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Environmental Impact Assessments of the Three Gorges Project in China: Issues and Interventions

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Abstract: The paper takes China's authoritative Environmental Impact Statement for the Yangzi Three Gorges Project (TGP) in 1992 as a benchmark against which to evaluate emerging major environmental outcomes since the initial impoundment of the Three Gorges reservoir in 2003. The paper particularly examines five crucial environmental aspects and associated causal factors. The five domains include human resettlement and the carrying capacity of local environments (especially land), water quality, reservoir sedimentation and downstream riverbed erosion, soil erosion, and seismic activity and geological hazards. Lessons from the environmental impact assessments of the TGP are: (1) Hydro project planning needs to take place at a broader scale, and a strategic environmental assessment at a broader scale is necessary in advance of individual environmental impact assessments; (2) National policy and planning adjustments need to react quickly to the impact changes of large projects; (3) Long-term environmental monitoring systems and joint operations with other large projects in the upstream areas of a river basin should be established, and the cross-impacts of climate change on projects and possible impacts of projects on regional or local climate considered.

Key Words: Environmental Impact Assessment; Three Gorges Project; Human Displacement and Environmental Carrying Capacity; Water Quality; Reservoir Sedimentation and Downstream Riverbed Erosion; Seismic Activity

1 Introduction

Development and climate change mitigation and adaptation projects increasingly involve large-scale infrastructure projects (e.g., hydropower, irrigation and water transfer projects). This is particularly the case in China (National Development and Reform Commission, 2007a, 2007b, 2010) and other developing countries (Pottinger, 2008; Millikan, 2010; Pittock, 2010). Such projects are growing in their potential to displace massive numbers of people and will continue to yield a range of environmental consequences in the affected countries or regions in the near future (United Nations Environmental Program, 2007; Cernea, 2008). Large infrastructure projects are only approved subject to impact assessments, which estimate possible negative environmental and social impacts on affected communities and populations (especially resettlement of people to be displaced), and propose strategies for minimizing the adverse impacts. Despite this, issues of complexity and uncertainty, conflicts of interest, and problems with accountability can mean that impact assessments fall short of their potential to estimate, and mitigate, the most crucial impacts on affected areas and people.

The Three Gorges Project (TGP) on the Yangzi River is the world's largest hydroelectric power project. The TGP began in 1993 and was completed in 2009. This project however has been one of the most controversial projects in China due to its sheer scale and the consequent environmental and social issues. Baseline environmental, demographic, and social impact assessments of the TGP were completed by the Environment Impact Assessment Department of the Chinese

Academy of Science (EIADCAS) and the Research Institute for Protection of Yangzi Water Resources (RIPYWR) in 1992 and reported in the publication titled *Environmental Impact Statement for the Yangzi Three Gorges Project* (EIS Report hereafter) (EIADCAS and RIPYWR, 1995). The EIS Report has been employed by the Chinese government at all levels as an authoritative guideline for TGP policy and plans. Since the Three Gorges reservoir began filling with water to 135m in 2003, some new environmental consequences have emerged and captured the attention of researchers and environmental activists around the world (e.g., Wu et al., 2003; Stone, 2008, 2011; Gleick, 2009; Tullos, 2009; Fu et al., 2010). Contentious environmental issues surrounding the TGP have centered on water quality (Yang et al., 2007; Bi et al., 2010), fishery (Duan et al., 2009; Gao et al., 2010), sedimentation and downstream riverbed erosion (Yang et al., 2006; Lu et al., 2011), reservoir-induced seismicity and geological instability (Wang et al., 2004; Guo et al., 2007), and the human displacement and carrying capacity of the environment in the reservoir area (Tan 2008; Xu et al., 2011a). The Chinese Academy of Engineering (CAE) completed the *Staged Assessment Report of the Three Gorges Project* (CAE Report hereafter) commissioned by the State Council Three Gorges Project Construction Committee Executive Office in 2010 (Staged Assessment Group of CAE, 2010). The CAE Report has systematically assessed the impacts of the TGP with a particular focus on 10 environmental dimensions with respect to the EIS Report. As the CAE Report has political ramifications and there are limitations in the observed data used for the assessment, it is not surprising to find bias in its results. Such bias relates particularly to ecological and environmental impact issues such as water quality in the reservoir area and riverbed erosion downstream in the Yangzi. Recently, the Chinese central government has addressed critical problems associated with the TGP, including pollution, silt accumulation, ecological deterioration, and geological hazards in the vicinity of the Three Gorges Dam (Qiu, 2011). It is thus imperative to have increased understanding of a set of crucial environmental outcomes associated with the TGP. The present paper seeks to make a contribution in this area.

The paper takes the EIS Report as a benchmark against which to evaluate major environmental outcomes since the initial impoundment of the Three Gorges reservoir in 2003. It begins by briefly reviewing the environmental issues predicted in the EIS Report. It then examines five domains of the environment on which the TGP has impacted significantly and explores the outcomes. The five domains include human resettlement and the carrying capacity of the environments (especially land), water quality, reservoir sedimentation and downstream riverbed erosion, soil erosion, and seismic activity and geological hazards. It concludes with a discussion of the lessons that can be learned from the environmental impact assessment research and experience of the TGP and the policy implications for project design, evaluation, and management of large dams and other forms of large infrastructure projects in China and in other parts of the world.

2 General Environmental Impact of the TGP

Fourteen environmental issues are considered in this section comparing their actual state since 2003 and the likely consequences as estimated by the EIS Report

(Table 1). Strikingly, the actual results of six environmental domains were underestimated in the EIS Report. These include eutrophication, reservoir bank stability, four major domestic fish species, downstream riverbed erosion, the impact on Lake Boyang, and the magnitude of human displacement and the related carrying capacity of the environment in the Three Gorges Reservoir Area (TGRA, shaded in grey in Fig. 1). The scale of both reservoir sedimentation and soil erosion in the reservoir area was overestimated, while the remaining six domains are more-or-less consistent with the estimated consequences in the EIS Report. There are also some divergences between the findings of recent studies and the CAE Report, which concluded that the environmental issues and their impacts primarily fall into the range of the estimates of the EIS Report (Staged Assessment Group of CAE, 2010).

Due to the short time horizon after the ultimate impoundment of the Three Gorges reservoir (filling to 175m normal pool mark) in 2009 and limited availability of monitoring data, some ecological and environmental consequences might not yet have surfaced. Nevertheless, a few new ecological and environmental problems have emerged and urgently need countermeasures to solve. Such problems involve eutrophication and algal blooms in the reservoir area, dramatic reduction of four major domestic fish species, severe downstream riverbed erosion, and apparent declines of water levels in Lake Dongting and Lake Boyang (the two largest fresh water lakes in China). Moreover, the cross-effects between global climate change and the possible impact of the TGP on regional or local climate make it difficult to distinguish the impact of the TGP itself. However, it is clear that the hydroelectricity generated by the

TGP reduced carbon emissions from 2003 to 2010 by 406.7 million tons (Mt), compared to an equivalent amount of coal fired power. This is the equivalent of 0.84 percentage points of the total greenhouse gas (GHG) emission reduction of China over the same time (Wu et al., 2011). The extreme droughts in 2006 and 2011 triggered a hot debate on the impact of the TGP on the lakes of Dongting and Boyang (Kent, 2011; Mo, 2011; Liu et al., 2012; Zhang et al., 2012). Long-term monitoring and scientific research on relevant ecological and environmental issues are of particular importance and need to be strengthened. The environmental impact of the TGP should be assessed using a greater temporal and spatial scale, and it should consider the impact of global climate change on the biophysical environments of the TGRA and the Yangzi River Basin.

[Table 1 about here]

3 Crucial Environmental Outcomes of the TGP

3.1 Human Displacement and Environmental Carrying Capacity

Human displacement and the carrying capacity of the environment (especially land) in the TGRA has been a vital issue from the initial feasibility study of the TGP in the mid-1980s throughout the building of the Dam and up until today. It was planned that some 1.13 million people were to be displaced and resettled locally in the reservoir area, and that there was a potential capacity to accommodate the majority of people to be displaced within their own county (EIADCAS and RIPYWR, 1995). In fact, approximately 1.25 million people were displaced over a 16-year period to the end of 2008 (SCTGPCCEO, 2010). Of these, about 190,000 rural residents (or 15% of the total) were displaced and resettled in 11 provinces via ‘government-organized distant resettlement’ (GODR) schemes, including Shanghai, Zhejiang, Jiangsu, Fujian, Guangdong, Hunan, Anhui, Jiangxi, Sichuan, Chongqing and Hubei. The increased number of resettlers (120,000 persons) was mainly influenced by three factors as follows.

First, the natural population growth rate in some counties of the TGRA was greater than 1.2% per annum, which was assumed in the EIS Report as its estimation of population to be affected. The directly affected populations (DAP, i.e., people whose land and houses were submerged by the reservoir) estimated in the field surveys in 1985 and 1992 were 725,500 and 847,500, respectively. In the event, the actual number of urban residents and rural people increased from 322,900 and 332,600 in 1985 to 496,200 and 350,000 in 1992, respectively. Using the baseline data for the DAP in 1985 and the assumed average growth rate (1.2%), the estimated DAP (788,680) in 1992 was 58,820 less than the actual DAP. One causal factor was that rural people displaced from hillsides between the 135m and 175m water level marks had a higher growth rate than the growth rate assumed by the EIS Report. By the end of 2009, the actual number of rural people displaced from hillsides at the 135-156m and 156-175m water level marks in the Chongqing reservoir section amounted to 183,113 and 185,113, respectively. These were far more than the original estimated numbers (102,397 and 149,169) of resettlers in these areas (Chongqing Municipal Bureau of Statistics, 2011). Clearly, the assumed average annual population growth rate (1.2%) in the EIS Report did not reflect the demographic trends in the TGRA rightly. This was especially the case for the major resettlement-related counties of Wanzhou, Yunyang and Fengjie (located in the lower part of the Chongqing reservoir section) where local residents were disproportionately affected by the TGP.

Second, the extensive sprawl of newly built cities and towns and the improvements in urban housing standards increased the demand for farmland to be expropriated for urban expansion, thereby reducing the availability of land to accommodate rural residents to be displaced. The expanded area of new cities and towns totaled 54.95 km^2 (47.53 km^2 in Chongqing and 7.42 km^2 in Hubei) and 14.35 km^2 (11.39 km^2 in Chongqing and 2.96 km^2 in Hubei), respectively, by 2010. In other words, the built area in the cities was expanded by 18.6% and in townships by 25.9%, compared to the resettlement planning in the EIS Report. Moreover, the housing area of urban residents is 25m^2 per capita, 10m^2 larger than that before the population displacement (Staged Assessment Group of CAE, 2010). Due to expropriation of farmland from the peri-urban areas, 28,938 farmers lost their land and were resettled in the urban areas.

Third, 6,453 residents previously residing on some islands, which formed from the inundation of low lying lands to the reservoir, were resettled. This group of the displaced was not considered in the EIS Report. About 124 islands have formed since the lands were submerged to the 175m water level of the reservoir, according to the Island Development Planning of the Three Gorges Project in 2006. Most of the islanders residing on 103 islands were displaced and resettled locally, in combination with ecological rehabilitation schemes implemented on the islands (Guo et al., 2010).

The human carrying capacity of the environment in the TGRA is a key factor in devising resettlement policies and schemes. The human carrying capacity in the EIS Report was estimated based on a set of assumptions about the agricultural production grounded on a self-reliant food (especially grain) provision system in the region, the maximum population that local land resources can support, the capacity of secondary and tertiary industries to absorb rural migrants, and the number of farmers that would be willing to transfer their agricultural status to urban resident status. The EIS Report stated that the reservoir area had an adequate capacity to accommodate all resettlers and that most of rural people could be resettled within their original townships. Specifically, the EIS Report optimistically estimated that the carrying capacity of the land in the rural areas could support 1 million rural resettlers, while 0.37 million people could be resettled in the secondary and tertiary industry sectors. A huge amount of cropland (684.9 km^2) was inundated by the reservoir from 1995 to 2007. Resettlement of the displaced rural and urban residents and urban relocation have taken, 724.9 km^2 of paddy field land, even though there was a small increase (40.0 km^2) in newly developed dry land farming areas (Staged Assessment Group of CAE, 2010). In spite of per capita landholding of farmers slightly increasing from 1992 (0.099 ha) to 2007 (0.102 ha), both the soil fertility and the productivity of the newly cultivated cropland (mainly converted from dry land on steep slopes) are inferior to those of paddy fields lost. This has resulted in a further reduction of the land carrying capacity in the region. This overestimation has caused the displacement of about 190,000 rural residents to be resettled in 11 provinces via GODR schemes during the 2000-2008 period. The lack of the human carrying capacity of the local environments and high environmental vulnerability in the region after the devastating floods occurring in the Yangzi River Basin in 1998 caused the Beijing government since 2000 to shift its resettlement policy from “near resettlement” only to encouraging distant resettlement. Based on an ecological footprint model, the CAE projected that the suitable population in the TGRA should be 17.7 million in 1994, 15.96 million in 2003, and 15.84 million in 2006. Compared to the actual populations in the TGRA, there would have been a surplus carrying capacity for 350,000 persons in 1994, but a shortage of carrying capacity of 1.32 million in 2003 and 1.64 million in2006 (Staged Assessment Group of CAE, 2010). Clearly, the human carrying capacity of local environments was overly estimated in the EIS Report. This overestimation was mainly influenced by four factors as follows.

First, the area designated for resettling the displaced people involved 361 towns, encompassing an area of 12,300 km². In practice, however, only 245 towns with 5,700 km² below the elevation of 600m above the sea were considered in the resettlement planning. Second, the prohibition of cultivating farmland on steep slopes with a gradient of 25 degrees or greater (a national environmental policy commenced in 1998) led to a reduction of 129.7 km² of unfarmed grassland, which could be developed as sloping land, directly reducing the carrying capacity of the land. Consequently, 77,800 rural residents could not be resettled in the agricultural sector in terms of the threshold (0.17ha) of land needed to resettle a farmer. The ongoing implementation of this national ‘Grain to Green’ program has reduced the provision of arable land and associated carrying capacity. A great deal of sloping cropland (1,020 km^2) was converted to forest or grassland from 1993 to 2008. Another 2,900 km^2 of farmland on steep slopes is also planned to be returned to forest or grassland by 2020 (TGPEEMSIMC, 2009). Third, rapid urbanization in the reservoir area has taken a large amount of cropland for urban construction. Urban land area increased by 398 km^2 from 1992 to 2007, of which 83% was converted from cropland. Urbanization was one of the key drivers of cropland reduction in the reservoir area, contributing to 44% of total reduced cropland (TGPEEMSIMC, 2009; Zhang et al., 2011). Lastly, only 113,500 people (accounting for 30.8% of the planned total) were resettled in the local secondary and tertiary industry sectors as the development of township-owned enterprises did not achieve the expected prosperity (Staged Assessment Group of CAE, 2010).

The discrepancy between the estimated number of people to be displaced and the actual population displaced was considered acceptable (10%) in the Chinese context. The tolerance level of discrepancy, set up by the Water Resources and Hydropower Reservoir Inundation Treatment Design and Planning in China (SD130-84), is ±10% (Staged Assessment Group of CAE, 2010). With such a gigantic resettlement as the TGP it is difficult to predict the exact population to be resettled and the exact carrying capacity of the environment in the reservoir area. The concept of “human carrying capacity” and associated methods used for predictions of the carrying capacity in the EIS Report are problematic in practice. This concept and estimating methodologies could not capture significant effects of a range of other factors that can influence both demand for and supply of food to feed the growing population in the TGRA. Key factors include demographic change, economic growth, urbanization, industrialization, structural change, environmental change and constraints of local resources, change in consumption, and change in food markets (locally, nationally, and internationally).

To respond to the unanticipated growth of resettler populations and the inadequacy of the environmental carrying capacity, the Chinese central government made a couple of adjustments to the TGP resettlement policy in 1999. The first, commencing in 2000, involved a shift from a policy of settling rural residents to uphill sites within the TGRA to motivating more rural people to move to more distant resettlement destinations. The second adjustment, commencing in 2001, related to the policy on relocation of industrial enterprises in the reservoir area, shifting from simply re-establishing them at a location to restructuring and merging small and non-profitable enterprises. The two adjustments to the resettlement policy marked a turning point in the process of the TGP resettlement, and played an important role to mitigate the adverse impacts of a huge resettlement program on the local ecological environment (Xu et al., 2011a). However, the resettlement implementing plan was not adjusted until 2007, when 14,000 more resettlers were added. By 2007 over 200,000 rural residents, some of whom were resettlers produced by the TGP, still lived in the vulnerable environments near the 175m shoreline of the reservoir, and needed to be relocated again (Liang, 2007). In response, the central government introduced the *Follow-up Comprehensive Planning of the Three Gorges Project* in 2011. More than RMB 85 billion yuan (USD 1 = RMB 6.14 yuan as of May 11, 2013) were to be invested to promote social and economic development, to create jobs in the reservoir area, and to subsidize the resettlers to get basic asset and medical insurances (Chinese News Net, 2011). Another strategy was to pilot an ecological migration program in the Chongqing reservoir section, particularly the counties of Wushan, Fengjie, Wuxi and Yunyang. This migration program aimed to move people out of the ecologically vulnerable areas in order to rehabilitate the degraded environments and lift people out of poverty. It was planned that about 100,000 people would be resettled via ecological resettlement schemes in the four years up to 2013 (21st Century Economic Report, 2009).

3.2 Water Quality

Water quality is a crucial factor influencing water supply and safety for all residents and sustainable development in the reservoir area. Increased pollutant concentration and slowing velocity of water flows in some bays of the reservoir have resulted in eutrophication since the initial impoundment of the reservoir in 2003. Although the scale and severity were underestimated, this environmental consequence was correctly predicted by the EIS Report. Eutrophication has become a prominent environmental event since an algae bloom flourished in the Xiangxi River (a primary tributary of the Yangzi River) in June 2003. Observed data on water quality across six sections of the Yangzi show that water quality in the main course of the Yangzi has remained stable and in good condition since 2003 (Fig. 2) (Yang et al, 2009; Ministry of Environmental Protection, 2012). Nevertheless, there is a great risk of worsening water quality, dropping from level II to level III, and even to level IV in some years.

[Fig. 2 about here]

The water quality in over 38 small tributaries (each with a watershed area larger than 100 km^2) has declined dramatically since 2003. The proportions of the river segments with water quality at levels II and III dropped from 56% and 33% in 2003 to 14% and 29% by 2008, respectively. The proportion of the river segments with water quality at level IV increased dramatically from 11% to 43% over the same time. In some areas, water quality even dropped to level V after 2008. The proportion (90%) of the river segments between levels of I-III from March to October in 2010 increased by 110% compared to the corresponding proportion in 2008, and the river segments with water quality at level V or worse has continued to decline (Fig. 3) (Ministry of Environmental Protection, 2012). As a result, the proportion of river sections experiencing eutrophication increased from 16% in 2007 to 34% in 2010. Moreover, the frequency of algal bloom events in the reservoir area is tending to increase, changing from 3 events in 2003 to 26 events in 2010 (Fig. 3), and the scope of water body affected by eutrophication is widening (Yang et al, 2009). Although there have been fluctuations in the frequency of algal blooms in some years, many authoritative research institutes including the Ministry of Environmental Protection (MEP), the Chinese Academy of Engineering (CAE) and the Chinese Academy of Science (CAS), have come to a consensus that the eutrophication in the reservoir area is a significant issue and thus needs close attention (Yang et al., 2009; Staged Assessment Group of CAE, 2010; MEPPRC, 2012). The underestimated eutrophication in the reservoir area could be a major weakness of the EIS Report.

[Fig.3 about here]

The incidence of algal blooms in the reservoir area relates to slowing tributary flows caused by the dam impoundment, which has transformed the hydrological characteristics of the water body from a river to lake-like bays in the reservoir and the backwater areas of the tributaries (Yang et al., 2009; Fu et al., 2010). Pollutants from the upstream Yangzi have also had a significant impact on the water quality in the TGRA. The EIS Report downplayed this effect (Staged Assessment Group of CAE, 2010). Chongqing municipality (with 10 million population) residing beyond the TGRA) and Sichuan province (with 81 million population), located in the upper streams of the Yangzi, generated 1,204 Mt of industrial sewage (133Mt and 1,071 Mt respectively) and 1,282 Mt of residential sewage (214Mt and 1,068 Mt respectively) in 2010. These figures are 2.8 times and 1.1 times greater than the corresponding total amounts of sewage produced in the TGRA, respectively (Chongqing Municipal Bureau of Statistics, 2011; Sichuan Provincial Bureau of Statistics, 2011). Both Chongqing and Sichuan have used the Yangzi as a means of exporting their wastes. Moreover, pollutants in the reservoir have not been reduced due to extensive industrial expansion, rapid urbanization and increasing living standards. Rather, total emissions of sewages, COD (chemical oxygen demand) and NH_3-N increased (ammonia nitrogen) by 22.1%, 14.9% and 7.9% from 2000 to 2005, respectively (Yang et al., 2009). The worsening water quality is further exacerbated by land-use change driven by local economic development and human resettlement (Yang et al., 2009; Ye et al., 2009; Xu et al., 2011a).

The underestimated eutrophication in the reservoir area was also caused partly by a lack of understanding of the mechanisms and risks of algal blooms appearing in reservoirs. Historically, no vital algal blooms broke out in the TGRA or in any other large lakes (e.g., Lake Taihu) throughout China in the 1980s. The risk of algal blooms in China did not attract sufficient concern until the water crisis induced by algal blooms in Wuxi city of the Lake Taihu Basin in 2007 (refer to Fig. 1). Globally, there was no eutrophication observed among the existing large dams after the reservoirs began to fill water, such as the Aswan High Dam in Egypt (White, 1988) and Itaipu Dam in Brazil (Huang et al., 2006). The Chinese government has budgeted RMB 22.8 billion yuan from the *Water Pollution Prevention Plan for the Three Gorges Reservoir and the Upper Reaches of the Yangzi River (Revised)*, to improve the water quality and reverse eutrophication. As a result of implementing this Plan, there was a reduction of 0.22 Mt of COD and 26,000 tons of NH_3-N per annum from domestic sewages and industrial discharges in 2010, accounting for 16.1% and 22.6% of the emissions of total COD and NH_3-N in the region in 2005, respectively (Ministry of Environmental Protection, 2008).

3.3 Reservoir Sedimentation and Downstream Riverbed Erosion

Reservoir sedimentation determines the water holding capacity of the Dam and its lifespan. The inflows of water and sediments in the reservoir are primarily concentrated in the flood season (May to September). The sedimentation regime is also related to the operating mode of the reservoir, by which clean water during the dry season (October to April) is stored and muddy water during the flooding season is shed. The process of scouring and silting was anticipated to reach a balance after 100 years of service of the Dam by 2109; and after that about 86% of the flood storage and 92% of the controllable storage could still remain effective (EIADCAS and RIPYWR, 1995). In 2003-2007, sediment averaged 142 Mt per year, which was equivalent to 40% of the estimated 355 Mt per year in the EIS Report (Sedimentation Panel of the TGP, 2008; Yang et al., 2009). The latest monitored data for the 2008-2010 period, at the 175m pool level, shows that the sedimentation exhibits a gentle upward trend (on average 176 Mt per year), and that the peak of sedimentation appeared in the backwater section of the reservoir (Lu et al., 2011). Sedimentation in the reservoir is still much less than the estimate of the early environmental impact assessments.

This huge discrepancy is closely associated with a reduced inflowing amount of sediments from the upper reaches of the Yangzi River. This reduction (by 59% of the sediment volume in the 1960s) is mainly attributed to a number of national environmental projects that have been carried out in the upper Yangzi and in the reservoir area since the late 1990s. These include the Soil and Water Conservation (SWC) program in the upper reaches of the Yangzi River (started in 1988), Grain to Green Project (GGP), Natural Forest Protection (NFP), and Forest Protection in the Upper Yangzi River (FPUYR) (Yang et al., 2009). In addition, a series of large hydropower projects (e.g., Bikou, Baozhusi) have been constructed in the upper Yangzi and these have intercepted the vast majority of sediments from the primary tributaries of the Jialing River flowing to the Yangzi (refer to Fig. 1). China’s ambitious hydropower cascade development in the upper Yangzi River in the next decade has gained momentum accelerated by China’s climate change mitigation and adaptation plans. In *China's Policy and Actions to Adapt to Climate Change* and in the *National Plans for Renewable Energy in the Medium- and Long-Term Future of China*, the Chinese government firmly states that developing hydropower (and other forms of renewable energy) is a crucial strategy for adapting to climate change (NDRC 2007a, 2007b). The hotspot areas of hydropower development include the catchments of rivers of Wu, Jinsha, Yalong, Dadu, Jialing and Min (refer to Fig. 1) (Huang and Chen, 2006; YWRC, 2009; Cai, 2011). Nine large-scale hydropower projects will be implemented in the next two decades. The ongoing Xiluodu and Xiangjiaba mega hydropower projects (planned to be completed in 2015) in the Jinsha River are two of them (refer to Fig. 1). On completion they will become the second and third largest hydropower stations in China, with electricity generating capacities of on average 57.12 billion KWh and 30.75 billion KWh per annum, respectively. These two large dams will further curtail the sedimentation in the upper reaches of the Yangzi flowing to the Three Gorges reservoir.

Downstream riverbed erosion impacts not only on the embankment stability of the Yangzi but also on the interaction between the Yangzi and China's mega lakes, including Boyang and Dongting in the middle reaches of the Yangzi (refer to Fig. 1). The balance between erosion and sedimentation across the mid-reaches of the Yangzi (stretching 955km from Yichang city to Hukou city) has been upset, shifting from an approximate balance to net erosion since 2003 (Fig. 1). This is evidenced by average total erosion of 108.8 million m^3 from October 2002 to October 2010, or at an intensity of 13,927 m^3/km^2 per annum. Such erosion peaks across the segment of the Yangzi from Yichang city to Zhicheng city, accounting for nearly two thirds (64%) of the overall erosion in the Yangzi (Lu et al., 2011). Both the volume and severity of river-course erosion since 2003 have been greater (by 115.9%) than the observed average (6.3 million m^3 per annum) in 1975-2002, and also greater (by 54.5%) than the estimate of the EIS Report (average 8.8 million m^3 per annum in the first ten years of operation of the TGP commencing in 2009). Again, the impact on downstream riverbed erosion in the EIS Report was underestimated significantly.

Tremendous riverbed erosion is primarily a mixed result of three forces. First, intercepting sediment and discharging clear water since the initial impoundment of the reservoir has enhanced the scouring ability of water on the mid- and down-stream river banks. Second, reduced sediment from the upper Yangzi has significantly curbed sediments downstream of the Dam. Third, extensively mining river sand by human beings alongside the Yangzi has exacerbated the process of river-course erosion (Yang et al., 2007; Sedimentation Panel of the TGP, 2008).

Severe riverbed erosion has caused unexpected downstream bank collapse (Yang et al., 2009). According to the statistics of the Bureau of Hydrology, Yangzi Water Resources Commission, on average, 19 bank collapses (stretching 10 km long) occurred in the Jingjiang section of the middle Yangzi each year in 2001-2003. By contrast, a total of 124 bank collapses occurred in 2003-2007, stretching 31.7 km long on average per year (21st Century Economic Report, 2011). Moreover, bank collapse not only occurs in the midstream of the Dam but also has expanded to the downstream Yangzi. For example, 76 bank collapses (with a total length of 418 km) happened along the lower section of the Yangzi and within Anhui province from 2003 to 2009 (Liu, 2010).

Decreasing sedimentation and serious downstream riverbed erosion has dramatically influenced the lake-river interrelationship between the Yangzi and lakes of Dongting and Boyang (Gong and Yang, 2009; Yang et al., 2009), the nutrient circulation (Hu et al., 2009), and the degradation of the aquatic ecosystems in the TGRA, the middle stretches of the Yangzi (Wu et al., 2004; Stone, 2008; Fu et al., 2010) and the estuary of the Yangzi River. The latter three effects are not unusual as such environmental outcomes have been already observed in other large dams of the world, e.g., Glen Canyon Dam (Melis et al., 2011) and another 137 dams in America (Graf, 2006), increasing nutrients and estuary degradation in the Nile (White, 1988) and Guadiana estuary (Morales et al., 2006). The impact of the Three Gorges Dam on Lake Boyang was not addressed in the EIS Report, as it considered the impact of discharge of reservoir water from January to May only. Zhang et al. (2012) stated that the new flow regime of the Yangzi downstream of the Dam has intensified the fluctuation of water levels between wet and dry seasons in Lake Boyang. The water level of the lake remains particularly low during the dry period from late summer to autumn. Liu et al. (2012) argued that extreme droughts in Lake Boyang from 2000 to 2010 were mainly caused by significant declines of water supply from the upper streams of the Boyang Lake Basin, and that the hydrological change in the Yangzi River, mediated by the dam, aggravated the deficiency of water inflows to the lakeBoyang. Yet the extent of corresponding impact of the two factors needs to be further studied based on a longer term of monitoring data.

Sedimentation in the Three Gorges reservoir can be expected to be less than the estimated extent of the EIS Report in the next decades. Nevertheless, the downstream riverbed erosion and its effects on riverbank stability, lake-river interactions, and the evolution of the aquatic and estuary ecosystems will have greater uncertainties. Hence particular attention should be paid to monitoring and scientific studies addressing the impact of decreasing sedimentation and severe downstream riverbed erosion. Prototype observation of sediments and environmentally friendly dam operation are some good practices in point (Fu et al., 2010; Lu et al., 2011).

The central government policy on the issue of sedimentation has changed significantly. The government has acknowledged the adverse impact of the Dam on the mid- and down-streams of the Yangzi, officially and for first time in the Executive Meeting of the State Council on May 18, 2011, and subsequently approved the *Follow-up Comprehensive Plan of the Three Gorges Project (2010-2020).* The country is implementing a complementary project to stabilize the river regime, to reinforce embankments, and to improve waterways and water facilities. China’s ecological rehabilitation programs will be sustained to improve the environment and protect biodiversity. Monitoring and scientific studies on the joint operational management of the major reservoirs in the upper Yangzi will be a priority (Chinese News Net, 2011). A key scientific research project titled *Lake-River Relationship Evolution and Its Environmental and Ecological Effects and Regulation in the Middle Reaches of the Yangzi River*, funded by the Ministry of Science and Technology under the National

Key Basic Research Development Program (namely '973 Program'), was undertaken by CAS in 2012 to investigate the mechanism of the lake-river interaction, evolving characteristics and environmental effects. The implementation of the Plan and the scientific research Project can be expected to identify solutions for jointly regulating the operating modes of the major reservoirs in the upper Yangzi to mitigate, or greatly reduce, the inflows of sediments to the Three Gorges reservoir.

3.4 Seismic Activity and Geological Hazards

Large dams, e.g., Kariba Dam in Zimbabwe (Talwani, 1997), Glen Canyon Dam in the US (Ivan, 2000) and Aswan High Dam in Egypt (Deif et al., 2009), can induce seismic risks when they are filled with water as the pressure on faults underneath the earth heightens. The Three Gorges Dam is located in a region where the seismic condition is weak although no major fault exists in the reservoir area. The EIS Report has pointed out that there would be no geological condition that can generate strong reservoir-induced seismicity but there would be a possibility of induced seismicity in some areas. For example, there would be a possibility of induced seismicity within the zone of the Xiannüshan-Jiuwanxi fault (18km upstream of the Dam site), at a magnitude ranging from 5.0 to 5.8 on the Richter scale. The biggest seismicity recorded in the Three Gorges region was at magnitude about 5.0 on the Richter scale, which would not have a direct effect on the Dam's major structure, designed to resist seismicity at magnitude 7 on the Richter scale (EIADCAS and RIPYWR, 1995).

The frequency of reservoir-induced seismic activity in the TGRA has increased since 2003 (Table 2). The frequency of seismic activity has a significant positive correlation with the water level of the reservoir. About 1,964 earthquakes occurred in 2009, increasing by 32.2 times on the 2002 level. Annual average frequency over the 2003-2009 period increased by 45.2 fold, compared to the incidences from 1959 to May 31, 2003. Moreover, annual average frequencies across a spectrum of earthquake magnitudes in 2003-2009 were all higher than those before 2003. However, the intensity of the majority of seismic events (96.1%) since 2003 has been smaller than 2.0 Richter scale. About 36 seismic events were above 3.0 Richter scale magnitude (with the largest recorded earthquake at magnitude 4.9) since 2003 and were felt by local residents. The reservoir-induced seismicity of the Dam presents a high frequency and low intensity pattern, which is almost consistent with the anticipation of the EIS Report.

[Table 2 about here]

However the risk of secondary geological disasters such as landslides and mud-stone flows in the peripheral areas nearby both banks of the Three Gorges with steep slopes becomes heightened. There were 1,302 landslides under close field investigations in 1991-1999. This figure climbed to 3,053 landslides by 2009, as monitored by the geological hazard monitoring and warning system in the reservoir area (Guo et al., 2007; Ministry of Environmental Protection, 2012). For example, in July 14, 2003, a major landslide occurred near the town Qianjiangping where the Qinggan River joins the Yangzi (Wang et al., 2004). Another landslide occurring in Qianjiangping in the same day destroyed 346 houses and four factories, resulting in a direct economic loss of USD 7 million. These geological disasters in the reservoir area caused severe damage to navigation and great economic loss, and aggravated soil erosion and resettlers' anxiety. The increasing secondary geological disasters are mainly influenced by a couple of factors. One is that increasing seismic activity after the initial impoundment of the Dam has enhanced the frequency of secondary geological disasters. The other is partly caused by inappropriate infrastructure construction, especially road works (Guo et al., 2007). By the end of 2008, approximately 7.6 billion yuan was invested to rebuild roads in the TGRA. This investment was 4.2 times the total GDP (1.8 billion yuan) in the TGRA in 2008 (SCTGPCCEO, 2010). Of this, 3.8 billion yuan was allocated to reconstruct urban roads due to urban relocation, 3.4 billion yuan for rebuilding highways due to relocation of industrial enterprises, and 0.4 billion yuan for the construction of rural roads due to rural displacement. Hence, landslides and mud-stone flows induced by road and highway constructions were indirectly related to the TGP.

The challenge of preventing geological hazards (especially landslides and mud-rock flows) since 2009 is tremendous. The central government has recognized its significance at the very beginning of the TGP and adopted a number of strategic plans and scientific research. Back in 1958 a network of seismic monitoring stations was established in the reservoir region. Six large-scale field investigations into geological hazards in the reservoir area were carried out from 1986 to 2002 and reliable scientific data about geological hazards and mechanisms collected (Guo et al., 2007). Subsequently, the geological hazard monitoring and alerting system was established in the reservoir area in 2003, at an investment of 110 million yuan (MLR, 2001). The

Comprehensive Plan for Preventing and Controling Geological Hazards in the TGRA was enforced by the Ministry of Land and Resources of China in 2001. Four billion yuan was invested to control and monitor 3,053 landslides from 2001 to 2009 (Ministry of Environmental Protection, 2012). As a result, 465 landslides were controlled; 45,822 persons who originally resided on those landslide bodies had been relocated by the end of 2009 (Xinhua News Agency, 2010a). The implementations of this plan has played, and will continue to play, an important role in predicting and monitoring seismic activity and secondary geological hazards, thereby reducing potential loss and damages in the future.

3.5 Soil Erosion

Soil erosion is another contentious issue, as its extent and intensity has a direct effect on the sedimentation of the reservoir, the lifespan of the Dam, the capacity to control flooding, and ecological status in the upper and middle reaches of the Yangzi River Basin. The EIS Report estimated that soil erosion would be exacerbated by massive resettlement (EIADCAS and RIPYWR, 1995). Observed data of the Chongqing's Environmental Monitoring Station of Soil and Water Conservation (2006) and findings of a recent study of Xu et al. (2011b) point out that both the extent and severity of soil erosion in the Chongqing reservoir section (1999-2004) and even in the entire reservoir region (2000-2008) present a "declining trend". One of chief engineers at the Bureau of Water and Soil Conservation, Yangzi Water Resources Commission stated that the total amount of soil erosion, and the eroded area, in the TGRA decreased significantly, by 27% and 28% respectively, from the 1980s to 2007, based on remote sensing data and analysis of soil erosion (Renmin Yangzi Newspaper, 2010). Clearly, the actual impact of the TGP on soil erosion is less than the estimation of the EIS Report.

The overestimation of the likely impact of the TGP on soil erosion was primarily related to three factors that were not anticipated in the EIS Report. The first is associated with the implementation of several major ecological projects in the last two decades (Yang et al., 2009). As a result of implementing these projects, the forest coverage rate in the TGRA increased from 21.9% in 1997 to 34.5% in 2008, greater than the national averages of 13.9% in 1997 and 20.4% in 2008 (Yang et al., 2009). Approximately 1,020 km^2 of cropland distributed on steep slopes (25° or above) were returned to forest or grassland through implementing the GGP in the reservoir region over the 2000-08 period (Ministry of Environmental Protection, 2012). The ongoing ecological projects have played a key role in offsetting soil erosion in the reservoir region. The second factor relates to the practice of transforming sloping cropland to terraced land, which was used as an important countermeasure to secure land for resettling rural residents locally. About 2,186 km^2 of sloping cropland were converted to terraced land in 1993-2000, and 276 km^2 added in 2006-2008. Together, nearly two thirds (64%) of the overall sloping cropland distributed on the slopes of 7°-25° in the TGRA were transformed to terraced land (Staged Assessment Group of CAE, 2010; Ministry of Environmental Protection, 2012). This transformation has not only increased food production but also played an important role in reducing soil erosion in the region. The third factor is the utilization of some new agricultural techniques in the resettlement communities. These include planting hedgerows, cultivating along contours, and agro-forestry techniques (Chen et al., 2003; Liao et al., 2008). Specifically, planting hedgerows on steep sloping land could curb surface runoff by 84-95% and soil erosion by 90-97%, while soil fertility can be improved by 5-22% (Staged Assessment Group of CAE, 2010). These techniques helped prevent the deterioration of soil erosion in the resettlement communities, as rightly expected in the EIS Report.

4 Conclusion

Environmental impact assessments (EIA) of large infrastructure projects, such as the Three Gorges Project (TGP) on the Yangzi River of China, have been highly instrumental in making policies and operational plans for human displacement and environmental protection in the project affected communities. To a large extent the dimensions and overall trends of potential environmental impacts of the TGP are rightly estimated in China's authoritative report titled *Environmental Impact Statement for the Yangzi Three Gorges Project* (EIS Report) in 1992. This Report has played a significant role in guiding the implementation processes of human resettlement, construction of the Three Gorges Dam, and a host of environmental and socio-economic development projects in the Three Gorges Reservoir Area. Yet there is great complexity and uncertainty regarding the scale and scope of possible environmental impacts of a large development project. This study provides an overall evaluation of the major environmental consequences of the TGP by comparing recent studies with the estimations of the EIS Report. The evaluation results are summarized in Table 3. These evaluations were grounded on empirical studies and existing observing data on vital environmental consequences over a short time span since the initial impoundment of the Three Gorges reservoir in 2003. The time horizon (less than 10 years) is rather short for some environmental consequences to manifest or evolve. A long-term monitoring and scientific study into the environmental outcomes of the TGP is needed to gain a full understanding of the TGP impact on affected communities and populations.

[Table 3 about here]

China, as elsewhere, has improved EIA for large infrastructure or other development projects. EIA has been one of the most contentious issues in the debates on the feasibility and consequences of large infrastructure projects. To eliminate or reduce adverse environmental impacts in the regions affected by the project, the nation (China in this study) needs to make adjustments to relevant policies and invest tremendously to environmental programs. It is possible to not only cope with these changes but also to minimize irreversible environmental consequences. Two adjustments to the TGP resettlement policy and carrying out environmental programs to prevent geological hazards and water quality from being further worsened are examples in point. In order to do this, however, there will need to be major improvements in many areas. Four aspects need to be particularly addressed and taken into account in EIA for ongoing and future dam and other infrastructure projects. First, a strategic environmental assessment at a broader scale is necessary in advance of individual EIA. Strategic environmental assessment systematically assesses upstream and downstream impacts, as well as cumulative impacts of other associated future infrastructure projects. Second, long-term environmental monitoring systems in the affected regions are necessary to collect first-hand data for calibrating the models and to assess environmental impacts of large dams and other mega infrastructure projects. It is also imperative to establish prototype observation and joint operations with other large projects in the upstream areas of a river basin, to assist forecasts and assessment of potential environmental risks and impacts. Third, national policy and planning adjustments need to react quickly to the impact changes of large projects to mitigate the unanticipated adverse impacts in the EIA at a large extent. Lastly future environmental impact assessments need not only focus on project impacts on the environment and communities, but also incorporate the cross-impacts of climate change on projects, and assess possible impacts of projects on regional or local climate.

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References

Bi, Y.H., Zhu, K.X., Hu, Z.Y., Zhang, L., Yu, B.S., Zhang, Q., 2010. The effects of the three Gorges Dam's (TGD's) experimental impoundment on the phytoplankton community in the Xiangxi River, China. International Journal of Environmental Studies 67(1): 207-221.

Cai, Q.H., 2011. Integrated River Basin Management for A Healthy Yangzi River. Changjiang Press, Wuhan, 187p.

Cernea, M., 2008. Compensation and investment in resettlement: Theory, practice, pitfalls, and needed policy reform. In: M. Cernea, H.M. Mathur (Editors), Can Compensation Prevent Impoverishment? Oxford University Press, New Delhi, pp.147-179.

Chen, Z.J., Liao, X.Y., Liu, S.Q., Wang, H.M., 2003. Sustainable utilization technology of slope cropland and its benefit in the Three Gorges Reservoir. Research of Soil and Water conservation 11(3): 85-87 (in Chinese, with English Abstr).

Chinese News Net, 2011. State Council executive meeting approved the Follow-up Compressive Planning of Three Gorges Project. http://www.chinanews.com/gn/2011/05-18/3050194.shtml, May 18, 2011.

Chongqing’s Environmental Monitoring Station of Soil and Water Conservation (CEMSSWC), 2006. Gazette of soil and water losses in 2005 (in Chinese). http://www.cqsbjc.com/view.asp?id=732, June 14, 2006.

Chongqing Municipal Bureau of Statistics, 2011. Chongqing Statistical Yearbook 2011 (in Chinese). China Statistics Press, Beijing, 588p.

Deif, A., Nofal, H., Elenean, K.A., 2009. Extended deterministic seismic hazard assessment for the Aswan High Dam, Egypt, with emphasis on associated uncertainty. Journal of Geophysics and Engineering 6(3): 1742-2132.

Duan, X.B., Liu, S.P., Huang, M.G., Qiu, S.L., Li, Z.H., Ke, W., Chen, D.Q., 2009. Changes in abundance of larvae of the four domestic Chinese carps in the middle reach of the Yangzi River, China, before and after closing of the Three Gorges Dam. Environmental Biology of Fishes 86(1): 13-22.

EIADCAS (Environment Impact Assessmenet Department, Chinese Academy of Science), RIPYWR (Research Institute for Protection of Yangzi Water Resources), 1995. Environmental Impact Statement for the Yangzi Three Gorges Project (a brief edition). Science Press, Beijing, 72p.

Fu, B.J., Wu, B.F., Lü, Y.H., Xu, Z.H., Cao, J.H., Niu, D., Yang, G.S., Zhou, Y.M., 2010. Three Gorges Project: Efforts and challenges for the environment. Progress in Physical Geography, DOI: 10.1177/0309133310370286.

Gao, X., Zeng, Y., Wang, J.W., Liu, H.Z., 2010. Immediate impacts of the second impoundment on fish communities in the Three Gorges. Environmental Biology of Fishes 87(2):163-173.

Gleick, P.H., 2009. Three Gorges Dam Project, Yangzi River, China. In: P.H. Gleick (Editor), The World’s Water 2008-2009: The Biennial Report on Freshwater Resources. Island Press, Washington D.C., pp.139-150.

Gong, P., Yang, W.J., 2009. Preliminary study of river-lake evolution effect due to Three Gorges progect. Part 2. The effect on river-lake relation and channel storage capacity. Journal of Hydroelectric Engineering 28(6): 120-125 (in Chinese, with English Abstr).

Graf, W.L., 2006. Downstream hydrologic and geomorphic effects of large dams on American rivers. Geomorphology 79: 336-360.

Guo, H., Hu, Q., Zhang, Q., Feng, S., 2012. Effects of the Three Gorges Dam on Yangzi River flow and river interaction with Boyang Lake, China: 2003-2008. Journal of Hydrology 416-417: 19-27.Guo, T., Dai, G.M., Feng, Y., 2010. Planning and conduction of island disposal in ThreeGorges Reservoir. Yangzi River 41(3): 25-27 (in Chinese, with English Abstr).

Guo, X.Z., Huang, X.B., Xu, K.X., 2007. Prevention and Treatment of Landslide and Collapse Geological Hazards in Three Gorges Reservoir Area (in Chinese). China Water Power Press, Beijing, 334p.

Hu, B.Q., Yang, Z.S., Wang, H.J., Sun, X.X., Bi, N.N., Li, G.G., 2009. Sedimentation in the Three Gorges Dam and the future trend of Changjiang (Yangzi River) sediment flux to the sea. Hydrology and Earth System Sciences 13: 2253-2264.

Huang, W., Chen, J., 2006. A preliminary approach on impacts of hydropower development in upper Yangzte River on ecological environment. Hydropower 8: 1098-1106.

Huang, Z.L., Wu, B.F., Ao, L.G., 2006. Study on Eecological and Environmental Eurvey System of Three Gorges Project (in Chinese). Science Press, Beijing, 363p.

Ivan, W., 2000. Probabilistic seismic hazard analysis: Glen Canyon Dam. Technical report, URS Greiner Woodward Clyde, Washington, D.C.

Kent, J. L., 2011. Has the Three Gorges Dam created Chinese drought zone? CNN, June 3, 2011. http://edition.cnn.com/2011/WORLD/asiapcf/06/03/china.dam.drought/index.html.

Liang, F., 2007. Study on ecological resettlement in Three Gorges reservoir area. Forum on Science and Technology in China 10: 29-32 (in Chinese).

Liao, X.Y., Luo, C.D., Chen, Z.J., Wang, H.M., Chen, D.P., 2008. Soil moisture character of agro-forestry and contour ridge tillage technique of slope cropland in Three Gores Reservoir Area. Agricultural Research in the Arid Areas 26(5), 75-79 (in Chinese, with English Abstr).

Liu, D.F., 2010. The Anhui section of Yangzi River situation change and bank collapse study after the Three Gorge store water. Jianghuai Water Resources Science and Technology 5: 11-13 (in Chinese).

Lu, J.Y., Huang, Y., Wang, J., 2011. The analysis on reservoir sediment deposition and downstream river channel scouring after impoundment and operation of TGP. Engineering Sciences 9(3):113-120.

Liu, Y.B., Zhang, Q., Liu, J., Li, H.P., 2012. Climatic, Hydrologic and Environmental

Change in Boyang Lake Basin (in Chinese). Science Press, Beijing, 262p.

Melis, T.S., Grams, P.E., Kennedy, T.A., Ralston, B.E., Robinson, C.T., Schmidt, J.C., Schmit, L.M., Valdez, R.A., Wright, S.A., 2011. Three experimental high-flow releases from Glen Canyon Dam, Arizona; effects on the downstream Colorado River ecosystem: U.S. Geological Survey Fact Sheet 2011-3012, 4p.

Millikan, B., 2010. Brazil's dam-building industry: Crony capitalism goes global. World Rivers Review 25(4): 4.

Ministry of Environmental Protection of the People's Republic of China (MEPPRC), 2008.Water Pollution Prevention Planning of the Three Gorges Reservoir and the upper reaches of Yangzte River (Revised) (in Chinese). http://www.mep.gov.cn/pv_obj_cache/pv_obj_id_B0FEA8956D45F361C7D442CD947E4E47100F0E00/filename/W020080203462094746002.pdf, January 31, 2008.

Ministry of Environmental Protection of the People's Republic of China (MEPPRC), 2012. Gazette of eco-environmental monitoring of Three Gorges Project, Yangzi River, China 1997-2011 (in Chinese). http://jcs.mep.gov.cn/hjzl/sxgb/2011sxgb/201206/P020120608565218279423.pdf, April 27, 2012.

Ministry of Land and Resources (MLR), 2001. Comprehensive plan on prevention and control of geological hazards in Three Gorges Reservoir Area (in Chinese). http://www.sxdzfz.gov.cn/, October 19, 2001.

Mo, H.E., 2011. No evidence that dam causes drought: experts. Xinhua English News, May 25, 2011. http://news.xinhuanet.com/english2010/indepth/2011-05/25/c_13893205.htm

Morales, J.A., Delgado, I., Gutierrez-Mas, J.M., 2006. Sedimentary characterization of bed types along the Guadiana estuary (SW Europe) before the construction of the Alqueva dam. Estuarine, Coastal and Shelf Science, 70: 117-131.

National Development and Reform Commission (NDRC), 2007a. The 11th five-year plan for aid-the-poor through displacement of the poor (in Chinese). http://www.ndrc.gov.cn/fzgh/ghwb/115zxgh/P020080407603189621311.pdf.

National Development and Reform Commission (NDRC), 2007b. National plans for renewable energy in the medium- and long-term future of China (in Chinese). Issued on 31 August, 2007, State Council, Beijing. http://www.sdpc.gov.cn/zcfb/zcfbtz/2007tongzhi/t20070904_157352.htm.

National Development and Reform Commission (NDRC), 2010. Recommendations for National Economic and Social Development in the 12th Five-Year Plan (2011-15) (in Chinese). Issued on 18 Oct. http://www.ndrc.gov.cn/125gh.pdf.

Pittock, J., 2010. Better management of hydropower in an era of climate change. Water Alternatives 3(2): 444-452.

Pottinger, L., 2008. Bad deal for the planet: Why carbon offsets aren’t working… and how to create a fair global climate accord. International Rivers, Berkeley, California, USA, 24p.

Qiu, J., 2011. China admits problems with Three Gorges Dam. Naturenews 2011, doi:10.1038/news.2011.315.

Renmin Yangzte Newspaper, 2010. Area of soil erosion in the Three Gorges Reservoir area decreased by 1.08 million ha in the past 20 years (in Chinese). http://node.cjw.com.cn/index/detail/20100530/126237.asp, May 30, 2010.

Sedimentation Panel of the Three Gorges Project (SPTGP), 2008. Summary of Field Data for Sedimentation in the Three Gorges Project during the Cofferdam Impoundment Period (2003-2006). China Water Power Press, Beijing, 58p.

Sichuan Provincial Bureau of Statistics, 2011. Sichuan Statistical Yearbook 2011 (in Chinese). China Statistics Press, Beijing, 535p.

Staged Assessment Group of Chinese Academy of Engineering (CAESAGTGP), 2010. Staged Assessment Report of the Three Gorges Project (Comprehensive Volume) (in Chinese). Chinese Water Power Press, Beijing, 490p.

State Council Three Gorges Project Construction Committee Executive Office (SCTGPCCEO), 2010. China Three Gorges Construction Yearbook 2009 (in Chinese). China Three Gorges Construction Yearbook Press, Beijing, 354p.

Stone, R., 2008. Three Gorges Dam: Into the unknown. Science 321: 628-632.

Stone, R., 2011. The Legacy of the Three Gorges Dam. Science 333: 817.

Tan, Y., 2008. Resettlement in the Three Gorges Project. Hong Kong University Press, Hong Kong, 274p.

Talwani, P., 1997. On the nature of reservoir-induced seismicity. Pure and Applied Geophysics 150(3-4):473-492.

Three Gorges Project Ecology and Environment Monitoring System Information Management Center (TGPEEMSIMC), 2009. Report of Land Resource Change and its Ecological Effects (in Chinese). Technical report, State Council Three Gorges Project Construction Committee Executive Office, Beijing.

Tullos, D., 2009. Assessing the influence of environmental impact assessments on science and policy: an analysis of the Three Gorges Project. Journal of Environmental Management 90: 208-223.

United Nations Environmental Programme (UNEP), 2007. Dams and Development: Relevant Practices for Improved Decision-Making. Progress Press Ltd., Malta, 192p.

Wang, F.W., Zhang, Y.M., Huo, Z.T., Matsumoto, T., Huang, B.L., 2004. The July 14, 2003 Qianjiangping landslide, Three Gorges Reservoir, China. Landslides 1(2): 157-162.

Wang, Y.C., Lai, X.J., Jiang, J.H., Huang, Q., 2011. Effect of the Three Gorge Reservoir on the water regime of the Lake Boyang wetlands during typical water-regulation period. Journal of Lake Sciences 23(2):191-195 (in Chinese, with English Abstr).

White, G.F., 1988. The environment al effects of the high dam at Aswan. Environment 30(7): 4-11, 34-40.

Wu, B.F., Chen, Y.B, Zeng, Y., Zhao, Y., Yuan, C., 2011. Evaluation on effectiveness of carbon emission reduction of the power generation and shipping functions of the Three Gorges Reservoir. Resources and Environment in the Yangzi Basin 20(3):257-261 (in Chinese, with English Abstr).

Wu, J.G., Huang, J.H., Han, X.G., Xie, Z.Q., Gao, X.M., 2003. Three-Gorges Dam--experiment in habitat fragmentation? Science 300: 1239-1240.

Wu, J.G., Huang, J.H., Han, X.G., Gao, X.M., He, F.L., Jiang, M.X., Jiang Z.G., Primack, R.B., Shen, Z.H., 2004. The Three Gorges Dam: An ecological perspective. Frontiers Ecology and the Environment 2: 241-248.

Xinhua News Agency, 2010a. Monitoring and warning network of geological hazards in the Three Gorges Reservoir area has been basically constructed (in Chinese). http://www.gov.cn/jrzg/2010-06/01/content_1618509.htm, June 1, 2010.

Xinhua News Agency, 2010b. China's Three Gorges Dam project stands biggest flood-control test. http://news.xinhuanet.com/english2010/photo/2010-07/20/c_13406457.htm, July, 20, 2010.

Xinhua News Agency, 2012.Three Gorges Dam withstands huge flood. http://news.xinhuanet.com/english/video/2012-07/25/c_131737567.htm, July,25,2012.

Xu, X.B., Tan, Y., Yang, G.S., Li, H.P., 2011a. Three Gorges Project: effects of resettlement on nitrogen balance of the agroecosystems in the reservoir area. Journal of Environmental Planning and Management 54: 517-537.

Xu, X.B., Tan, Y., Yang, G.S., Li, H.P., Su, W.Z., 2011b. Soil erosion in the Three Gorges reservoir area. Soil Research 49:212-222.

Yang, Z., Wang, H., Saito, Y., 2006. Dam impacts on the Changjiang (Yangzi) River sediment discharge to the sea: The past 55 years and after the Three Gorges Dam. Water Resources Research 42: W04407.1-W04407.10.

Yang, G.S., Wen, L.D., Li, L.F., 2007. Yangzi Conservation and Development Report 2007 (in Chinese). Yangzi River Press, Wuhan, 272p.

Yang, G.S., Ma, C.D., Chang, S.Y., 2009. Yangzi Conservation and Development Report 2009 (in Chinese). Yangzi River Press, Wuhan, 293p.

Yangzi Water Resource Commission (YWRC), 1999. Atlas of the Yangzi River Basin (in Chinese). Sinomap Press, Beijing, pp.154-155.

Yangzi Water Resource Commission (YWRC), 2009. Comprehensive Planning Report of the Yangzi River Basin (in Chinese). Technical report, Yangzi Water Resource Commission, Wuhan.

Ye, L., Cai, Q.H., Liu, R.Q., Cao, M., 2009. The influence of topography and land use on water quality of Xiangxi River in Three Gorges Reservoir region. Environmental Geology 58: 937-942.

Zhang, L., Wu, B.F., Yuan, C., Zhu, L., Wang, P., Zhou, Y.M., 2011. Urban development and environment change before and after Three Gorges Project construction in Three Gorges Reservoir Area. Resources and Environment in the Yangzi Basin 20(3):317-324 (in Chinese, with English Abstr).

Zhang, Q., Li L., Wang, Y.G., Werner, A.D., Xin, P., Jiang, T., Barry D.A., 2012. Has the Three-Gorges Dam made the Boyang Lake wetlands wetter and drier? Geophysical Research Letters 39, L20402, doi:10.1029/2012GL053431.

21st Century Economic Report, 2009. Academician Sciences recommended 5 million ecological migrants in the Three Gorges reservoir area (in Chinese). http://news.163.com/09/0912/02/5IVPC60R0001124J.html, September 12, 2009.

21st Century Economic Report, 2011. Unexpectation of the Three Gorges Project: water storage greatly increasing the risk of bank collapse (in Chinese). http://finance.ifeng.com/news/20110629/4204547.shtml, June 29, 2011.

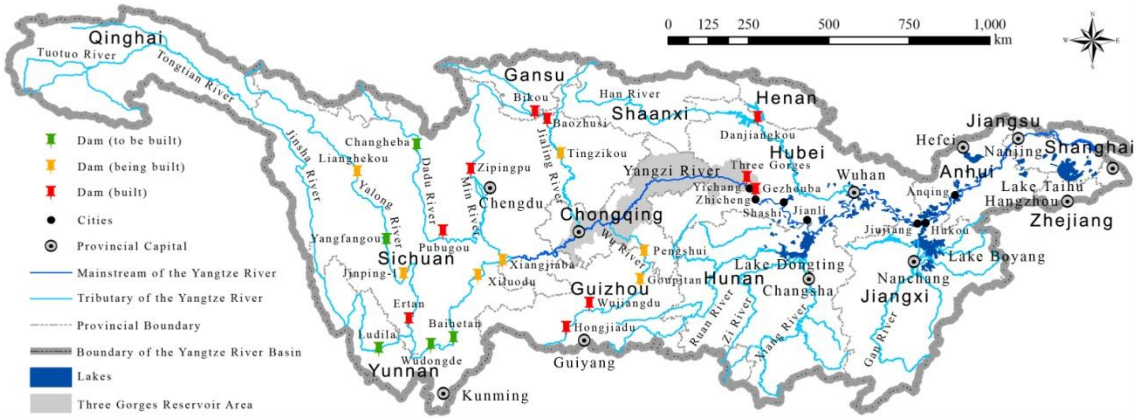

Fig. 1 The Yangzi River Basin and large dams on the Yangzi River

Source: YWRC, 1999; Yang et al., 2007; Cai, 2011.

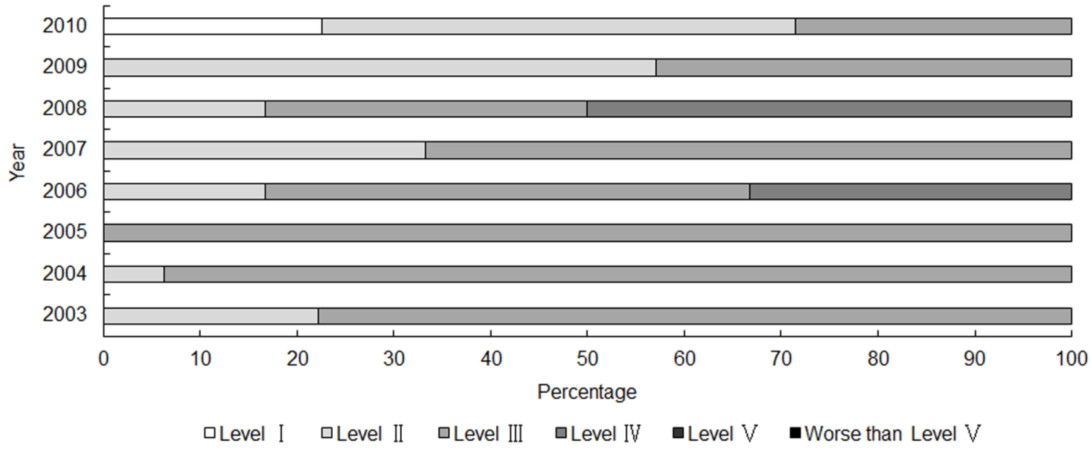

Fig. 2 Change in water quality across the monitored sections of the mainstream of the Yangzi River, 2003-2009

Source: Ministry of Environmental Protection of the People's Republic of China, *Eco-environmental Monitoring Bulletin of the Three Gorges Project, Yangzi River, China (2004-2010) (in Chinese).*

Note: The x axis denotes the percentage of the monitored sections of the mainstream of the Yangzi River at specific water quality level Yangzi. According to the environmental quality standards for ground water in China (GB3838-2002), the main indexes for chemical indicators for different quality levels of water include:

Level I: NH3-N $\leq$ 0.15 mg/L; TP $\leq$ 0.02 mg/L; COD $\leq$ 15 mg/L.

Level II: 0.15mg/L $<$ NH3-N $\leq$ 0.5 mg/L; 0.02mg/L $<$ TP $\leq$ 0.1 mg/L; COD $\leq$ 15 mg/L.

Level III: 0.5 mg/L $<$ NH3-N $\leq$ 1.0 mg/L; 0.1mg/L $<$ TP $\leq$ 0.2 mg/L; 15 mg/L $<$ COD $\leq$ 20 mg/L.

Level IV: 1.0 mg/L $<$ NH3-N $\leq$ 1.5 mg/L; 0.2 mg/L $<$ TP $\leq$ 0.3 mg/L; 20 mg/L $<$ COD $\leq$ 30 mg/L.

Level V: 1.5 mg/L $<$ NH3-N $\leq$ 2.0 mg/L; 0.3 mg/L $<$ TP $\leq$ 0.4 mg/L; 30 mg/L $<$ COD $\leq$ 40 mg/L.

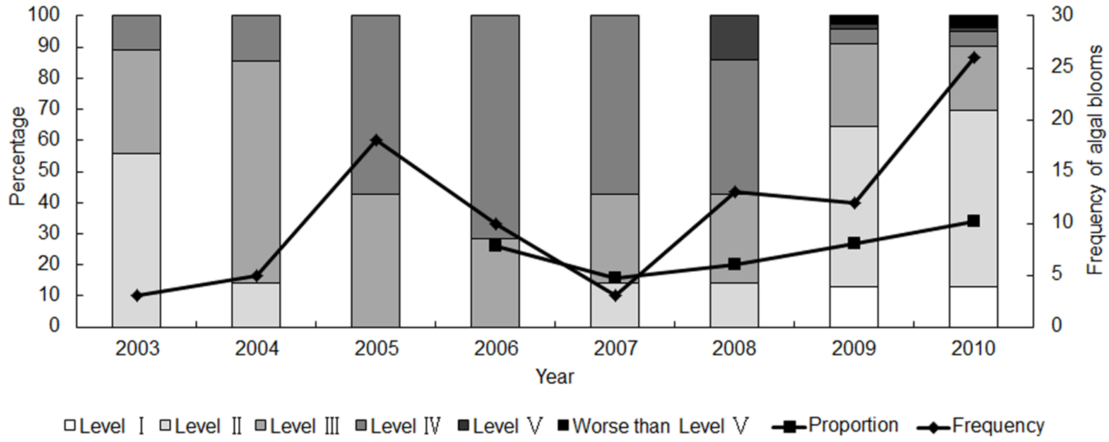

Fig. 3 Change in water quality and frequency of algal blooms across the monitored sections of the major tributaries of the Yangzi River in the TGRA, 2003-2009

Source: Ministry of Environmental Protection of the People's Republic of China, *Eco-environmental* M*onitoring Bulletin of the Three Gorges Project, Yangzi River, China (2004-2011) (in Chinese).*

Note: The left-hand y axis denotes the percentage of the monitored sections of the major tributaries at specific water quality level, and the percentage of the monitored sections where eutrophication occurred against the total monitored sections. The right-hand y axis denotes the frequency of algal blooms appearing in the major tributaries of the Yangzi. The observed water quality and monitored sections in 2009 and 2010 only included months from March to October. The observed frequency of algal blooms in 2010 only included the major tributaries in the Hubei reservoir section.

Table 1 An overview of major environmental issues associated with the TGP

Environmental Issues		Evidence	References
Displacement and environmental carrying capacity	**Displacement**	• 120,000 more resettlers were displaced than the estimated number in the EIS Report. • Some 190,000 rural people were resettled beyond the Three Gorges Reservoir Area (TGRA).	EIADCAS and RIPYWR, 1995; Tan, 2008; SCTGPCCEO, 2010; Xu et al., 2011a
	Environmental carrying capacity	• There was a shortage of human carrying capacity of land in the TGRA, by 1.32 million and 1.64 million persons in 2003 and 2006, respectively.	Staged Assessment Group of CAE, 2010
Sedimentation		• The volume of sediments averaged 142 million tons (Mt) per year, being equivalent to 40% of the estimated 355 Mt per year in the EIS Report.	EIADCAS and RIPYWR, 1995; Sedimentation Panel of the TGP, 2008; Yang et al., 2009
Soil erosion in the reservoir area		• Both the extent and severity of soil erosion in the TGRA are smaller than the estimates of the EIS Report.	EIADCAS and RIPYWR, 1995; CEMSSWC, 2006; Xu et al., 2011b
Water quality	**Eutrophication**	• Eutrophication and algal bloom in many bays of the reservoir has become a prominent issue since 2003.	EIADCAS and RIPYWR, 1995; Yang et al, 2009; Fu et al., 2010; MEPPRC, 2012
Downstream riverbed erosion		• The annual erosion rate from October 2002 to October 2010 averaged at 108.8 million m³, which was much greater than the average 6.25 million m³ per annum in 1975-2002.	EIADCAS and RIPYWR, 1995; Sedimentation Panel of the TGP, 2008; Lu et , al., 2011
Four major domestic fish species		• The stock of four major domestic fish species dropped dramatically between 2005 and 2010, reducing by 78.2% on the 1981 level, compared to the estimated reduction of 50-60% in the EIS Report.	EIADCAS and RIPYWR, 1995; Duan et al., 2009; Gao et al., 2010
Reservoir bank stability		• On average, 31 bank collapses occurred per year in the reservoir in 2003-2007, compared to 19 bank collapses in the Jingjiang section of the middle Yangzi in 2001-2003.	EIADCAS and RIPYWR, 1995; Yang et al., 2009; 21st Century Economic Report, 2011
Reservoir induced seismicity		• Reservoir-induced seismicity shows a high frequency and low intensity pattern, lying within the range as indicated by the EIS Report.	EIADCAS and RIPYWR, 1995; MEPPRC, 2011a
Local climate	**Air temperature**	• Annual mean temperature in the TGRA increased by 0.2-1.0℃ over the 2003-2009 period, compared to the average level in	EIADCAS and RIPYWR, 1995; MEPPRC, 2011a

		1996-2002.	
	Precipitation	• Annual mean precipitation in the TGRA increased by 2-9% over the 2003-2009 period, compared to the average level in 1996-2002.	EIADCAS and RIPYWR, 1995; MEPPRC, 2011a
	Fog	• The number of foggy days per annum in the TGRA in 2003-2009 decreased slightly, compared to incidences in 1980-2002. • The spatial range shrank due to global warming and urbanization.	EIADCAS and RIPYWR, 1995; MEPPRC, 2011a; Staged Assessment Group of CAE, 2010
Downstream flooding risk		• The TGP has substantially improved flooding control capacity in the middle and lower reaches of the Yangzi River. The Three Gorges Dam withstood catastrophic floods in July, 2010 and 2012.	EIADCAS and RIPYWR, 1995; Yang et al, 2009; Staged Assessment Group of CAE, 2010; Xinhua Net, 2010b, 2012
Impacts on the lakes in the middle reaches of the Yangzi River	**Lake Dongting**	• The effect of the TGP on water and sediment exchanges between the Yangzi and the lake is close to the estimate from the EIS Report.	EIADCAS and RIPYWR, 1995; Yang et al, 2009
	Lake Boyang	• The impact of the TGP on Lake Boyang was little addressed in the EIS Report. • The new flow regime of the Yangzi downstream of the Dam intensifies the fluctuation of water levels between wet and dry seasons in the lake. The water level of the lake remains particularly low during the dry period from late summer to autumn.	EIADCAS and RIPYWR, 1995; Yang et al, 2009; Wang et al., 2011; Guo et al., 2012; Zhang et al., 2012

Table 2 Frequency and magnitude of earthquakes in the TGRA, 1996-2009

Year	Frequency	Magnitude (M_L)				
		0.0≤M_L<0.9	1.0≤M_L<1.9	2.0≤M_L<2.9	3.0≤M_L<3.9	4.0≤M_L<4.9
1996	173		125	41	7	
1997	93		63	24	5	1
1998	94		80	14		
1999	38		17	19	2	
2000	40			37	2	1
2001	56			52	3	1
2002	61			57	4	
2003	541	287	220	33	1	
2004	1062	625	378c	56	3	
2005	905	431	405	67	2	
2006	1019	510	448	57	4	
2007	1402	551	751	96	4	
2008	2121	1112	889	105	14	1
2009	1964	1144	721	92	7	
Annual average from 2003 to 2009	1287.7	665.7	572.3	72.3	5	0.14
Annual average from 1959 to 31 May 2003	28.5	13.4	13.8	1.1	0.1	0.05

Source: Ministry of Environmental Protection of the People's Republic of China 1997-2010; Stage Assessment Group of CAE, 2010.

Table 3 Evaluation results of major environmental consequences of the TGP against estimations of the EIS Report

Environmental Issues		Evaluation
Displacement and environmental carrying capacity	**Displacement**	Slightly greater
	Environmental carrying capacity	Significantly smaller
Sedimentation		Significantly smaller
Soil erosion in the reservoir area		Significantly smaller
Water quality	**Eutrophication**	Significantly worse
Downstream riverbed erosion		Significantly greater
Four major domestic fish species		Significantly reduced
Reservoir bank stability		Slightly worse
Reservoir induced seismicity		Essentially consistent with the EIS Report
Local climate	**Air temperature**	Essentially consistent with the EIS Report
	Precipitation	Essentially consistent with the EIS Report
	Fog	Essentially consistent with the EIS Report
Downstream flooding risk		Essentially consistent with the EIS Report
Impacts on the lakes in the middle reaches of the Yangzi River	**Lake Dongting**	Essentially consistent with the EIS Report
	Lake Boyang	Significantly greater