiangxi, Jiangsu, Zhejiang, Anhui, Guangzhou) and one municipality (Shanghai) by three electricity transmission paths (Figure 6). The middle line, 4970 kilometres long with 9GW total transfer capability, mainly supports Hubei, Hunan, Henan, and Jiangxi provinces. The east line was built based on the previous transmission path by the Gezhouba Dam, which has 6GW of total transfer capability and mainly supports the Shanghai area. The south line is 973 kilometers long with 3GW total transfer capability and mainly supports

Guangzhou province. At the beginning of the power transmission project, Hubei province was the main receiver. In 2003, Hubei received 24.2% of its electricity from the Three Gorges Dam, with this percentage changing to 16.2% in 2010 (State Power Information Network, 2009).

Figure 6: Three Gorges Power Support

Source: Edited based on Provinces map, In *Wikipedia*, Retrieved October 28, 2013, from http://en.wikipedia.org/wiki/File:Hunan_in_China_(%2Ball_claims_hatched).svg. Copyright 2011 by TUBS, free to transmit under *GNU Free Documentation License*

The following steps provide the method used to calculate the CO_2 external benefit of the dam due to reduced coal transport. We multiply the coal equivalent to the dam by a scaling factor to account for coal loss by the percentage of coal carried by transport category "j" [19]multiplied by the emissions factor for that transport category as follows:

---

[19] j = electric locomotive train, diesel locomotive train, truck and waterway.

$$
\begin{aligned}
&Transportation\ Cost_j \\
&\qquad = Corresponding\ Coal\ Need_j \\
&\qquad * (1/1 - Coal\ lost\ during\ tranpsortation) \\
&\qquad * Percentage\ of\ the\ coal\ carried_j * CO_2\ emission\ factor_j \\
&\qquad * distance\ _i{}^{20}
\end{aligned}
$$

We then sum the equation above over all J categories, to obtain the transportation cost for every single year. From 2003 to 2011, taking all factors into consideration, including an under 0.8% coal loss rate, the total CO_2 emissions benefit is 9.454 Mt; if calculated using a 1% coal loss rate, the number is 9.457 Mt. The estimated result for future CO_2 emissions benefit is around 62.793 to 70.218 Mt.

6.1.1.3 Reduced Expenditure on Coal

Incidentally, an important private benefit from hydropower is the reduction in expenditure on coal. To calculate this, we can simply multiply the amount of coal that would be needed to achieve the Three Gorges Dam's power generation ability for each year and the annual coal price (Figure 7). From 2003 to 2011, the total benefit is 29.7929 billion dollars (corresponding to 31.443 billion dollars in 2013's current value). For future prediction, using the 2011 coal price, we estimate the future benefit to be 269.01 billion dollars (corresponding to 283.364 billion dollars in 2013's current value).[21] This is not included in our GHG external net benefit calculations as the cost is private not

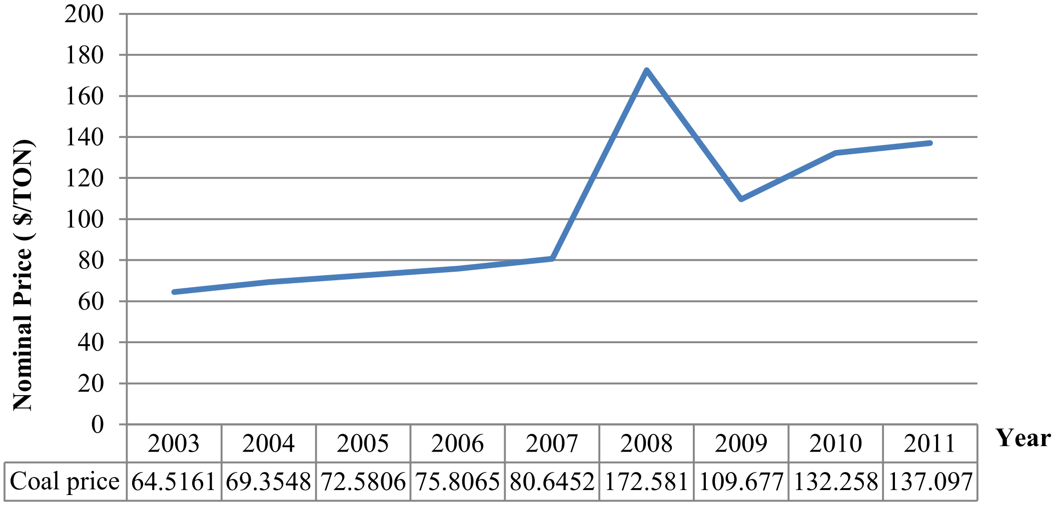
---

[20] i = 1500, 200, 3000 km.

[21] As mentioned before, since global coal production peak is expected to happen in the 2030s, the coal price probability is likely to increasing into the future. However, it's unrealistic to predict the coal price for the next 80 years, thus we used a flat coal price (which is the 2011 coal price) to calculate future benefits. We might underestimate the future benefits here.

external. Also, other coal external costs, such as energy for coal mining and processing and coal miner accidents are not included in the study.

Figure 7: Annual Coal Price



	2003	2004	2005	2006	2007	2008	2009	2010	2011
Coal price	64.5161	69.3548	72.5806	75.8065	80.6452	172.581	109.677	132.258	137.097

Source: National Bureau of Statistics of China, Yearbook (2003-2011)

6.1.2 Navigation GHG External Benefits

In 2003, when the permanent lock was opened for navigation, the Three Gorges Dam had enabled ships with a rating of 10000 tonnes to travel between Shanghai directly to Chongqing. According to the data from Ministry of Transport of the People's Republic of China (Figure 8) and taking into account the CO_2 emissions factors from each of the transport modes identified in the previous section, we were able to estimate the total CO_2 emissions benefits from the beginning of the project up to now as follows:

$$
\begin{aligned}
&Navigation\ Benefit\ (when\ t < 2013)\\
&\qquad = (Navigation\ volume_t - baseline\ navigation\ volume)\\
&\qquad * Percentage\ goods\ carried_J\\
&\qquad * \left(CO_2\ emission\ factor_J - CO_2\ emission\ factor\ for\ ship\right)\\
&\qquad * Average\ distance^{22}
\end{aligned}
$$

$$
\begin{aligned}
&Navigation\ Benefit\ (when\ t > 2013)\\
&\qquad = \Big(Estimated\ navigation\ volume_{t^{23}}\\
&\qquad - baseline\ navigation\ volume\Big)\\
&\qquad * Percentage\ goods\ carried_J\\
&\qquad * \left(CO_2\ emission\ factor_J - CO_2\ emission\ factor\ for\ ship\right)\\
&\qquad * Average\ distance
\end{aligned}
$$

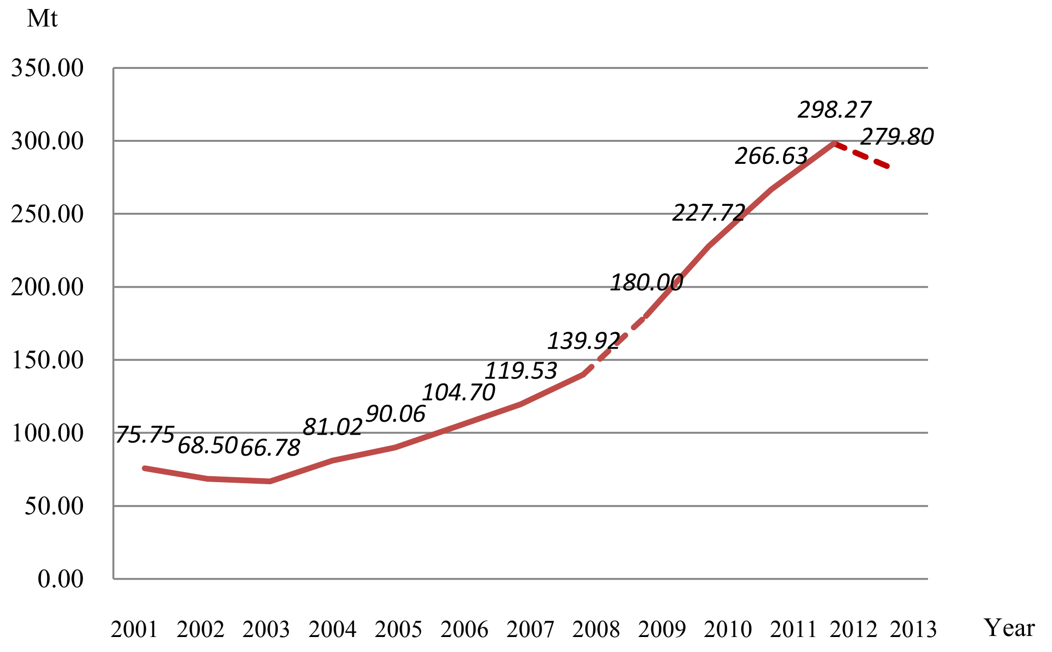
The final CO_2 emissions benefit from 2003 to 2013 is 9.423 Mt. For the future estimate, the potential CO_2 emission benefits from 2014 to 2092 lies in the interval between 97.167 to 116.553 Mt.

---

[22] Where baseline navigation volume= 70 Mt, it is the estimated navigation volume without the navigation improvement caused by the dam; t = 2003, 2014,… ,2092; j = electric locomotive train, diesel locomotive train, and truck; average distance = 1500 km. Detailed information about calculation method is provided in Appendix B: Equations.

[23] The estimated navigation volume after 2013 was calculated as follows: estimated navigation volume for t = (estimated navigation volume for t+1)*98%, where estimated navigation volume for 2013 is 275 Mt, 98% is calculated by (1-water flow decrease rate).

Figure 8: Freight Volume of Three Gorges Area (2001-2013)



Data Source**:** Ministry of Transport of the People's Republic of China
Data for 2009 and 2013 are made by prediction

6.2 COSTS

CO_2 emissions costs for the Three Gorges Dam project are considered in three sections in this study: construction costs and resettlement project costs. Unlike in the benefits calculations, many of the CO_2 emissions costs were happened before this study and will be maintained at that level. These include the construction and resettlement project costs, which make the costs part of the calculation more accurate.

6.2.1 Construction

Previous studies suggested the GHG emissions from construction can be separated into four parts. They are the manufacture of materials; the transportation of materials, equipment, and workers; the energy consumed during resource extraction and production and the use of equipment; and disposal of construction waste. Research suggests that almost 85% of the GHG emissions come from the manufacture of materials with transportation costing 6% to 8% of emissions, energy consumption accounting for about 8%, and disposal of construction waste costing 1% of total GHG emissions (Yan *et al*., 2010; Mao *et al*., 2013). To calculate the GHG emissions released by the construction process, we can use the estimates of GHG emissions factors of different construction materials (Table 7) multiplied by the amount of materials used. Based on this number, we can then estimate GHG emissions costs for other three sectors.

Table 7: GHG Emissions Factors of Each Material

Material	CO_2 emission factor	GHG emission factor
Ready-mixed concrete	0.113	0.12
Cement	0.653	0.698
Sand	0.0069	0.007
Steel	0.352	0.367
Brick	0.23	0.246
Glass	1.735	1.854

Source: Mao *et al*., 2013 Unit: kg CO_2/kg

We have to find the amount of material used for the construction. We have three sources for Three Gorges Dam construction material. However, the data provided by the Canadian International Development Agency were from 25 years ago and were not catalogued by material type. Thus we cannot rule out the possibility of double counting.

So, we will only used the other two sources, which will be introduced below in order to complete the GHG emissions cost accounting.

Data provided by the Executive Office of Three Gorges Project Construction Committee State Council of the People's Republic of China (Table 8) not only includes concrete usage and water supply pipeline for construction, but also residential and office buildings constructed for on-site workers and the afforestation project for the reservoir area. Data provided by the Center for Global Environmental Education (CEGG, Table 9) includes cement, rolled steel, and timber usage for construction. Unfortunately, both sources miscounted certain sectors. Data from the Executive Office of Three Gorges Project Construction Committee State Council of the People's Republic of China provides detailed data for residential and office buildings constructed for on-site workers and afforestation projects for the reservoir area, and data from CEGG provides material usage data, such that we can merge two data sources and get our own estimation.

To calculate the GHG emissions for construction, we simply multiply the GHG emissions factors for different materials by the amount of corresponding material[24]. Using GHG emissions factors by Yan *et al.* (2010) and Mao *et al*. (2013), the estimated material GHG emissions is around 17.692 to 17.751 Mt. After adding the other three sectors (transportation of materials, equipment, and workers; energy consumed during resource extraction and production and use of equipment; and the disposal of construction waste), it becomes 20.814 to 20.883 Mt.

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[24] Equations for this calculation were introduced in Appendix B: Equations.

Table 8: Material Usage for TGD Project

Concrete (unit:m^3)	28,040,000	
Stage I & II construction		22,490,000
Stage III		5,550,000
water supply pipe (unit: m)		29,378
Righe Bank Dam (production water supply)		3,275
Righe Bank Dam (domestic water supply)		3,000
DN900 Water Supply		700
DN600 Water Supply		5,753
Supplement Pipe for Stage II		2,000
Left Bank Dam (production water supply)		12,000
Left Bank Dam (domestic water supply)		2,650
Living District Construction (unit:m^2)	424,000	
Left Bank		105,000
Right Bank		305,000
Office construction		14,000
Afforestation Project (unit:m^2)	946,000	
Eco-park		36,000
Coastal Park		210,000
Left Bank		700,000

Source: Executive Office of Three Gorges Project Construction Committee State Council of the People's Republic of China

Table 9: Material Usage for TGD

Material (unit: million ton)	
Cement	10.8
Rolled Steel	1.9
Timber	1.6

Source: CGEE, 2010

6.2.2 Resettlement Project GHG Emissions

To support the resettlement project, a relocation plan was introduced. According to Chongqing Migration Bureau’s research, the original plan for relocation was divided into four phases with the number of migrants being 0.1156 million, 0.5321 million, 0.3498 million and 0.2113 million, respectively. Reconstruction including highways (819.97km), ports (2), electricity stations (53), communication lines (3555.66km), TV broadcasting stations (20), and natural gas lines (47.32km) (Chongqing Migration Bureau). The total reconstruction area was 36.778 km^2. 442 thousand people from rural areas were displaced. Among them, 322 thousand were relocated within the reservoir area, 65 thousand were moved out to other provinces, 20 thousand were moved out of reservoir area but within the Chongqing municipality, 10 thousand were moved out of the reservoir area and lived with their relatives, and 25 thousand were replaced to Hubei province (Heggelund, 2006). During the resettlement process, reconstruction for migrants will cost a huge amount of GHG emissions and these should be taken into account.

First thing we have to consider is the extra building construction GHG emissions for privately and publicly-used places (Table 10). The GHG emissions costs for residential and office building construction were calculated with the same method we used to do the construction cost estimation[25]. We used the GHG emissions factors from Yan *et al*. and Mao *et al.*'s studies (Table 10) to multiply the amount of construction area. Our result stays in the interval of 12.32 to 13.58 Mt. This range was calculated using the Chongqing Migration Bureau's report (total resettled are 1.2 million people); if we take into account the actual number of resettled (1.39 million people), the GHG emissions cost increases to 14.47 to 16 Mt. By adding transportation costs (assume 10% resettled people who moved to other provinces traveled by train while the others used public transportation), the GHG emissions increase from 14.6 to 16.12 Mt.

---

[25] Equations for such calculation were introduced in Appendix B: Equations.

Table 10: GHG Emission Factors for Reconstruction Plan

Reconstruction area (m^2)		GHG emission factor (kg/m^2)
Residential	36,264,000	336-368[a]
Office	614,000	226-386[b]

Source: [a] Mao *et al.*, 2013; [b] Yan *et al.*, 2010

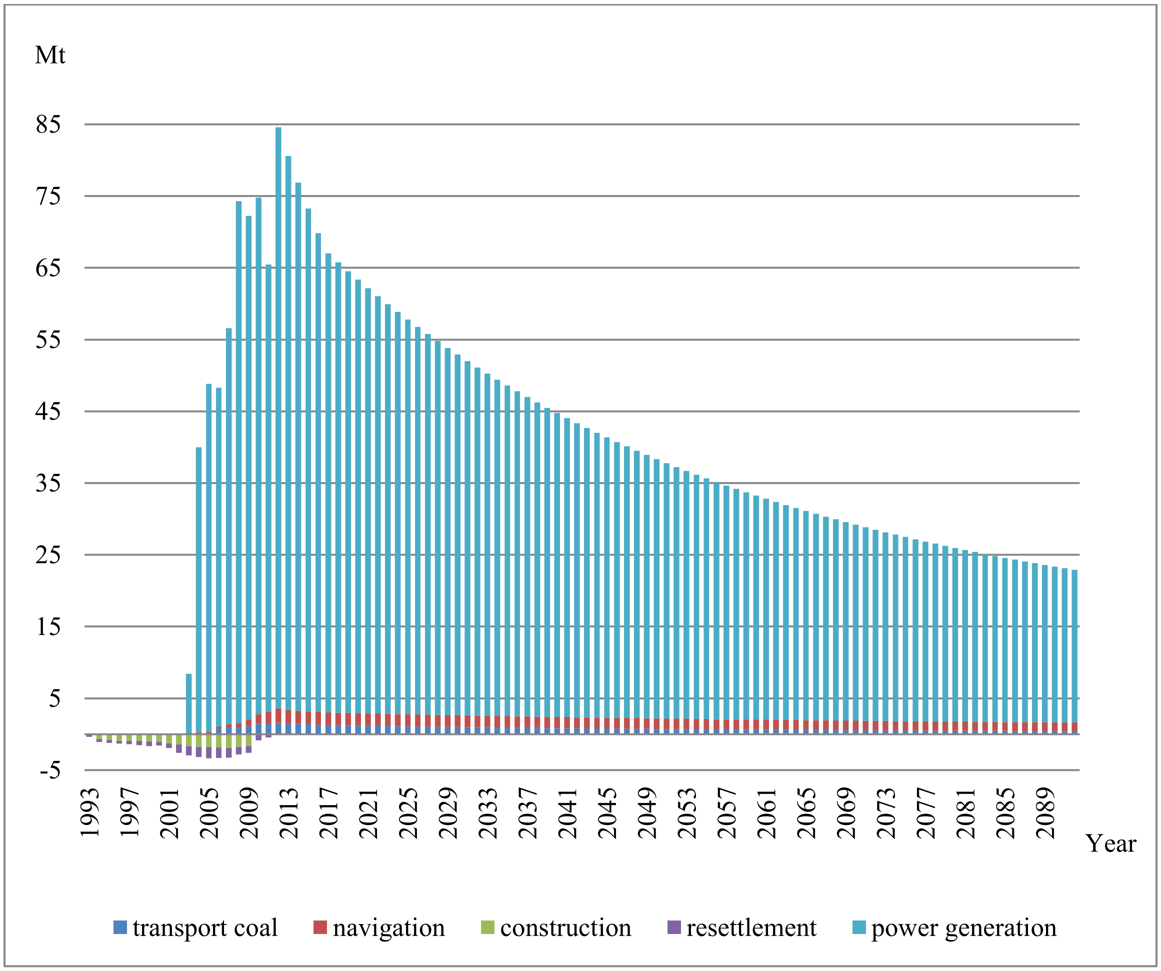
6.3 AGGREGATION OF NET GHG EXTERNAL BENEFITS AND THEIR MONETIZATION

From the GHG emissions point of view, without including reservoir emissions and ecosystem degradation, the Three Gorges Dam is estimated to be an emissions beneficial project. We calculate the total GHGs as follows:

$$\begin{aligned} Total\ GHGs_t = {} & Power\ Generation\ benefits_t \\ & + Coal\ Transport\ reduction\ GHG\ benefits_t \\ & + Navigation\ Improvement\ Benefits_t - Construction\ Cost_t \\ & - Resettlement\ Costs_t \end{aligned}$$

According to above equation, the total GHG emissions per year for Three Gorges Dam are shown as follows:

Figure 9: GHG Emissions for Three Gorges Dam



In Figure 9, data before 2013 was calculated in 6.1 to 6.2 while data for the projection (after 2013) was estimated using the method described in section 6.1.1.1. In our estimation the GHG emissions for power generation and navigation improvements will keep decreasing after 2013. Reasons that are expected to cause this decrease are the loss of water discharge and the sedimentation as we discussed in 6.1.1. Benefits from avoiding transport coal are expected to decrease after 2013 based on the prediction that the dam's generation power will decrease such that corresponding coal consumption will also decrease.

Considering the data from 2003 to 2013, the total GHG external benefits are 468.0982 Mt, yet the total GHG external costs are 37.403 Mt based on the results we got in sections 6.1 to 6.2. Estimation of future GHG emissions also shows a significant increase in benefits compared to costs. We assume the dam's lifespan is 80 years, thus until 2092, the estimated future benefit would be around 3237.4322 to 3637.7333 Mt. In 2092, estimated power generation is 29.539 TWh, which is 34.87% of its designed ability; the navigation improvement is 67.9676 Mt, which is 29.77% of the 2012 level.

Now we are going to monetize carbon benefits and costs using carbon prices. The reason for doing this is that, when we release more GHG emissions into the atmosphere, the marginal damage caused by the extra amount of GHG emissions will be higher than the previous level. As a result, the more GHG emissions released into the atmosphere, the more damages caused by an additional unit of emissions, such that we cannot only consider GHG emissions for the future but also must consider the damages that extra GHG emissions will cost.

The way to monetize the present value of GHGs is introduced below, taking year 2005 as an example.

$$PV_{2005} = \frac{(Carbon\ Price_{2005} * GHG\ Emission_{2005})}{(1 + Discount\ rate)}$$

$$= \frac{[27.28 * (48.48879 + 0.1683023 + 0.1711257 - 1.864513 - 1.45499)]}{(1 + 4\%)}$$

$$= \frac{(27.28 * 45.47457)}{1.04} = 1.1192(billion\ dollars)$$

The general case is provided in the following equation.

$$PV_t = \frac{(Carbon\ Price_t * GHG\ Emission_t)}{(1 + Discount\ rate)^{t-2005}}$$

Using Nordhaus's optimal carbon price and a 4% social discount rate,[26] the benefit of the Three Gorges Dam is between 22.986 billion dollars and 24.759 billion dollars; the cost is 557.8533 million dollars (2005 U.S. dollars). Corresponding to 30.817 billion dollars to 33.253 billion dollars benefits and 0.681 billion dollars in 2013's current value[27].

Another thing that is worth mentioning is that discounting the power loss over time causes the NPV to decrease over time (Figure 9). Meanwhile the increasing carbon price (Table 11) causes the NPV to increase. Figures 10 and 11 illustrated that the NPV decreases after 2013 under all of the different social discount rates analyzed such that for the range of discount rates considered, the first two effects outweigh the last.

Table 11: Carbon Price (Nordhaus's assumptions)

Year	2005	2015	2025	2035	2045	2055	2065	2075	2085	2095
Optimal Carbon Price	27.28	41.9	53.39	66.49	81.31	98.01	116.78	137.82	161.37	187.68

Source: Nordhaus (2008) Unit: 2005 U.S. dollars per ton of carbon

---

[26] The Dynamic Integrated Climate Change model run under the Nordhaus's assumptions provides the 4% average social discount rate over the century, which is the one that we used. Social discount rates will be lower for lower growth rates and will depend upon assumptions about preferences for inequality aversion and choice of pure time preference rate (i.e. per capita utility discount rate)

[27] Power generation, coal transporting, and navigation improvement accounts for 29.2819, 0.587, and 0.803 billion dollars respectively in 2013' current value.

CHAPTER 7. SENSITIVITY ANALYSIS

Our sensitivity analysis will consider the results of the Nordhaus climate economy (integrated assessment model) using two different sets of assumptions, the Nordhaus assumptions and the Stern assumptions.[28] The two different set of assumptions will give us two illustrative of net GHG benefits using two well-known sets of carbon price trajectories. We will check the social discount rate for 1%, 2%, 3% and 4% using Nordhaus's optimal carbon price (Table 11) and Stern's carbon price (Table 12).

Figure 10 below shows our results using Nordhaus's assumptions and various discount rates. The bottom purple curve using the average discount rate (4 %) was generated by the Nordhaus optimal baseline given Nordhaus's baseline model assumptions. Every point on the curve shows the NPV for corresponding year. The total NPV for the project is the area under the curve.

In Figure 10, the increasing NPV from 2003 to 2013 was caused by the increase in power generation; as we mentioned before, the power generation of the dam started at 2003 and the full operation began at 2012. The first drop of NPV happened in 2011. The significant precipitation reduction during that time was the main reason for this drop. The maximum NPV happened during 2012 and 2013 was caused by significant increase in power generation (as shown in Figure 4). After 2013, the NPV is predict to decrease and reasons which caused this drop were discussed in section 6.3.

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[28] The Nordhaus assumptions and the Stern assumptions use different carbon price trajectories. Using t=100 as an example, under Nordhaus's assumptions, Nordhaus puts 22% weight on utility per capita for people who are living 100 years from now in comparison with those living today; under Stern's assumptions, 90% of weight on utility per capita was put on for people who are living 100 years from now.

Figure 10: NPV using Nordhaus's Carbon Price and Various Discount Rates

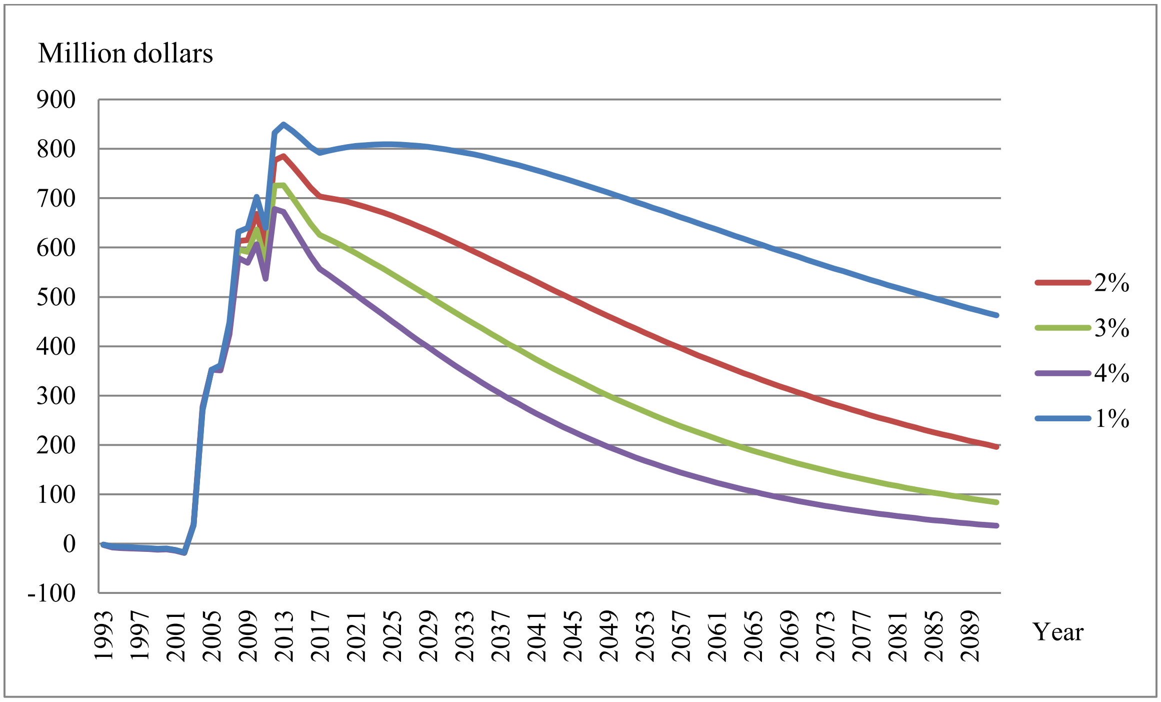
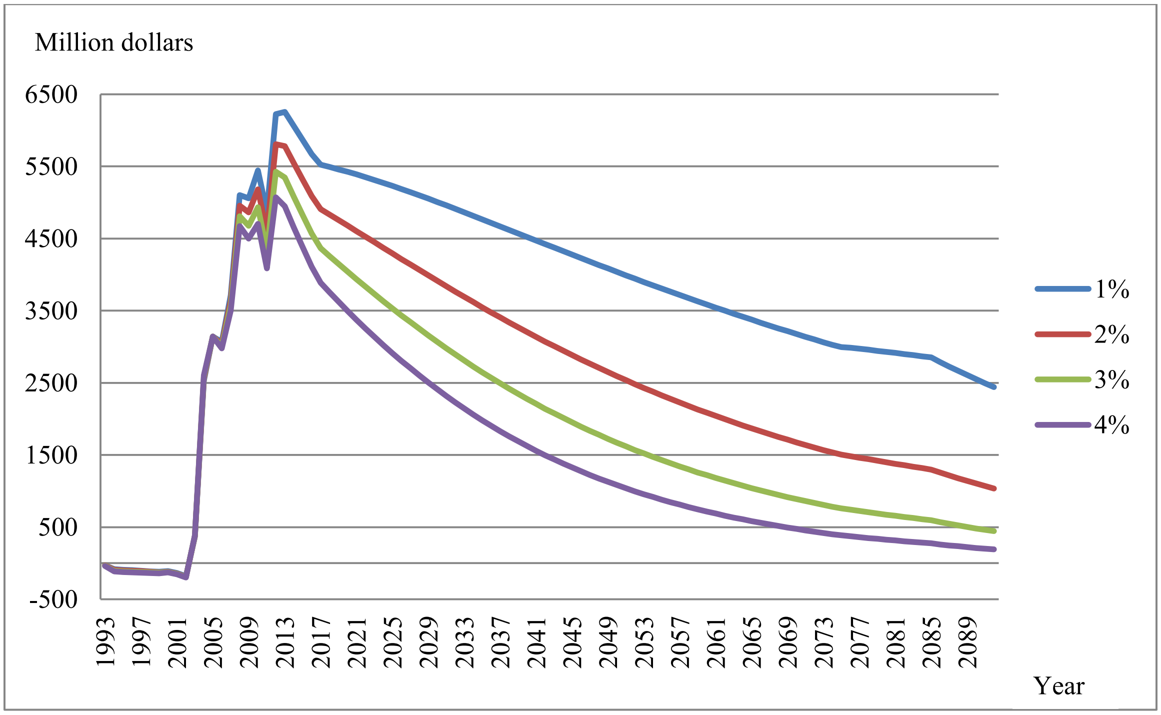


Figure 11 shows our results using Stern's assumptions and various discount rates.

Figure 11: NPV using Stern's Carbon Price and Various Discount Rates



For Figure 11, the top blue curve uses the average discount rate (1%) generated by Stern's carbon price. The benefit of the Three Gorges Dam is between 363.89 billion dollars and 405.430 billion dollars; the cost is 4.970 billion dollars (2005 U.S. dollars). Corresponding to 444.518 billion to 495.262 billion benefits and 6.071 billion in 2013's current value[29].

Table 12: Carbon Price (Stern's assumptions)

Year	2005	2015	2025	2035	2045	2055	2065	2075	2085	2095
Carbon Price	248.98	336.38	408.68	480.24	554.59	633.89	719.59	812.89	915.08	958.01

Source: Nordhaus (2008) Unit: 2005 U.S. dollars per ton of carbon

Figure 11 has similar trends as Figure 10 yet the NPV for Figure 11 was much higher than Figure 10. It is because these two figures were calculated using same results from Figure 9 while Stern's carbon price trajectory used in Figure 11 was much higher than Nordhaus's carbon price trajectory used in Figure 10.

As we discussed before, use of the average social discount rate instead of the full time trajectory of social discount rates will put relatively lower weight on the future. If we use the social discount rate that is falling over time, the net benefit for the future will be higher than what we are showing in Figure 10 and Figure 11 and the net benefit in the present will be lower.

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[29] Power generation, coal transporting, and navigation improvement accounts 464.259, 2.9371, and 14.13 billion dollars respectively in 2013's current value.

CHAPTER 8. A COMPARISON WITH MORIMOTO & HOPE'S METHOD

Morimoto and Hope (2008) did a broader CBA and a very extensive sensitivity analysis, while this study has focused on the GHG component and provided a literature review of the impacts that would need to be considered in a full CBA. To demonstrate the differences, we are going to compare results from both studies in this section.

In Morimoto and Hope's study, the "benefit from replacing coal use" (known as clean power) and the "benefit from navigation improvement" were carefully introduced. The way the authors calculated the benefits of clean power was introduced in chapter 3. One thing that is worth mentioning is that M&H took into account the case that the power generated by the dam did not replace electricity generated from coal when the amount of coal-fired electricity did not reach the market demand, such that some of the power generated by the dam did not cause a reduction in GHGs relative to the situation without the dam. In our study, we assume P_t=0 (the "initial proportion of time during when alternative power is not available") which means we consider the situation that the coal-fired energy will be displaced by the power generated by the dam leading to reduced GHG emissions.

The ways to calculate clean power were different in M&H and this study. Given the assumption that the electricity generated by the Three Gorges Dam was predicted to be the equivalent of 50 Mt coal per year, Morimoto and Hope estimated that the consumption of coal would range from 45 Mt/y to 60 Mt/y. This corresponded to a CO_2 emissions range lying between 90 Mt and 120 Mt per year, and an SO_2 emissions range lying between 1.8 Mt and 2.4 Mt per year. However, based on our study in hydropower generation, the results indicate that to achieve the Three Gorges' power generation ability, the corresponding coal consumption never has exceeded 41 Mt. The reason that the coal usage for each unit of electricity has been decreasing for the past 11 years, which means that energy efficiency was increasing as the technology was changing. We accounted for the actual changes in energy efficiency as illustrated in Table 6 on page 44. Due to underestimating the energy efficiency of the thermal plants, Morimoto and Hope overestimated the GHGs emissions benefits (before monetizing). However, in Morimoto and Hope's study, they introduced a fixed carbon price over time without considering that the carbon price should be increasing. This, in itself, would lead to an underestimate of clean power benefits. They suggested a NPV of 17 billion dollars in 2004 dollar price (20.76 billion dollars in 2013's current value) benefits for clean power under the 100-year lifespan, while our estimation indicates a 21.951 billion dollars NPV in 2013's current value for the power generation using Nordhaus's assumptions with 4% social discount rate and a 145.971 billion dollars NPV in 2013's current value using Stern's assumptions with 1% social discount rate under the 80-year lifespan condition. Based on this result we can say that H&M's study underestimated the GHG external benefits.

The methods to calculate the navigation improvement were different too. Morimoto and Hope first calculated the shipping capacity (SC) while considering the decrease in navigation control caused by the sedimentation$\left(1 - C[30] * t\right)$. Then, they multiplied the shipping capacity to the shipping cost (TR_t).

$$NI = [SC * (1 - C * t)] * e[31] * TR_t$$

---

[30] C= annual rate of decline in navigation control benefit as a result of sedimentation.

[31] e = annual rate of reduction in shipping costs.

$$TR_t = \begin{cases} TR_0 & for\ t = 0 \\ (1+g)TR_{t-1}{}^{32} & for\ t > 0 \end{cases}$$

The shipping capacity introduced in this study lies in the range from 40 to 60 Mt. In the navigation section, our study suggested that by comparing the data between 2003 and 2010 (which is when the dam began to fully operate), the freight volume increased 200 Mt. This means Morimoto and Hope's study may have underestimated the economic benefits from navigation improvement.

We also used different calculation methods for construction and resettlement cost. Morimoto and Hope simply used point estimates to predict construction and resettlement costs for future. Our study provides a more accurate estimation because the construction work was finished in 2009, so we have the actual numbers to calculate GHG emissions and we included the fixed GHG component of the dam construction. We also used estimates of general residential and office building costs when we estimate the GHG cost for the resettlement project.

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[32] g = annual rate of change in transportation costs.

CHAPTER 9. CONCLUSIONS

Our partial GHG emission Cost-Benefit study suggests that the Three Gorges Dam is a GHG emissions beneficial project with a NPV of 109.886 billion dollars under Nordhaus assumptions and 359.01 billion dollars under Stern assumptions. However its benefits are highly dependent on the water flow and sedimentation conditions of the Three Gorges area. Also, sensitivity analysis shows that the social discount factor highly affects the results.

Our results may overestimate the project's benefit and underestimate its costs. First, we made the assumption that the energy alternative is coal-fired electricity plants, although a more realistic assumption would have been a mixed electricity supply from coal-fired plants, solar plants, wind plants, and nuclear plants. Also, there is uncertainty regarding how quickly the share of these low GHG energy sources would rise. Since this mixed power supply would be more GHG emissions friendly than coal-fired plants, given that we only consider one alternative, we are overestimating the GHG emission benefits.

Second, when we estimated the future power generation ability, we assumed that water discharge would decrease 0.5% to 1% each year. This was done following Mahmood's study mentioned in 5.1(1987). But the actual water discharge changing rate might be higher if the rate of temperature increase accelerates in the future.

Third, even though we considered the changing of proportions for different transportation types when we calculated the CO_2 emissions for the past, we used the average the CO_2 emissions for future projection. We did not consider the changing of proportions of different transportation types for the next 80 years because it is difficult to make predictions so far ahead into the future given a lack of data.

Fourth, when we estimated the navigation GHG emissions benefits, we used freight volume for 2003 as the baseline and assume the navigation improvement is equal to the freight volume for year t subtracted from the freight volume for 2003. We did not, however, consider that the partial navigation improvement was caused by economic growth, which means that the freight volume should be increasing as time goes by even without the existence of the Three Gorges Dam.

Fifth, the CO_2 emissions factors for different construction materials, which were used to calculate the construction cost and resettlement project cost are from recent studies. However, if we go back to 20 years ago when the Three Gorges Dam project started, the CO_2 emissions factors should be higher than the recent level. Since we do not have CO_2 emission factors for the past 20 years it is highly likely that we underestimated the project cost.

Sixth, the reservoir is not a GHG emissions-neutral factor, but we failed to cover the GHG emissions records for the Three Gorges' reservoir. Steinhurst *et al.*'s study suggested that reservoirs may release significant GHG emissions. This indicates there may be a significant error in estimating the reservoir's emissions. Recent studies show there is no suitable scientific model to calculate the reservoir's GHG emissions for the TGD, so we cannot do such estimation for future GHG emissions.

And finally, given the fact that the carbon price trajectory estimates may be lower than the actual values (Tol, 2008), we may have underestimated the GHG benefits.

Moreover, since this study is a partial CBA that focused on the GHG emissions, we only estimated the GHG components of costs and benefits including power generation, navigation, construction, and resettlement. Other impacts that we discussed in the quantitative analysis that have not been incorporated into the CBA include flood control, ecosystem effects, reservoir GHG emissions, fishery, tourism, and architectural heritage.

For a future study, a full CBA could be done if we include all of these impacts. But, in order to do this, we would first have to carefully monetize certain impacts such as ecosystem costs and geological hazards costs. This process would require lots of calculations and investigations of methods. At the same time, we would have to consider the ethical issues during our study. For example, what is a reasonable value to put on the species extinctions? Also, Morimoto and Hope's study could be updated by using Monte Carlo analysis to consider identified uncertainties such as river flow rates and the development of China's energy mix.

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Data

Chongqing Migration Bureau: Resettlement plan (http://jym.cq.gov.cn/xxgk/3/)

Executive Office of Three Gorges Project Construction Committee State Council of the PRC (http://www.3g.gov.cn/3GIndex.ycs)

IEA: CO2 emissions (http://www.iea.org/statistics/topics/CO2emissions/)
China's coal consumption (http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=1&pid=1&aid=2&cid=regions&syid=1990&eyid=2012&unit=TST)

National Bureau of Statistics of China: Electricity supply (http://data.stats.gov.cn/workspace/index;jsessionid=678A45EB3E6D4CC7FCCF6CF021B1A764?m=hgnd), Coal price (http://data.stats.gov.cn/workspace/index;jsessionid=678A45EB3E6D4CC7FCCF6CF021B1A764?m=hgnd), TGD power generation, and Freight volume (http://www.stats.gov.cn/tjgb/)

State Railway Administration: Distance (http://www.gaotie.cn/tieluju/)

The Three Gorges Dam Ecological and Environmental Monitoring Centre: Three Gorges Dam Ecological and Environmental Monitoring Information Bulletin (http://www.tgenviron.org/tgoffice/download.html)

The World Bank: GHG emissions (http://databank.worldbank.org/data/views/variableSelection/selectvariables.aspx?source=world-development-indicators)

APPENDIX A TABLES AND FIGURES

Table 13: Rural Area Resettlement Plan

Replaced within reservoir area		322
Replaced out of the reservoir area		120
Other provinces		65
	Sichuan	9
	Jiangsu	7
	Zhejiang	7
	Shandong	7
	Guangzhou	7
	Shanghai	5.5
	Fujian	5.5
	Anhui	5
	Jiangxi	5
	Hunan	5
Hubei		25
Chongqing		20
Moved to relatives and friends		10

Data Source: Chongqing Migration Bureau Unit: thousand

Table 14: Distance from Chongqing to Other Cities

City	Distance
Sichuan	504
Jiangsu	1646
Zhejiang	2312
Shandong	1837
Guangzhou	1571
Shanghai	1949
Fujian	1967
Anhui	1492
Jiangxi	1364
Hunan	1159

Source: State Railway Administration Unit: km

Table 15: Material Usage for Recommended Project

Weathered Material and Rock	79056000	
Maoping Creek Diversion		723000
Diversion Channel		19973000
Right Bank Dam and Intake		2817000
Right Bank Powerhouse and Concrete Station		5479000
Left Bank Dam, Intake, Spillway		6526000
Left Bank Dam Powerhouse		5979000
Temporary Shiplock		9223000
Permanent Flight Locks		24534000
Downstream Navigation Channel		3802000
Silt	8037000	
Diversion Channel		2650000
Downstream Navigation Channel		5387000
Fill	34126000	
Maoping Creek Diversion		204000
Stage I Cofferdam		6639000
Stage II Upstream Cofferdam		6659000
Stage II Downstream Cofferdam		6303000
Stage III cofferdam		3350000
Left Bank Isolating Dyke		1984000
Downstream Navigation Dyke		7100000
Miscellaneous Backfill		1887000
Concrete	24586000	
Longitudinal Cofferdam		1826000
Stage III RCC Cofferdam		1412000
Spillway		5697000
Right Bank Intake and Dam		3889000
Right Bank Powerhouse		1051000
Left Bank Intake and Dam		4461000
Left Bank Powerhouse		97100
Temporary Shiplock		603000
Permanent Flight Locks		4077000
Miscellaneous		363000
Cut off Walls		226000

Source: Canadian International Development Agency, 1988 Unit: m^3

APPENDIX B EQUATIONS

POWER GENERATION

$PG_i = (TEG_i/TEC_i) * PT_i * (CEE_i/TEG_i)$

PG_i: CO_2 emission saved by TGD at year i

TEG_i: Total electricity generated by coal at year i

TEC_i: Total coal used to electricity generation at year i

PT_i: Power generated by TGD at year i

CEE_i: CO_2 emission of electricity generated by coal at year i

i=2003 to 2092

TRANSPORTATION COST

$TC_j = TT_j * (1/1 - CL) * PC_i * CEF_i * DT_i$

TC_j: Transportation cost for amount of coal needed to generate same amount electricity as TGD's

TT_j: Total coal saved by TGD power generation

CL: Coal loss during transit

PC_i: Percentage of the coal carried by different type of transit

CEF_i: CO_2 emission factors for different type of transit

DT_i: Distant for different type of transit

i=diesel locomotive train, electric locomotive train, truck, and ship

j=year

NAVIGATION

$\mathrm{NB} = \left(EPV_j - 70\right) * PC_i * \left(CEF_i/CEF_{ship}\right) * DT_i$

NB: Navigation benefit

EPV_j: Estimated navigation volume for j year

PC_i: Percentage of the goods carried by different type of transit

CEF_i: CO_2 emission factors for different type of transit

DT_i: Distant for different type of transit

i=diesel locomotive train, electric locomotive train, and truck

j=year

70: estimated baseline freight volume of TGD (Mt)

CONSTRUCTION COST

$\mathrm{CC} = (MU_i * CEF_i)/85\%$

CC: construction cost

MU_i: Material usage for different material i

CEF_i: CO_2 emission factors for different type of material

i= concrete, cement, sand, steel, glass, brick

85%: 85% of the GHG emissions are come from materials

RESETTLEMENT COST

$\mathrm{TRC} = \mathrm{TR} + \mathrm{RC}$

TRC: Total resettlement cost

$\mathrm{TR} = NP_P * PC_i * CEF_i * DT_p$

TR: Transportation cost for resettlement process

NP_P: Number of people moved to location p

PC_i: Percentage of the migrants traveled by different type of transit

CEF_i: CO_2 emission factors for different type of transit i

DT_p: Distant between Chongqing to relocated place i

i=diesel locomotive train, electric locomotive train, and truck

p=Sichuan, Jiangsu, Zhejiang, Shandong, Guangzhou, Shanghai, Fujian, Anhui, Jiangxi, and Hunan

$$\text{RC} = RC_i * CEF_i$$

RC: Reconstruction cost

RC_i: Total reconstruction area by different type of building i

CEF_i: CO_2 emission factors for different type of building i

i: residential building, office building

IN M&H'S STUDY

ECONOMIC GROWTH

$EG_t = P_t * [(QE_t * 10^3) * EO_t]/10^9$

$P_t = P_0 * e^{[-\varphi t]}$

EG_t: Economic growth

QE_t: The quantity of electricity generated at each year

EO_t: The expected increase in economic output considering increasing power supply

THE VALUE OF LOST ARCHAEOLOGICAL SITES

$$AS_t = \begin{cases} AL * t/T_C & for\ t \le T_C \\ AL & others \end{cases}$$

AS_t: The value of lost archaeological sites

AL: Archaeological loss

T_C: The construction period

THE CONSTRUCTION COST

$$CC_t = \begin{cases} MCC * \mathrm{t}/T_{MCC} & for\ t \le T_{MCC} \\ [(1-(t-T_{MCC})/(T_C - T_{MCC})] * MCC & otherwise \end{cases}$$

CC_t: Construction cost

MCC: The max construction costs

T_{MCC}: The time when construction costs reach maximum value

THE RESETTLEMENT COST

$$RE_t = \begin{cases} MRE * \mathrm{t}/T_{MRE} & for\ t \leq T_{MRE} \\ [(1 - (t - T_{MRE})/(T_C - T_{MRE})] * MRE & otherwise \end{cases}$$

RE_t: Resettlement cost

MRE: The max resettlement costs

T_{MRE}: The time when resettlement costs reach maximum value