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Applying a CBA model to the Three Gorges Project in China

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Abstract

The world's largest hydro project, the Three Gorges Dam in China is currently under construction. The project is controversial as large environmental and social impacts are expected despite the fact that the project is supposed to control the region's severe floods, to generate 18.2 GW of hydropower, and to improve river navigation. This paper uses the cost benefit analysis (CBA) model developed in Morimoto and Hope (2001) to examine all the major economic, environmental and social impacts of this massive project. Probabilistic analysis allows the distribution of the net present value to be calculated, and the most significant impacts to be identified. The mean and the 95th percentile of the cumulative net present value at the 5% discount rate were positive, whereas the 5th percentile was negative. The variables with the largest contribution towards cumulative net present value were benefits of power generation, associated economic growth, and clean hydropower; and costs of construction resettlement and lost archaeological sites. The project seems to be promising as the benefits of power generation, flood control, and navigation improvement are expected to be large. Nevertheless, the analysis in this paper has illustrated that the uncertainty associated with the project is huge and cannot be ignored.

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1. Introduction

The Three Gorges Project (TGP) is the world's largest hydro project. It is currently under construction and is expected to be completed in 2009. The project involves about 20,000 workers of whom 40% are women, according to the China Yangtze Three Gorges Project Development Corporation (CTGPC)[2]. The dam site is surrounded by scenic landscape with beautiful gorges and many important cultural sites. The area to be submerged is fertile and densely populated. Opposition around the world argues that the project would be a social and environmental disaster, having seen the tragedies of large dams elsewhere in the world[3]. This paper uses the cost benefit analysis (CBA) model developed in Morimoto and Hope (2001) to examine all the major economic, environmental and social impacts of this massive project. Probabilistic analysis allows the distribution of the Net Present Value to be calculated, and the most significant impacts to be identified.

2.1. The Three Gorges Project

China's rapid economic growth results in both dramatic improvements in living standards and serious damage to its environment. China's real GDP grew by 8% in 2000 and is forecast to grow by 7.5% in 2001 (EIA 2001). More than 70% of electricity in China is generated by coal; in total, 80% is thermal (coal, gas, and crude oil); 19% hydro; and 1% nuclear (Zeng and Song 1998)[4]. Such high dominance of coal use in China creates serious environmental problems such as air, land and water pollution[5]. Burning coal produces greenhouse gases, and emission levels of CO_2 in China are increasing continuously. According to Chinese officials, electricity supply would have to increase

[2] This information was collected during the fieldwork conducted in China in March 2001.
[3] For example, serious negative impacts on agriculture in the case of Aswan High Dam in Egypt, or large resettlement problems in the case of Narmada Valley project in India.
[4] See also http://www.pnl.gov/china/outmix.htm
[5] See Simbeck et al (1994) for a detailed discussion on coal induced environmental problems.

by 20-30% to eliminate present power shortages; the economic cost of these power shortages is very high (Wu & Li 1995). The installed hydro capacity in China is less than 15% of its exploitable hydro potential (Zeng and Song 1998). The Chinese government is intending to obtain 40% of its power from clean hydroelectric sources[6] (WCD 2000).

As a result of an economic slow down and demand reductions from closures of inefficient state owned industrial units, China's electric power industry experienced oversupply in 1998-1999 (EIA 2001). However, this was a short-term event and growth in electricity consumption is projected at 5.5% per year through 2020 (EIA 2001). More electricity is required in order to boost the economy, including still underdeveloped regions, to meet expected future economic growth, and to meet future increases in household electricity consumption as a result of increased use of electric appliances due to improvements in the standard of living. Currently, the electricity transmission capacity is limited. However, once this distribution problem is solved, a huge increase in electricity consumption in remote areas will be expected[7].

The most environmentally controversial project in China today is the construction of the Three Gorges Dam (TGD) on the Yangtze River in western Hubei province. Dr Sun Yat-Sen, the forerunner of China's democratic reform, first proposed to dam the Three Gorges in 1919. The dam is intended to raise flood control capacity from the present 10-year frequency to 100-year frequency, to provide one tenth of China's existing energy

[6] Today, China has the world's largest number of dams (85000 dams including 20000 large dams, most of which have been built since 1949).
[7] 70 million of Chinese population had no access to electricity in 1996 compared to 120 million in 1994 (Buczek 1996; Sharman 1994)

needs, and to improve navigation along the river (CTGPC 1995) [8]. In order to generate the same amount of electricity, 50 million tons per year of coal, 25 million tons per year of crude oil or 18 nuclear-power plants would be required (Thurston 1996; National Geographic 1997 September). The plan of the project has been interrupted over the years by war, the Cultural Revolution, economic troubles and other events.

In 1989, the 70m high Gazhouba Dam (40km downstream of the TGP) opened after nearly 20 years of construction in response to the increasing demand for electric power in the region. In August 1996, two major projects to improve transportation in the Three Gorges area, the Xiling Bridge and the airport, were completed and went into service. Construction of the TGD is divided into three stages. The river was blocked at the end of Stage I (1993-1997), then the hydro power station will start operating at the end of the Stage II (1998-2003), and the project will be completed at the end of the Stage III (2004-2009).

The world's third largest river, the Yangtze, carves its route through the mountains of southwestern China, springing from the glacial mountains of northern Tibet. It heads North East to surge through a spectacular 200km reach of deep, narrow canyons known as the Three Gorges. From there, the river widens and meanders across southern China's vast fertile plains to the East China Sea at Shanghai. The Yangtze River valley is China's agricultural and industrial heartland. It is supporting one third of China's population, producing 40% of the nation's grain, 70% of its rice, and 40% of China's total industrial output (Morrish 1997).

[8] The hydroelectric power generated from the TGP is to be used in eastern and central China regions and the eastern part of southwest China's Sichuan province.

The river possesses 300 species of fish (of which one third are endemic) and its annual aquatic production output accounts for 50% of the whole nation's gross output (CTGPC 1995). Fish resources in the river are declining due to human activities. After the completion of the dam, the change may benefit some species and adversely affect some others since different fish species have different living habits (CTGPC 1995).

The project area is a great tourist attraction, which has scenic natural landscapes as well as cultural relics and sites with high aesthetic value. Construction of the dam will result in not only the loss of a large number of artifacts from this area, but also the destruction of an important link in understanding China's civilization. Only some of the relics can be removed or reproduced (CTGPC 1995).

The Yangtze River has produced some of China's worst natural flood disasters. In 1954, the Yangtze floods killed 30,000 people (Fung 1999). The heavy rains and flooding along the Yangtze River damaged 100,000 houses, toppled 34,000 houses, inundated 1.13 million hectares of farmland causing a grain output loss of 880,000 tons, forced more than 2,000 companies to limit production, killed 36 people and 5,200 livestock, and induced economic losses of more than 4.6 billion yuan in less than one month[9]. In Hubei province alone, the 1998 flood resulted in total economic losses of 30 billion yuan. Agricultural production in this region accounts for about 22% of GDP and the flood inundated about 1.7 million hectares of crops (Saywell 1998).

[9] http://www.irn.org/programs/threeg/991029.central.html

The project would displace about 1.98 million people; submerge approximately 150,000 acres, including 160 towns, 13 cities, 1352 villages, 1500 factories, 12000 cultural antiquities and 16 archaeological sites[10]. There is a fear of depriving downstream fisheries due to a decline in water quality (Thirston 1996; ASCE 1997). Over 3000 factories and mines are in the reservoir area; they currently produce 10 billion tons of waste annually containing 50 different toxins (Topping 1996). Topping (1996) argues that if we assume the waste water level remains unchanged, the waste content will increase 11 times in some areas due to the dam. There is also a possibility of dam failures and earthquake (Thurston 1996)[11]. Large dams can be a prime military target; for example, Kajaki dam in southern Afghanistan was bombed by the American air force on the 1st November 2001.

The water of the Yangtze River carries the fifth largest sediment discharge in the world, most of which is conveyed during floods[12]. The Three Gorges area has been intensively cultivated so that soil erosion has become a very serious problem due to a loss of a forest cover (CTGPC 1995). Sedimentation problems are likely to reduce power generation capacity[13].

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[10] See Topping (1996); Goldstein (1998); Ren (1998); Childs-Johnson and Sullivan (1998); Caufield (1997)

[11] On average, there are 110 dam collapses per year and the official deaths toll shows 9937 deaths due to dam failures (Fu 1998). See WCD (2000); Topping (1996); Si(1998) for the details of dam failures in China. Many Scientists argue that the pressure from the reservoir and the dam to fragile geological structures may cause earthquakes. The first record was in the late 1930s when seismic activity started after the building of the Hoover dam in the US. See also New Scientist 2 Nov 1991 p.13 for the article on dam and earthquake in the Hymalayas.

[12] The Yangtze river discharges 486 Mt of sediment into the sea annually (CTGPC 1995).

[13] About 230 dams in China have a significant problem of sediment deposition, leading to a combined loss of 14 % of the total storage capacity (Leopold 1998). The Three Gate Gorge dam on the Yellow River produces less than 1/3 of the power that was promised due to heavy sedimentation (Qing 1998). Some dams have lost more than 50 % of the storage capacity (Chunhong 1995). The Sanmexia Reservoir was decommissioned because of sedimentation in 1964 four years after completion. The Laoying reservoir silted up before the dam was completed (Sullivan 1995).

2.2. Modifications to the CBA model

Since the characteristics of the TGP are different from the previous application of the model to Sri Lanka, five new variables are added to the model as shown in Table I: NI (navigation improvement), FC (flood control benefit), FI (negative impact on downstream fishery), DE (mitigation cost of downstream water pollution) and AS (loss in archaeological sites). The size of the dam is massive; therefore an expression of the possibility of dam collapse due to special circumstances (earthquake, technical failures and being a military target) is also added to the evaluation of the variable AC (accident cost). Descriptions of the main parameters in the model and their distributions are presented in Table II and Table III respectively. The rest of the parameters are found in Table A-I in the Appendix. Some of these data may not be very accurate or precise. However, this is inevitable, as many variables are not readily quantifiable and some data have a limited availability because of the project complexity. Hence, the data are given as ranges representing our best attempts to extract as much up-to-date information as possible from various sources. Repeated runs of the model obtain a probability distribution of possible outcomes, which is a more defensible procedure than just using single values for inputs that are in reality not well known.

Table I **New variables added to the model**

Variable	Description
FC (flood control)	The monetary value of flood control benefits. Reductions in flood control benefit due to sedimentation problems are also considered.
NI (navigation improvement)	The benefit from navigation improvements is expressed by reduction in shipping costs (improvement in river transportation). Changes in transportation costs and reduced navigation improvement benefit due to sedimentation problems are also considered.
DE (downstream effects)	The cost for dealing with downstream pollution caused by the dam construction
FI (impacts on downstream fishery)	The impacts on fishery are expressed by a decline in fish catches.
AS (value of the lost archaeological sites)[14]	The value of the lost archaeological sites is approximated by the proportion of the budget for the preservation of cultural antiquities under the international standards and the budget to rescue those cultural sites.

[14] How archaeology is perceived is different from place to place and generation to generation (Carver 1996). Although there are many studies on how to place values on archaeological sites, there is no simple conclusion for this argument. See Carman et al (1999); Carver (1996); Darvil, Saunders, and Startin (1987); Lipe (1984); Schaafsma (1989). Hence, the proxy is used as an approximation in this analysis.

Table II **Main input parameters**

Parameter	Units	Description
P0		Initial proportion of time during which an alternative power generation technology is not available
φ		Parameter which describes the rate of decrease in P over time
EO	Yuan/MWh	Initial expected increase in economic output due to increased power supply
a		Annual rate of decline in power generation due to sedimentation[15]
GC	GW	Generation capacity
AL	GYuan	Archaeological loss

Table III **Main parameter values and descriptions**

Parameter	Minimum value	Most likely value	Maximum value
P0	0.17[a]	0.2[b]	1[c]
φ	0[d]	0.018[e]	0.085[f]
EO[g]	3200	7800	12500
A	0.001[h]	0.005[i]	0.03[j]
GC	12.6[k]	16.4[l]	18.2[m]
AL	1.5[n]	4.9[o]	33[p]

Notes: PERT distribution (a special form of Beta distribution) is used for all the parameters except EO; [a] About 40 million rural households out of 232 million have no access to electricity. 40/232=0.17 (*China's Energy: a forecast to 2015*); [b] The State development and planning Commission estimated that about 20% of China's area suffered power shortages in 1998 (*South China Morning Post 10 December 1998* 'Obstacles block path to reform of industry' China Business Review: Power and Infrastructure). See also Sinton and Fridley (2000); [c] The projected rate of China's total energy requirement is increasing continuously in the next 20 years (US Department of Energy 1996); [d] According to WCD (2000b), coal cannot be considered as an alternative to hydropower as a source of peaking power due to its inefficiency. Gas turbines could be an alternative, but would offer fewer benefits. Hence, assume that alternative

[15] Experiences of dams worldwide in the past show that sedimentation problem is a common issue. See e.g., WCD (2000); Smith (1999); Dixon (2000); Leopold (1998); Chunhong (1995). However, there is little data avaialble on loss of live storage capacity (WCD 2000b).

techniques would not be available in a feasible period; [e] Electricity generated by coal and gas fired thermal power plants increased by 1.8% in 1998 (China Energy Efficiency Information Bulletin March 1999); [f] Electricity generated by coal and gas fired thermal power plants increased by 8.5% in 1995 (China Energy Efficiency Information Bulletin March 1997); [g] In China, each kWh of power shortage results in a loss of economic output of $0.38-1.5 (MOF 1990); [h] The samples examining rates of loss of active storage due to sedimentation in WCD Cross-Check Survey are clustering around a line of 0.1% annual loss[16] (WCD 2000); [i] It is estimated that after 100 years, 50% of the reservoir will be filled due to sedimentation. Thus, the annual rate will be 50/100 = 0.005 (Ryder and Barber 1993); [j] The maximum annual rate of loss of active storage due to sedimentation in WCD Cross-Check Survey. A relatively high rate is set in order to challenge project optimism (WCD 2000); [k] The energy output of Victoria Dam in Sri Lanka is about 31% lower than the planned figure (WCD 2000); [l] The WCD Cross-Check Survey shows that over half of the projects in the sample generate power less than the planned figure. The most likely case is 10% below the target (WCD 2000); [m] The current planned installed capacity (CEB 1994); [n] The estimated cost of the necessary excavations in the proposed reservoir area is $180 million (Topping 1995); [o] The estimated cost of salvage work for the TGP area is $590 million (The Associated Press News 29th January 1995); [p] The maximum value for TCC above is 660 Gyuan. The budget for the preservation of historical relics and cultural antiquities should be about 3-5% of the total budget according to the international standards (Qing, 1998 Chapter 9). Thus 660Gyuan*5%=33Gyuan.

2.3. Mean present value results

A simulation with 10000 iterations was run. There are three large positive impacts, EG (economic growth), PG (power generation), and CP (clean power); three large negative impacts, CC (construction cost), AS (archaeological loss), and RE (resettlement cost) as shown in Table IV. Figure 1 gives a visual presentation of the mean present values by year; the areas under the lines in Figure 1 are the cumulative net present values in Table IV. The scale of resettlement for the TGP is extremely large compared to most dams since the area is densely populated.

[16] A sample of 47 dams are chosen, and the age of dams against the % active storage loss is plotted. See Figure 2.14 in WCD (2000) p.65. Assuming storage volumes and power generations have a positive linear relationship.

Table IV Cumulative net present value for the fourteen variables at t=100 in billion yuan.

Benefits		(Billion Yuan)	Costs		(Billion yuan)
PVEG	Economic growth	744	PVCC	Construction cost	417
PVPG	Power generation	263	PVAS	Archaeological loss	120
PVCP	Clean power	141	PVRE	Resettlement	93
PVFC	Flood control	43	PVOM	O & M cost	39
PVNI	Navigation improvement	26	PVAC	Accident cost	29
			PVDE	Downstream effect	29
			PVFI	Fishery loss	27
			PVLT	Tourism loss	14
			PVIN	Land inundation loss	2

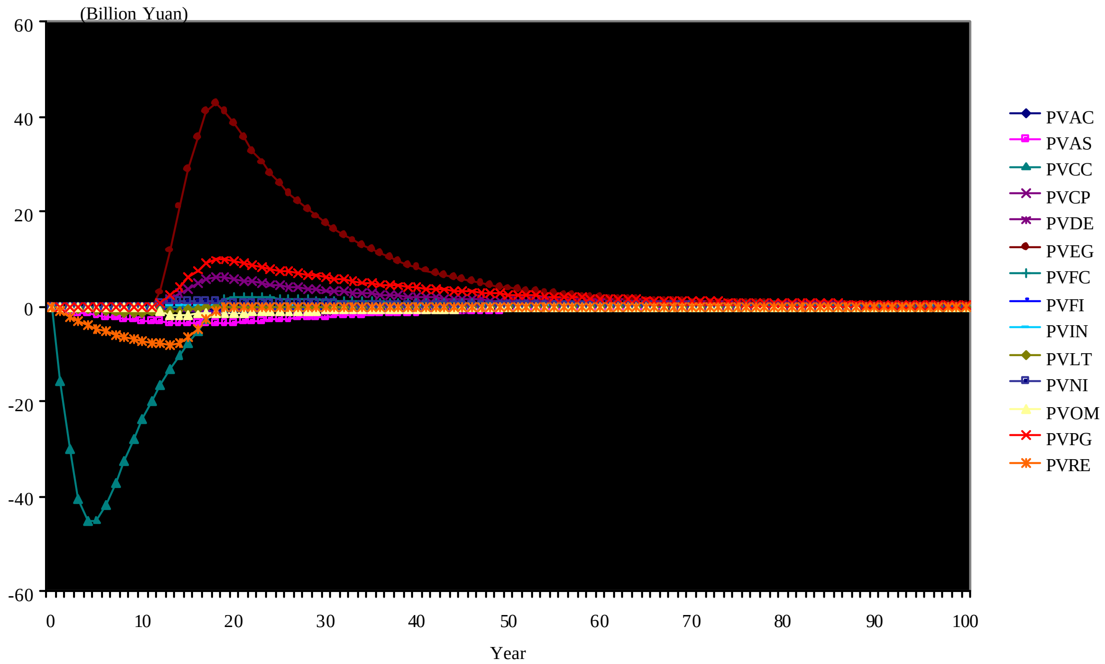

Figure 1 Mean present values for the fourteen variables in the model by year

2.4. Ranges of the six most influential variables

According to Table IV and Figure1, the variables EG (economic growth), PG (power generation), CP (clean power), CC (construction cost), RE (resettlement cost), and AS (archaeological loss) are likely to have the largest impact on the NPV. Figure 2 plots the 90% ranges of these six most influential variables over time in present value form. The variable PG (power generation) seems to have a long-lasting positive impact. Although both capital costs and resettlement costs are huge, they are required only during construction period. The variable CP (clean power) has a very similar trend to the one for PG (power generation), however with a smaller magnitude. This gives support to the view of hydropower as one of the cleanest energy generation techniques. The magnitude of the impact of EG (economic growth) is much higher than the other variables, though it ceases more rapidly, mainly because gradually alternative power generation techniques would be more readily available, and also the country's energy scarcity is likely to reduce as time passes.

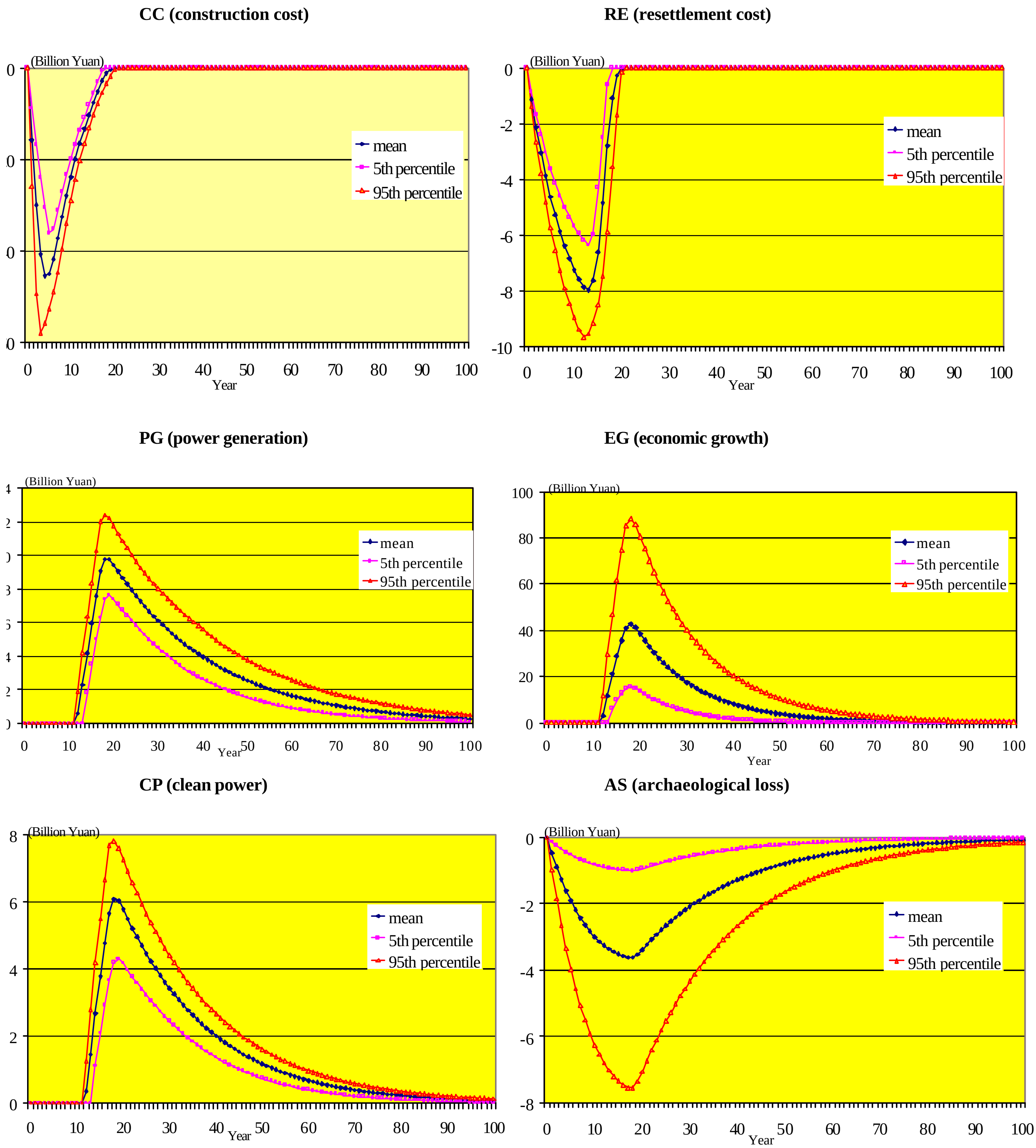

Figure 2 **Present value ranges of the six most influential variables**

2.5. Cumulative net present value

The evolution of the 5^{th} percentile, mean, and the 95^{th} percentile of the cumulative NPV with a 5% discount rate are shown in Figure 3. The final values are −114, 424, and 1321 billion Yuan respectively. The cumulative NPV is initially negative due to the large construction and resettlement costs as discussed above. However, a rapid upward movement follows as a result of increased clean electricity sale and stimulated economic growth. The benefit never outweighs the cost for the 5^{th} percentile of the cumulative NPV, due to the reduction in electricity generation because of sedimentation problems, low prices for electricity, ongoing costly operation & maintenance cost, and the loss of important archaeological sites. The model includes a premature closure option, where if the ongoing costs outweigh the benefits, the dam is closed down rather than keep making an increasing loss. In practice for the TGP, the possibility of premature closure does not affect the result, even at the 5^{th} percentile since the possibly recoverable costs (after premature closure) of OM (O&M cost), AC (accident cost), DE (downstream effect), and FI (fishery loss) are not very significant. Therefore, premature decommissioning would be highly unlikely to take place.

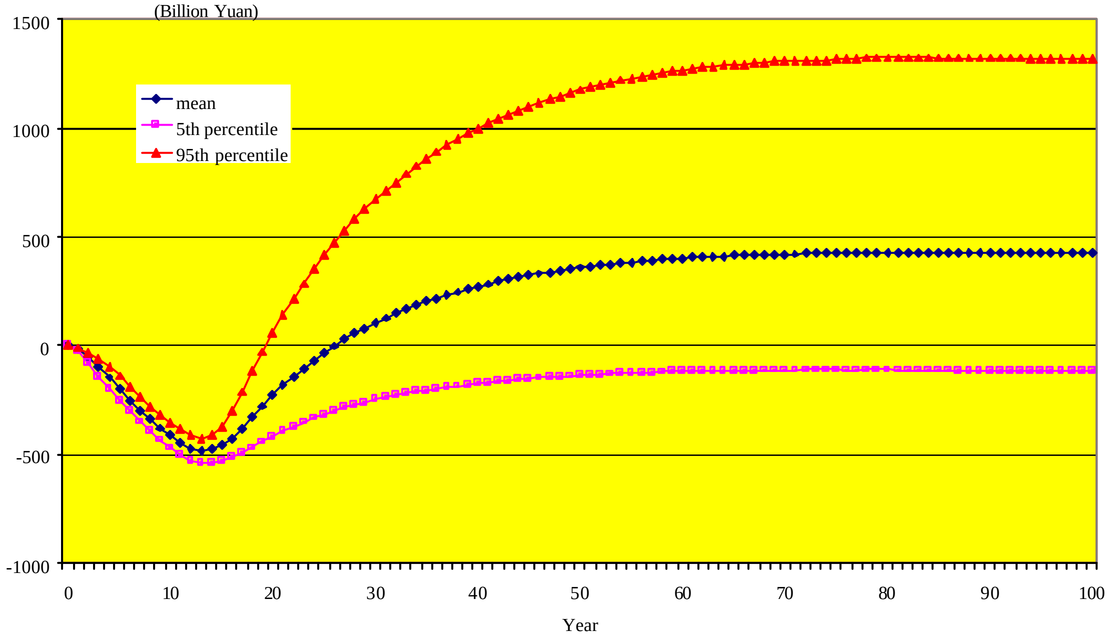

Figure 3 **Range of cumulative NPV with a 5% discount rate by year**

2.6. Sensitivity analysis

Table V shows that the following input parameters have the most significant impact on the cumulative NPV: P0 (Initial proportion of time during which an alternative power generation is not available.), φ (Parameter which describes the annual rate of decrease in P (proportion of time during which an alternative power generation is not available)), EO (Initial expected increase in economic output due to increased power supply), a (annual rate of decline in power generation due to sedimentation), GC (power generation capacity), and AL (Archaeological loss). Each parameter has a correct sign and is therefore consistent with the model. Although this massive project demands a huge cost, it seems not to have a large impact on the NPV. This may be due to the fact that a fairy small range of data (470-660 billion Yuan) is used for the variable TCC (construction cost), as it is thought that this parameter is fairy well known.

Table V **Statistically significant parameters**

Parameter	Description	Student b coefficient
P0	Initial proportion of time during which an alternative power generation is not available.	+ 0.58
φ	Parameter which describes the annual rate of decrease in P (proportion of time during which an alternative power generation is not available)	- 0.54
EO	Initial expected increase in economic output due to increased power supply	+ 0.39
A	Annual rate of decline in power generation due to sedimentation	- 0.19
GC	Power generation capacity	+ 0.15
AL	Archaeological loss	- 0.14

Note: The input parameter values are regressed against the output (NPV). The student b coefficient is a coefficient calculated for each input parameter in the regression equation.

Several variable discount rates were used to see the effect of different rates of pure time preference[17]. Figure 10 shows that choice of pure time preference rate (p) has a strong effect on the value of the cumulative NPV. The fixed discount rate of 5% used for the basic analysis lies in between p=1% and p=2%. The mean value of the cumulative NPV becomes negative when the pure rate of time preference is above about 5%.

[17] These discount rates are calculated in the same manner as the ones in Morimoto and Hope (2001). $r(t)=g(t)+p$, where $r(t)$=variable discount rate, g=annual growth rate and p=pure rate of time preference. The estimated growth rates in China are 4% (1999-2000); 3.5% (2000-2020); 3.3% (2020-2040); 3.1% (2040-2060); 3% (2060-2100); 2% (2100-2120), according to EME (1994).

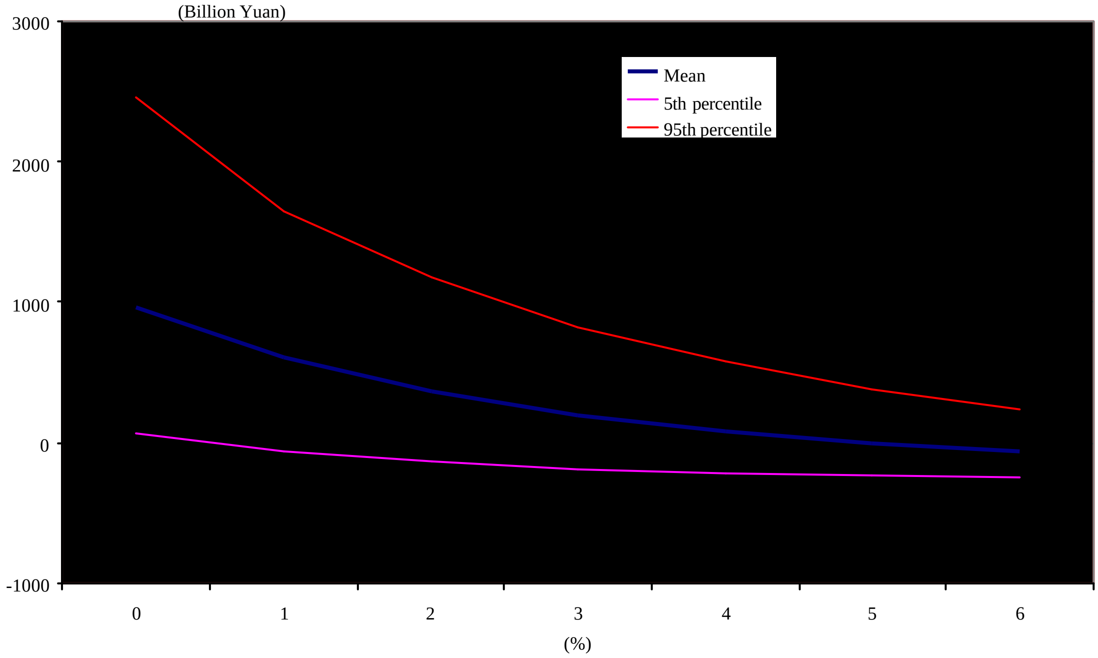

Figure 4 **The cumulative NPV against the pure rate of time reference**

3. Conclusion

This paper has illustrated the use of a CBA model of hydropower projects, slightly modified from the model presented in Morimoto and Hope (2001), using China's massive Three Gorges Project (TGP) as a case study. Five new variables were added, namely FC (flood control), NI (navigation improvement), DE (downstream effect), FI (impacts on downstream fishery), and AS (lost archaeological sites). The variables with the largest contribution towards the cumulative net present value were PG (power generation), EG (economic growth), CC (construction cost), CP (clean power), RE (resettlement cost), and AS (lost archaeological sites). These impacts are widely discussed in newspapers, related books and literature. The sensitivity analysis showed that the parameters P0 (Initial proportion of time during which an alternative power generation is not available) and φ (Parameter which describes the annual rate of decrease in P (proportion of time during which an alternative power generation is not available)) have particularly significant impacts on the project cost. The possibility of premature decommissioning was also added to the previous model, though its inclusion did not give a noticeable change to the outcome for the TGP. The improvements of the results could be seen only if sedimentation problems of the TGP were assumed to be even larger than expected, when premature decommissioning would take place.

The mean and the 95th percentile of the cumulative NPV at the 5% discount rate were positive, whereas the 5th percentile was negative. The project seems to be promising as the benefits of power generation, flood control, and navigation improvement are expected to be large. Nevertheless, the analysis in this paper has illustrated that the uncertainty associated with the project is huge and cannot be ignored.

Acknowledgement

We would like to thank Mr Tang Jie and the China Three Gorges Project Corporation (CTGPC) who provided us useful data/information. The interesting tour of the dam site and the visit to the research institute of Yangtze sturgeon, organized by the CTGPC should also be greatly acknowledged.

Appendix

I. Additional equations to the previous model in Morimoto and Hope (2001)

$$FIt=FB*(1-b*t) \qquad \text{for } t>Tc \qquad Gyuan/year$$

where FI=benefit from flood control in Gyuan/year, FB = mean annual benefits from flood control in billion Yuan and b=annual rate of decline in flood control benefit due to sedimentation.

$$NIt=[SC*(1-c*t)]*e*TRt \qquad \text{for } t=TS \qquad Gyuan/year,$$
$$TRt=TRo \qquad \text{for } t=0$$
$$=(1+g)TRt\text{-}1 \qquad \text{for } t>0 \qquad yuan/ton$$

where NI=benefit from navigation improvement in Gyuan/year (it starts functioning in TS), SC= annual shipping capacity in Gtons/yr, e= annual rate of reduction in shipping costs, c=annual rate of decline in navigation control benefit due to sedimentation, TRt= shipping costs in yuan/ ton, TRo= shipping costs at t=0 in yuan/ton, g= annual rate of change in transportation costs

$$CPt=(1-Pt)*\sum_{i=1,2}[CLi*CMi] \qquad Gyuan/year^{18}$$
$$CLi=(Ci*QEt)/10^9 \qquad Gtons/year$$
$$Pt=P0*\exp[-\varphi t]$$

where CP=benefit from replacing coal use, CL1= annual decreased CO_2 level due to a decrease in coal use as a result of the TGP in Gtons/yr, P0=initial proportion of time during which an alternative power generation technology is unavailable, φ=parameter which explains the rate of decrease in P over time, CL2= annual decreased SO_2 level due to a decrease in coal use as a result of the TGP in Gtons/yr, C1= annual decreased CO_2 level due to a decrease in coal use as a result of the TGP in tons/GWh/yr, C2= annual decreased SO_2 level due to a decrease in coal use as a result of the TGP in tons/GWh/yr, CM1= benefits of CO_2 reduction in yuan per ton of CO_2, CM2= benefits of SO_2 reduction in yuan per ton of SO_2

$$FIt=(FP*t)/Tc, \qquad \text{for } t\le Tc$$
$$=FP \qquad \text{for } t>Tc,$$

where FP= annual lost profits from fishery in billion yuan/year.

$$DEt=0 \qquad \text{for } t\le Tc$$
$$=ADE \qquad \text{for } t>Tc \qquad GYuan/year,$$

where ADE= annual investment costs to deal with downstream effects in billion yuan/yr (clean-up costs and water pollution mitigation costs).

$$ASt=AL*t/Tc \qquad \text{for } t\le Tc$$
$$=AL \qquad \text{for } t>Tc \qquad GYuan/year,$$

AS= value of lost archaeological sites in billion yuan, AL= archaeological loss in billion yuan,

Due to the scale of the dam and the geographical characteristic of its location, significant economic damage and deaths/injuries would be expected if the dam collapsed due to technical failures, being a target of terrorism and earthquake. Hence,

$$ACt=\sum_{j=1,2}ACCjt+DMt \qquad GYuan/year,$$
$$ACC1t=VD*[DCt+DOMt+DDt] \qquad GYuan/year$$
$$ACC2t=VM*[INCt+IOMt+IDt] \qquad GYuan/year$$

[18] The equation is slightly changed due to data abailablity.

where ACC1t= estimated annual costs of deaths due to accidents in billion yuan, ACC2t= estimated annual costs of injuries due to accidents in billion yuan, DMt= estimated annual damage costs due to special events (costs of economic loss) in billion yuan, VD= value estimate for deaths in Myuan/death, VM= value estimate for injuries in Myuan/illness, DCt= annual no of deaths during construction, INCt= annual no of injuries during construction, DOMt= annual no of deaths during O&M, IOMt= annual no of injuries during O&M, DDt= annual no of deaths due to dam technical failures/terrorism/earthquake, IDt= annual no of injuries due to dam technical failures/terrorism/earthquake,

Special events such as dam technical failures, terrorism, and earthquake are very rare cases so that each estimated accident costs will be multiplied by probability of occurrence of these events.

$$DDt = (GC*DCR'')*(P+P'+P'') \quad \text{for } t>Tc$$
$$= 0 \quad \text{for } t \le Tc \qquad \text{GYuan/year}$$

where DCR''= annual number of deaths due to special circumstances in deaths/GW/yr, P= probability of occurrence of technical failures per year, P'= probability of occurrence of terrorism per year, P''= probability of occurrence of earthquake per year,

$$IDt = (GC*MCR'')*(P+P'+P'') \quad \text{for } t>Tc$$
$$= 0 \quad \text{for } t \le Tc \qquad \text{GYuan/year}$$

where MCR''= annual number of injuries due to special circumstances in injuries/GW/yr

$$DMt = ECL*(P+P'+P'') \quad \text{for } t>Tc \qquad \text{GYuan/year}$$

where ECL= economic loss in Gyuan/yr

Decommissioning costs are presently difficult to predict due to the uncertainty surrounding the various parameters affecting the costs and the limited practical experiences with decommissioning (WCD, 2000). Decommissioning costs vary from project to project, though they are usually large[19].

$$DCCt = \pi*TCC \quad \text{if } t=TTDC$$
$$= 0 \quad \text{otherwise} \qquad \text{Gyuan/year}$$

where DCCt= costs of decommissioning the TGP in Gyuan./year, π=proportion of decommissioning costs in the construction cost, TDC=time of decommissioning. If policy makers choose premature closure as the cost outweighs the benefit, TDC=time of premature closure. If the costs start outweighing the benefits, it would be better to close down the dam prematurely. Policy makers have an option to close down if

$$TBt-(OMt+DEt+FIt+ACt)+DCCt-DCCt+1<0$$

Where DCCt+1=DCCt/(1+d)=the NPV this year of paying DCC next year.

Policy makers have a choice each year, either close down or stay open one more year. If they decide to close down, decommissioning costs have to be paid this year, otherwise they pay decommissioning cost next year. The costs of CC, RE, AS, IN and LT are not included in the above equation. This is because CC and RE have already been paid during construction; lost archaeological sites and inundated land may not recover; and the negative impact on tourism may remain since the aesthetic of the Three Gorges once lost cannot be recovered.

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[19] For example, it is approved to spend $225000 to remove the Chair Factory Dam in the US (IRN's *River Revival Bulletin* No 22 November 29 2000). Total removel cost for the Matilija dam in the US could be $22-200 million (IRN's *River Revival Bulletin* No21 October 17 2000).

$$NPVt = \sum_{t=0}^{T} (1+dt)^{-t}(TBt\text{-}TCt) \qquad \text{for } t = Tc+Tcl \qquad GYuan/year$$

$$NPVt=\sum_{t=0}^{T} (1+dt)^{-t}(TBt\text{-}TCt) \qquad \text{if } TBt\text{-}(OMt+DEt+FIt+ACt)+DCCt\text{-}DCCt+1 \geq 0$$

$$=-\sum_{t=0}^{T} (1+dt)^{-t}(CCt+REt+ASt+INt+LTt+DCCt) \text{ if } TBt\text{-}(OMt+DEt+FIt+ACt)+DCCt\text{-}DCCt+1<0$$

$$\text{for } t > Tc+Tcl \qquad GYuan/year$$

where TB=total benefits, TC=total costs, dt=discount rate (fixed/variable), and NPV_T= net present value at time T, Tc=construction period, and Tcl=time to close down the dam (time until which policy makers allow NPV to be negative after construction.

II. Data

Table A-I Parameters in the CBA model and descriptions[20]

Parameters	Units	Distribution[21] (min, most likely, max)	Description of each value
Tc (construction period)	Years	Pert(17, 18, 22)	The minimum value is the original plan. According to the WCD Cross-Check Survey, about 40% of the delayed projects shows 1-year delay of project schedule is the most common case among the delayed projects (WCD 2000). Similarly, about 5% show 5 years delay (WCD 2000).
PEo (initial price of electricity)	Yuan/MWh	Pert (290, 300, 330)	The minimum value is 5% lower than the most likely value. The most likely value is the price of electricity generated by the TGP based on the CTGPC calculation. The maximum value is 10% higher than the most likely value.

[20] \$1= 8.3 Yuan. This is a market rate end of the year period 1998. Source: IMF IFS 1999 Sept. Hereafter, this exchange rate will be used unless otherwise stated.

[21] Δ(.) refers to a trianguler distribution and Pert (.) refers to a PERT distribution (a special form of beta distributions).

ε (proportional reduction in annual number of tourists in the dam site)		Pert (0.1, 0.6, 0.9)	For the minimum value, assuming the loss of the Three Gorges aesthetics does not affect tourism in the area very much since tourists can visit other attractions in the area. Also tourists may visit the TGP itself. The rate of decrease in number of tourists after the terrorist attack in Sri Lanka during the 1st quarter of 1998 is used for the most likely value (CBSL 2000). For the maximum value, assuming majority of tourists only visit the dam site to see the Three Gorges
NT (annual number of tourists visiting the dam site in absence of the dam)	Persons	Δ(330000,370000,740000)	For the minimum value, assuming 10% less than the most likely value. The most likely value is the number of tourists in Wuhan and Chongqing (the base place to visit the Three Gorges area) in 1996 (China Statistic Year Book 1997). The project area is one of the most popular places for tourists, both domestic and foreign. Hence, assuming twice as much as the most likely value for the maximum value.
f20 (expected annual rate of change in electricity prices during 2000-2020)		Δ(0, 0.011, 0.03)	According to China Energy Efficiency Information Bulletin March 1997, China will not increase electricity prices largely in short term. Thus, assume zero rate of changes for the minimum value. Electricity prices were stable until 1986. A rate of increase in electricity prices from 1986 and 1987 was 0.011 (China Electric Power Industry Year Book 1995). This is used for the most likely value. The same source shows a reasonable rate of increase in electricity prices of 0.03 between 1994 and 1995, which is used for the maximum value[22].
α (parameter which describes the location of the peak of the distribution for the construction cost)		Pert(0.1, 0.2, 0.5)	The official forecast of the distribution of CC skewed to the left (Li 1994 p34 Graph1; Sumi 1971).

[22] Assume the minimum and maximum values are the same, however every 20 years-period

TCC (total construction cost)	GYuan	Pert(470, 610, 660)	The minimum value is the planned figure (CTGPC 1995). 70 hydropower projects commissioned between 1915 and 1986 financed by the World Bank show average cost overruns of about 30% (Bacon and Besant-Jones 1998). Average cost overruns for large dams excluding extreme cases are 40% (WCD 2000).
β (parameter which describes the location of the peak of the distribution for the resettlement cost)		Pert(0.6, 0.8, 0.9)	The official forecast of the distribution of CC skewed to the right (Li 1994 p34 Graph1; Sumi 1971).
σ (parameter which describes the location of the peak of the distribution for number of workers' death/injuries)		Pert(0.1, 0.5, 0.8)	For the minimum value, assuming the peak of the distribution is at the beginning while completing fundamental work. For the most likely value, assuming more complicated and large scale-dangerous work is carried out in the middle of the construction period. For the maximum value, assuming the peak of the distribution is towards the end of the construction period.
C1 (annual decreased CO_2 level due to a decrease in coal use as a result of the TGP)	Tons/GWh/yr	Pert(1250, 1390, 1670)	The minimum value is 10% lower than the most likely value. The TGP is expected to reduce 50 million tons of coal-use per year, which may reduce 100 million tons of CO_2 (Beijing Review July 8-14 1996). The maximum value is 20% higher than the most likely value.
C2 (annual decreased SO_2 level due to a decrease in coal use as a result of the TGP)	Tons/GWh/yr	Pert(25, 28, 34)	The minimum value is 10% lower than the most likely value. The TGP is expected to reduce 50 million tons of coal-use per year, which may reduce 2 million tons of SO_2 (Beijing Review July 8-14 1996). The maximum value is 20% higher than the most likely value.
CM1 (benefits of CO_2 reduction as a result of the TGP)	Yuan/tons of CO_2	Pert(120, 130, 160)	The minimum value is 10% lower than the most likely value. The most likely value is the estimated value (Battelle 198). The maximum value is 20% more than the most likely value.
CM2 (benefits of SO_2 reduction as a result of the TGP)	Yuan/tons of SO_2	Pert(3440, 3820, 4580)	The minimum value is 10% lower than the most likely value. The most likely value is the estimated value (Battelle 1998). The maximum value is 20% higher than the most likely value.

FB (mean annual benefits from flood control for the dam height of 180m scheme)	Gyuan/yr	Pert(0.76, 0.97, 35)	The minimum value is the estimated value (Luk & Whitney 1993). The most likely value is measured solely by economic criteria in 1986 prices (Rulan et al 1997). 'If an exceptionally huge flood similar to that of 1870 should occur, the project would reduce losses caused by inundation by 35 billion Yuan, and also prevent a great number of casualties caused by burst dikes' (Rulan et al 1997).
SC (annual shipping capacity of the TGP)	Gtons/yr	Pert(0.04, 0.05, 0.06)	He minimum value is 20% lower than the most likely value. The most likely value is the estimated value (Beijing Review March 1992). The maximum value is 10% more than the most likely value.
e (annual rate of reduction in shipping costs)		Pert (0.3, 0.36, 0.37)	According to Youmei (1997), 0.3 (min) -0.37 (max). According to Beijing Review March (1992); EAAU (1997); Edmonds (1999), 0.36.
TRo (initial shipping costs)	Yuan/ton	Pert(110, 120, 140)	The minimum value is 10% lower than the most likely value. The most likely value is the forecasted transport costs of goods from Central to East on Yangtze River of $15 per ton in 2005.Source: Energy Research Institute staff estimates in Table 5.4 Battlle (1998). The maximum value is 20% higher than the most likely value.
g (annual rate of change in transportation costs)		Pert(0, 0.01, 0.011)	Assuming no change for the minimum value. The most likely value is the estimated figure (Energy Research Institute stuff estimates in Table 5.4 Battlle 1998). The maximum value is 10% more than the most likely value.
EL (annual economic losses due to inundation of land in the project area)	GYuan/yr	Pert(0.12, 0.13, 0.26)	The minimum value is 10% lower than the most likely value. The project will submerge 31000 ha of farmland and 4933 ha of citrus orchards (Furedi 1999). The value for farmlands and orchards are assumed to be $380/ha/year, and $760/ha/year respectively[23]. Assuming twice as much as the most likely value for the maximum value.

[23] These values are the lost values of the submerged land for coconuts fields and paddy in monetary terms respectively. Source:CEB (1987).

FP (annual lost profit from fishery)	Gyuan/yr	Pert(0.04, 2.4, 2.7)	US Fish and Wildlife Service studies show that Savage Rapids Dam in Oregon has destroyed at least $5 million/year in fisheries benefits (The pacific Coast Federation of Fisherman's Associations 'From Fisherman's News may 1998). The most likely value is 10% less than the maximum value below. 'The National Marine Fisheries Service estimated the cost of Salmon fishery losses due to dams in the Colombia basin to be $6.5 billion fro the period 1960-80 alone' (McCulley 1997).
TRE (total resettlement cost)	Gyuan	Pert(120, 160, 180)	The minimum value is the planned figure (http: www.china.embassy.org / issues / gorges.htm). The most likely value is based on the actual number of resettled, people is 35% higher than the estimated figure according to the WCD Cross-Check Survey (WCD 2000). Similarly, the actual number is 47% higher than the estimated figure among the projects financed by the World Bank (World Bank 1996).
RS (per capita tourists recipients in the Dam site)	Yuan/yr	Pert(1490, 1660, 2490)	The minimum value is 10% less than the most likely value. The most likely value is per capita international tourist recipients in China in 1996 (China Statistic Year Book 1997). The maximum value is 50% more than the most likely value.
OMC (operation & maintenance cost)	Yuan/KW/yr	Pert(170, 220, 240)	O&M cost for large hydro dams is US$20/kW/year (Battelle 1998 Table 5.11). The same rates for TCC are used, that is 30% and 40% more than the planned figure for the most likely and maximum values respectively.
ADE (annual investment costs to deal with downstream negative impacts)	Gyuan/yr	Pert(3.2, 3.5, 4.2)	The minimum value is 10% lower than the most likely value. The most likely value is the estimated figure (Hui 1998). The maximum value is 20% higher than the most likely value.

VD (value estimate for deaths)	MYuan/death	Pert(33, 60, 550)	A wife of worker for the TGP, who was killed by a construction accident claimed $418,116 for compensation (China News Service 13 October 2000). The most likely value is the estimated value of a statistical life obtained from regression analysis using data from India (Shanmugam 2000). The maximum value of the range of the recent estimate of a statistical life in developed countries is 550 million Yuan per death (Viscusi 1993).
VM (value estimate for injuries)	MYuan/injury	Pert(0.009, 0.03, 3.30)	The minimum value of the estimated range of the statistical injury values obtained from regression analysis using data from India is 0.009 million Yuan per injury (Shanmugam 2000). The maximum value of the estimated range of the statistical injury values obtained from regression analysis using data from India is 0.03 million Yuan/injury (Shanmugam 2000). The average estimated value of injury from developed countries in the past studies is 3.3 million Yuan/injury (Shanmugan 2000).
DCR (estimated annual number of deaths during the construction period)	Deaths/GW/yr[24]	Δ(0.3, 0.8, 1.9)	The minimum value is the estimated value for the Hoover Dam in US (Inhaber 1982; Easton Express 1979). The most likely value is the estimated value for in the Canadian Ontario (Inhaber 1982; Morison 1977). The maximum value is the estimated value for the French hydropower. (Inhaber 1982; Potier 1969).
MCR (estimated annual number of injuries during the construction period)	Injuries/GW/yr	Δ(170, 310, 340)	The minimum value is a half of Inhaber's estimate below. The most likely value is 10% less than the Inhaber's estimate below since technology has improved. The maximum value is the estimated value for past projects. (Inhaber 1982; Potier 1969).
DCR' (estimated annual number of deaths during the O&M period)	Deaths/GW/yr	Δ(0.32, 0.57, 0.63)	The minimum value is a half of Inhaber's estimate below. The most likely value is 10% less than the Inhaber's estimate below since technology has improved. The maximum value is the estimated value for past projects. (Inhaber 1982; Potier 1969).

[24] Number of accidents (deaths/injuries) is likely to increase as construction period becomes longer.

MCR' (estimated annual number of injuries during the O&M period)	Injuries/GW/yr	Δ(7, 12, 13)	The minimum value is a half of Inhaber's estimate below. The most likely value is 10% less than the Inhaber's estimate below since technology has improved. The maximum value is the estimated value for past projects. (Inhaber 1982; Bertoletta and Fox 1974).
DCR'' (annual number of deaths due to special circumstances)	Deaths/GWh/yr	Δ (6750,12150, 13500)	The minimum value is a half of Inhaber's estimate below. The most likely value is 10% less than the Inhaber's estimate below since technology has improved. The maximum value is the estimated value for past projects (Inhaber 1982)[25].
MCR'' (annual number of injuries due to special circumstances)	Injuries/GWh/yr	Δ(34750,62550,69500)	The minimum value is a half of Inhaber's estimate below. The most likely value is 10% less than the Inhaber's estimate below since technology has improved. The maximum value is the estimated value for past projects (Inhaber 1982)[26].
ECL (economic loss due to special circumstances)	Gyuan/yr	Pert(17, 30, 45)	Honduras would need $US 2 billion to meet expected direct and indirect losses after a 1-in-100-year storm (Freeman 2000). The 1998 floods have cost about 30 billion yuan in total economic losses in Hubei province alone (Saywell 1998). The maximum value is 50% higher than the most likely value.
b (annual rate of decline in flood control benefit due to sedimentation)		Pert(0.0001,0.001,0.03)	Assume the rate is same as the annual rate of decline in power generation due to sedimentation.
c (annual rate of decline in navigation improvement benefit due to sedimentation)		Pert(0.0001,0.001,0.03)	Assume the rate is same as the annual rate of decline in power generation due to sedimentation.

25 According to Inhaber (1982), the estimated deaths per unit energy is 0.0011-0.0016 deaths/Mw. Assuming that the figures calculated by Inhaber are multiplied by probability of occurrence of such dam failures. Thus, DCR''= (1.1-1.6 deaths/Gw)/P= 13500 deaths/Gw/yr. P=10^{-4} according to IRN.

26 According to Inhaber (1982), the estimated injuries per unit energy is 0.0011-0.0128 injuries/Mw. Similar to the calculation for death, MCR''= (1.1-12.8 injuries/Gw)/P= 69500 injuries/Gw.

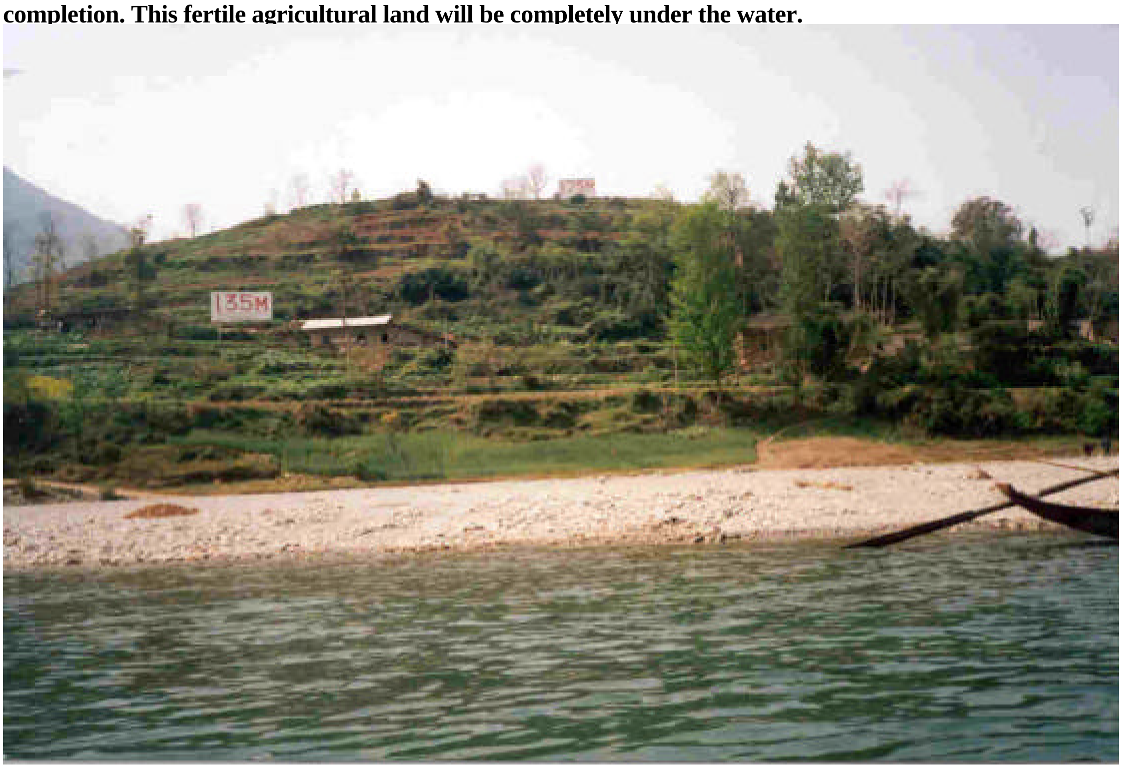
π (proportion of decommissioning costs in the construction cost)	Pert(0.025,0.08, 0.25)	The minimum and the most likely values value are one tenth and one third of the maximum value below respectively. Dam decommissioning costs hugely vary from project to project. The removal of the Marmot and Little Sandy dams which generate 22 MW is estimated to be $22 million. Based on this figure, the TGP needs 18.2 GW*8.3 Yuan / (mean TCC = 610) = 0.25.
TDC (time of decommissioning)	Pert(50, 75, 100)	The expected life of a dam is 50 years. About 5000 large dams in the world are now more than 50 years old (McCully 1997; Wade 1999). Assume 50% more than the above minimum value for the most likely value. The maximum value is T=100.
P (probability of occurrence of technical failures per year)	10^{-4}	According to IRN, average risk of dam breaking in given year is 1 in 10,000. Bacher et al (1980) also assume the rate to be 10^{-4}.
P' (probability of occurrence of terrorism per year)	10^{-5}	Large cities, nuclear power plants, and hydro projects are routinely considered prime military targets[27]. From historical experience the probability of its occurrence is assumed to be low. Hence, the probability of terrorism is assumed to be much lower than those for technical failures. P'= 10^{-5} shall be used.
P'' (probability of occurrence of earthquake per year)	10^{-5}	Assume that the probability of earthquake occurrence is the same as that for terrorism

III. Photographs taken by the author during the Three Gorges Dam site visit in March 2001

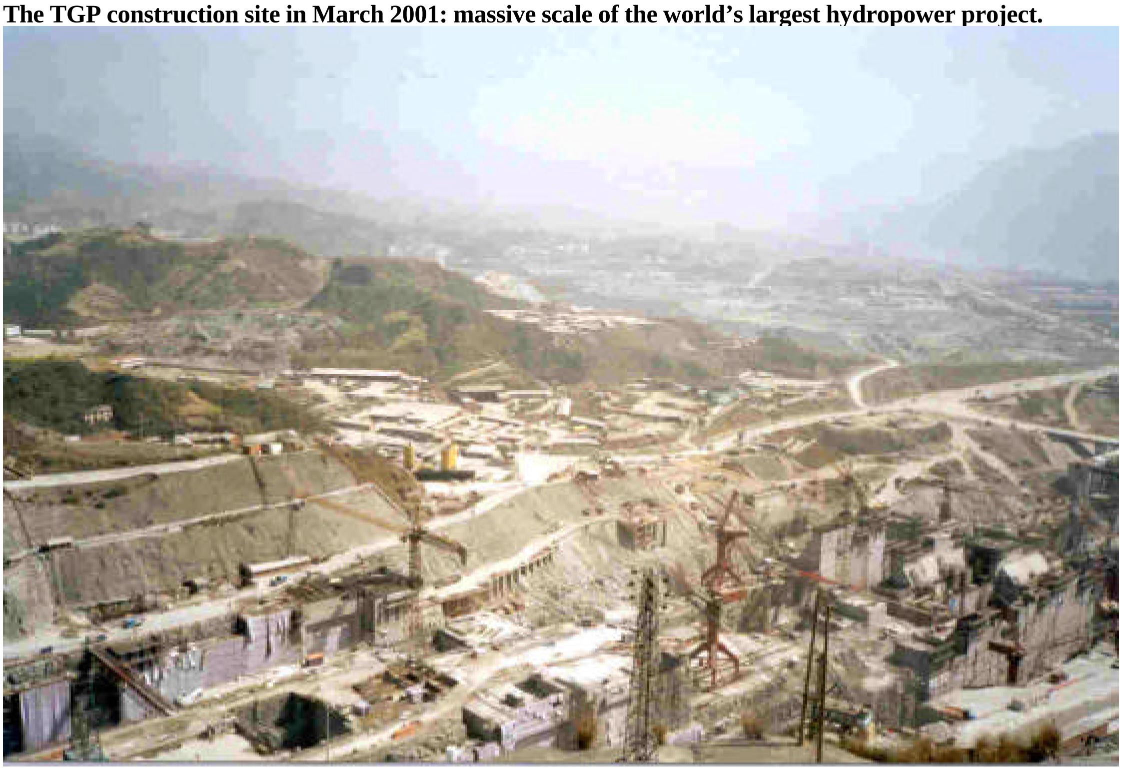
[27] For example, The British bombed Germany's Mohne and Eder dams during World War II, the US bombed North Korean dams during the Korean War and Vietnamese dams and dikes during the Vietnam War. (See Bing 1998 for more detail).

Town near the dam site on the Yangtze River to be submerged completely after the project completion

The sign shows the water level to be raised, initially up to 135m and then to 175m after the project completion. This fertile agricultural land will be completely under the water.



The TGP construction site in March 2001: massive scale of the world's largest hydropower project.



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