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# The environmental changes and mitigation actions in the Three Gorges Reservoir region, China

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ABSTRACT

The Three Gorges Dam (TGD) is by far the world's largest hydroelectric scheme. Due to its unprecedented magnitude, the TGD has been controversial ever since it was proposed in the early 20th century and building commenced in 1993. Recent problems, including geological disasters (e.g., landslides) in the uplands and algal blooms in the aquatic environment since the reservoir's partial filling to 156 m in 2006, suggest that the environmental challenge has never been greater than now. The environmental deterioration might be further intensified when the reservoir reaches its final water level of 175 m. Solving the environmental challenges will be essential for the sustainable development of the Three Gorges Reservoir region (TGRR), and environmental sustainability in the TGRR is a high priority for the nation considering its critical location in the Yangtze Basin, which contributes 40% of China's GDP. This article reviews primary environmental assessments for biodiversity conservation, the water environment, water level fluctuation zone, and the uplands after the partial filling in the reservoir region. It also discusses the success of mitigation efforts to date. Although there are successes in mitigation particularly in conservation of endangered plants and fishes, it seems likely that environmental conditions in the TGRR could only get worse in the short term. Building a partnership among the TGD stakeholders, including local residents, governments, and international communities is necessary to meet the mounting environmental challenge in the TGRR and beyond.



## 1. Introduction

Sun Yat-Sen first proposed that a series of large dams be built in the Yangtze River in his 1919 article "The International Development of China", and it remained an aspiration for China over the 20th century. Since the 1930s, a number of feasibility studies were undertaken for constructing a large dam in the upper reach of the Yangtze River even after the China's revolutionary governmental transition in 1949. From 1958 to 1984, China built the Lushui Dam in Chibi City, about 110 km south of Wuhan City of Hubei Province, and conducted a variety of small-scale experiments and technical tests for a big dam in the Yangtze River. The Gezhouba Dam, built 38 km downstream of the current Three Gorges Dam (TGD) site between 1970 and 1988, essentially concluded the final tests before commencing building the TGD.

The TGD, begun to be built in 1993 and completed in 2009, is by far the world's largest hydroelectric scheme. It is designed to help control floods and improve navigation on the Yangtze River, and perhaps more importantly increases China's energy supply for its rapid economic development. The dam is a concrete gravity type with a height of 185 m and total water storage capacity of 39.3 billion $m^3$. Its flood control capacity is

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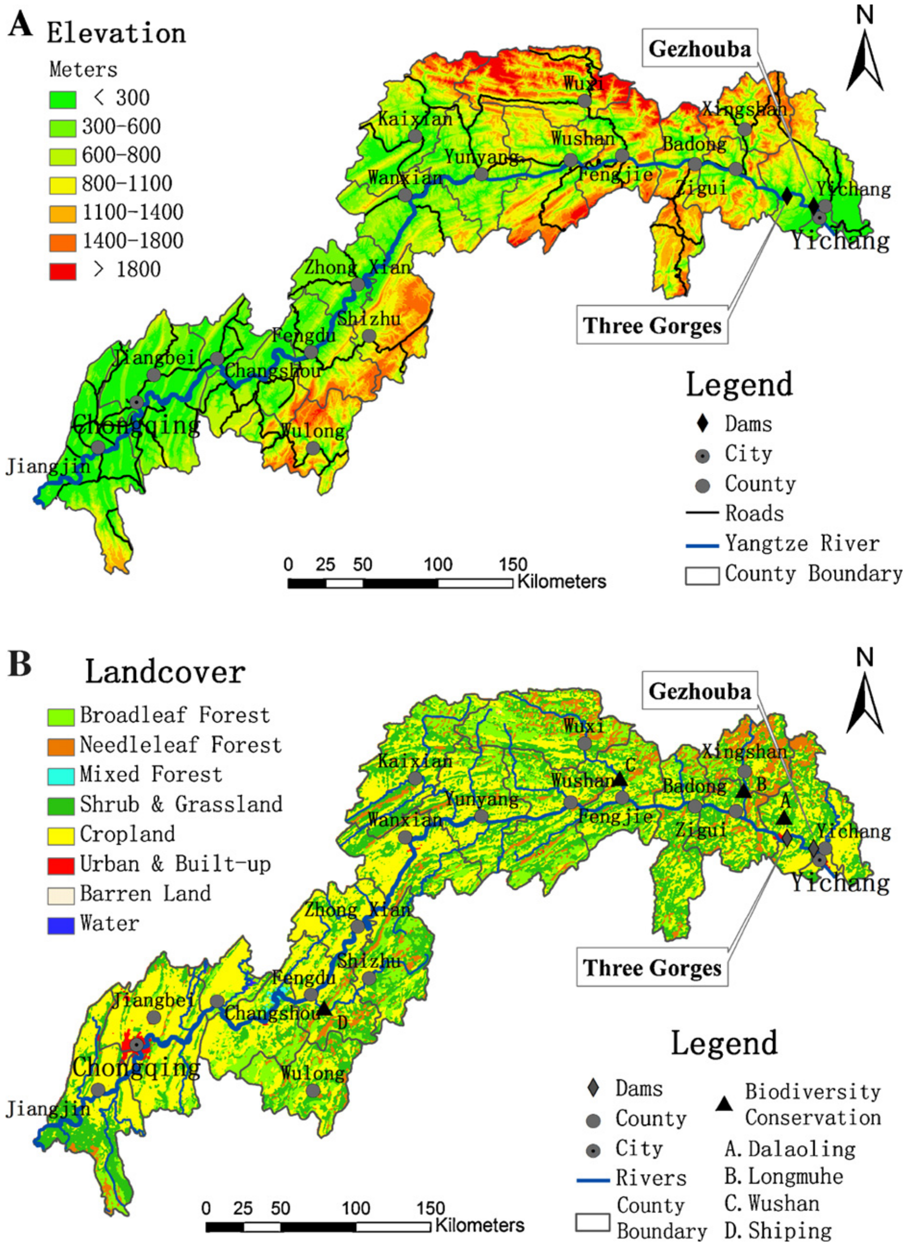


**Fig. 1 – The Location of the Three Gorges Dam, the Gezhouba Dam and the Three Gorges Reservoir Region (TGRR), China. (A) DEM and roads and (B) land use and land cover and locations for biodiversity conservation networks.**

22.1 billion m$^3$, increasing the flood control ability from the present 10-year to a 100-year frequency flood. It has installed a total generating capacity of 22,400 MW (100 billion kWh), equivalent to consumption of more than 60 million tonnes of raw coal annually, dramatically increasing energy supply for China's economic development. Meanwhile, the dam increases water depth by more than 100 m, effectively improving the navigability in the 600 km section of the Yangtze River between Yichang and Chongqing (Fig. 1A).

The TGD will form a reservoir with a total water surface area of 1080 km$^2$ in the Yangtze River between Chongqing and Yichang. The region surrounding the reservoir, with a total area of approximately 58,000 km$^2$, has now become known as the Three Gorges Reservoir Region (TGRR) (Fig. 1). Due to its unprecedented magnitude, the TGD has been controversial ever since its implementation. A comprehensive environmental impact assessment was conducted in the 1980s (RCEETG, 1987), and many of the predicted environmental problems have been realized recently by the partial filling of the reservoir in the past 5 years (RCEETG, 1987; Shen and Xie, 2004; Wu et al., 2004; Liu et al., 2006a,b; Xu et al., 2006; Zhang et al., 2006). Systematic monitoring since 1997 have also provided the evidence of environmental changes in the TGRR and downstream of the Yangtze Basin (http://www.tgenviron.org/).

Solving the environmental challenges surrounding the TGD will be essential for the sustainable development of the TGRR and remains a high priority for the country as well. However, any efforts will have to rely on the determination of the environmental changes in the region that are due to the construction of the TGD. The challenge has never been greater than now, indicated by the geological disasters (e.g., landslides) in the uplands and algal blooms in the aquatic environment that have occurred since the reservoir filled to 156 m in 2006 (Hu and Cai, 2006; Liu et al., 2006a,b; Ye et al., 2007; Fu et al., 2010), and the situation may be intensified when the reservoir reaches the final water level of 175 m in the next few years.

This article categorically summarizes the current status of the region based on environmental and ecological research, particularly those studies published in Chinese scientific literature. It presents the changes in biodiversity and associated conservation efforts, and it reassesses the environmental implications in the water environment, the water-level-fluctuation-zone, and the uplands after partial reservoir filling. In particular, mitigation strategies and conservation efforts are discussed. The ultimate objective is to help formulate strategies for the TGD management and environmental sustainability in the TGRR.

## 2. Biodiversity conservation

One of the most immediate consequences of the dam building is the loss and fragmentation of habitats due to both the inundation and the subsequent resettlement of the human population in new areas (Wu et al., 2004; Wang et al., 2006; Yang et al., 2006; New and Xie, 2008). As one of the biodiversity hot spots of China, the TGRR has nearly 6400 plant species (including cultivated varieties; 19.3% of the total number of species found in China), more than 3400 insect species (8.5% of the China's total), and about 500 terrestrial vertebrate species (22% of the China's total) (Huang, 2001). Because of its distinctive geographic location, complex topography and climatology, there are a number of endemic and ancient species in the terrestrial and aquatic environments of the TGRR (Chen et al., 1994, 2004; Xie, 2003). Ironically many unique species persisted during the Quaternary glaciations, yet the inundation and dam construction will be disastrous for many of these species and communities.

The inundation and the resettlement will affect at least 36 vegetation types, Fortunately most of them are considered to have low conservation or economic values, because they are mostly secondary shrub and grass communities that are widely distributed in other areas (Huang, 2001; Tian et al., 2007). Thus, conservation efforts have been primarily concentrating at the species level, with transplantation and conservation of more than 200 plant species including 37 threatened species in the TGRR. The conservation strategy has been following a strategy of ''introduction–propagation–reintroduction''. For instance, *Adiantum reniforme* var. *sinense* and *Myricaria laxiflora* are 2 species which are primarily distributed in the altitude of 80–480 m and 70–155 m in the Three Gorges valley from Yichang to Chongqing, respectively, areas which are largely impounded by the reservoir filling (Shi et al., 2005; Wang et al., 2003). Species like *Securinega wuxiensis* and *Neyraudia wushanica* will also lose their critical habitat (Huang, 2001; New and Xie, 2008). Without other viable options, those species were introduced into botanical gardens for *ex situ* preservation in early 1980s. A recent study has indicated that more than 85% of the species' genetic diversity has been preserved (Li et al., 2003). With the successful development of their propagation capacity including the sexual and asexual reproduction of individual plants (Lin, 1989; Xu et al., 1998), they have been reintroduced to their natural habitat with the objective of restoring the original communities that occurred before inundation in the TGRR (Chen et al., 1994).

The Yangtze River is also one of the richest areas in freshwater fish species diversity with 361 species, of which 177 are endemic. Up to 40 fish species have been affected due to interruption of their migratory paths and the loss of spawning grounds by the construction of the Gezhouba Dam (38 km downstream from the TGD) (Dudgeon, 2000; Fu et al., 2003). Sharp declines in the populations of three endemic ancient fish species namely the Chinese sturgeon (*Acipenser sinensis*), river sturgeon (*Acipenser dabryanus*), and Chinese paddlefish (*Psephurus gladius*) has been observed (Fu et al., 2003). Aquatic mammals, such as the Yangtze finless porpoise (*Neophocaena phocaenoides asiaeorientalis*) and the Chinese river dolphin (*Lipotes vexillifer*), which has nee recently categorized as ''functionally extinct'', are also seriously threatened (Wang et al., 2006; Turvey et al., 2007; Zhao et al., 2008). The TGD has further affected the survival of mammals due to the increased use of the river by shipping vessels, leading to physical injuries due to collision, and noise disturbance, as well as the changes in hydrological regime (Fu et al., 2003; Wu et al., 2004).

The impacts of dam construction on fish species and aquatic mammals seem inevitable (Rosenberg et al., 1997). Without adequate conservation measures to allow uninterrupted migration in the dam infrastructure (e.g., fish passages), conservation efforts have been focusing on identifying and establishing reserves for the endemic species in the tributaries of the upper Yangtze (Park et al., 2003). A program of artificial reproduction of endemic fish species has been performed for more than a decade. For plant species conservation, a program has been initiated recently to conserve three more endangered species, *Rhamnus tzekweiensis*, *Buxus ichangensis*, and *Plantago erosa* var. *fengdouensis* following the same strategy that has successfully preserved *A. reniforme* var. *sinense* and *M. laxiflora* (i.e., ''introduction–propagation–reintroduction''). Consequently, the efforts have also been shifted to the preservation of regional ecosystems with consideration of typical vegetation types (e.g., evergreen forests) and rare and endangered species in the region. An ecosystem conservation network has been developed in the TGRR including Dalaoling (Yichuang City, Hubei Province), Longmuhe (Xinshan County, Hubei Province), Shiping (Fengdu County, Chongqing), and Wushan (Wushan County, Chongqing) (Fig. 1). The three former sites are intended for evergreen forest preservation and Wushan is specifically for the conservation of vegetation on Karst.

## 3. The water environment

Pollutants of the Three Gorges Reservoir (TGR) primarily result from (1) runoff from the upper steams of the Yangtze, (2) industrial and domestic wastewater and agricultural runoffs in the TGRR, (3) waste materials from shipping, and (4) internal sources of pollutant from toxic industrial sediments left behind as the TGD filled (Liu et al., 2006a,b; Zhu et al., 2006). In 2006, the industrial and domestic wastewater released into the TGR from the TGRR was 1.124 billion tonnes, and fertilizer and pesticide application for agriculture (a total area of 977,700 ha) in the region was 154,000 and 655.47 tonnes, respectively. After the reservoir filled, increased shipping added an additional 3.8 million tonnes of waste materials into the reservoir (SEPA, 2009). The dam itself does not necessarily contribute to an increase in pollutants in the reservoir, but related activities including resident relocations, reservoir filling and mitigation strategies may have affected the water environment of the reservoir.

The authorities have been implementing an ambitious plan to build a total of 20 waste treatment plants in the TGRR to control the point-source pollution into the reservoir. The treatment facilities have the potential to treat at least 85% of sewage and garbage by 2010, dramatically reducing inputs of industrial and domestic pollutants from the TGRR into the Reservoir. Low treatment rates persist, despite the new capacity, due to inadequate financial support for facility operation and lack of wastewater collection pipelines, so untreated wastewater is still going directly into the river and finally to the reservoir.

A huge amount of toxic sediment from factories, mines, and garbage dumping sites remained on site after relocation of some 1.4 million people. There will be increasing internal source of pollution with toxics including arsenic, sulfides, cyanides and mercury from these sources remaining in the reservoir after it fills (Yu et al., 2006; Zhang et al., 2006; Ye et al., 2010). Although the government had campaigned to clean up the banks and the waste sites of the reservoir before the reservoir filling, the efforts have not completely decontaminated toxic wastes. Meanwhile, contaminated sedimentations from upstream will accumulate in the reservoir as the water level rises (Zhou et al., 2006).

The water chemistry of the reservoir has generally been stable since the reservoir began filling in 2003 (SEPA, 2009; Zhang et al., 2005; http://www.tgenviron.org/). Yet, algae blooms, an indicator of water quality, have frequently occurred since this time. Intensive studies have been carried out on the reason for these blooms in the Xiangxi River (Hubei) and Daning River (Chongqing) (Ye et al., 2007). It has been concluded that the occurrence is largely attributable to the accumulation of nutrients triggered by the change in the hydrological regime (Hu and Cai, 2006; Zeng et al., 2007). The water flow in the TGRR has been dramatically slowed down by the reservoir filling. Thus, the pollution could not be diluted and flushed to the sea as such has occurred for thousands of years before damming. Wastes, especially nutrients from the upper streams of the tributaries in the TGRR, have accumulated in the bays. Thus, algal blooming would be inevitable without substantial reduction of nutrients from the upper streams of the tributaries (Hu and Cai, 2006; Bi et al., 2010). Currently, there is any effective measure to control algae bloom and developing new prevention techniques are in high demand.

## 4. The water level fluctuation zone (Wlfz)

Perhaps the most visible change due to the reservoir filling would be the formation of a Yellow Belt along the riverbanks of the mainstream and tributaries in the TGRR. The full functional Reservoir would have a water level fluctuating between 145 m and 175 m, i.e., 145 m in summer (May–October) for flood control and 175 m in winter (November–April) for energy generation. The area between the high (i.e., 175 m) and low (i.e., 145 m) water level is called the water level fluctuation zone (WLFZ). A recent study has estimated the total area of the WLFZ in the reservoir is ca. 350 km$^2$ primarily composing of agricultural lands (30%), bare lands (40%) and urban areas (10%) before inundation (Zhang, 2008). For such a large area in the terrestrial-aquatic ecotone of the TGRR, its environmental implications should not be underestimated (New and Xie, 2008).

In this newly formed ecotone, the previous habitat is terrestrial, and the hydrological regime is the opposite of the natural one, with post-dam flooding occurring in winter rather than summer. Plant species adapted to previously terrestrial habitats would disappear and few species are expected to survive in the novel habitats, leading to potential invasion by exotic species, soil erosion and sedimentation, and the loss of amenity value for tourism in the TGRR (Zhao et al., 2007; New and Xie, 2008). Geological disasters including soil erosion and land sliding are likely to be intensified, threatening the safety of human life and property (Xu et al., 2006; Wang et al., 2008). Intensified agricultural activities due to relocation of the human population will certainly increase the pollutants into the reservoir (Xu et al., 2005). Wastes accumulating from the uplands and upstream in summer will be exposed in the WLFZ and subject to high temperature, becoming an ideal place for the propagation of bacteria, virus, and other pathogens; the occurrence of epidemic diseases is a great possibility (Su et al., 2003). The alteration of ecosystem construction and function will have significant consequences for human well-being (Kittinger et al., 2010).

There are few options available for meeting the challenges and demands for ecosystem restoration in the WLFZ. Currently, civil engineering approach, i.e., using concrete surface for slope protection and soil erosion control, has been widely applied in particular for slope stabilization in urban areas along the mainstream of the Yangtze River. However, building of concrete surface is costly and its resultant landscape is incompatible with the natural scene in the Three Gorges. Thus, civil engineering approach is not desirable in terms of cost, tourism and the environment. Revegetation of the WLFZ is an environmentally friendly alternative but would be challenging. The greatest challenge is that few species are expected to survive in an annual cycle of the aquatic–terrestrial environment with half a year under inundation as deep as 30 m (Zeng et al., 2007; Fan et al., 2006; Tan et al., 2010). Since 2000, research has been conducted to determine the suitability of potential plant species for the novel habitat in the WLFZ. A number of species including *Cynodon dactylon* and *Salix variegata* have showed their potential (Tan et al., 2010). Recently, revegetation demonstration projects have been carried out with success in Zhong County, Wanzhou District of Chongqing Municipality and Zigui County of Hubei Province.

Because of the water fluctuation level of 30 m and enormous demands of land for economic development in the TGRR, new approaches including integration of ecological and engineering procedures have been proposed and implemented in Kai County and Fengjie County of Chongqing. These options may be an applicable option particularly in the urban areas and tributaries for environmental restoration in the WLFZ. These proposals include building small dams to stabilize the water level to ~170 m in the tributaries, reducing the water fluctuation level to 5 m in the WLFZ and maintaining a minimum water level for wetland formation. The environmental restoration will therefore focus on a rather easier task of wetland restoration. However, water quality in the small reservoir is still of great concern and these projects will reduce the water storage capacity for flood control, one of the primary objectives of the dam construction.

## 5. The uplands

Geographically, the TGRR is located in the transitional zone from the Tibetan Plateau in the west to the east rolling hills and plains of China. 96% of the total landscape areas (i.e., approximately 85,000 $km^2$) are mountains and hills, and about half of them are forested lands, shrubs, and meadow (Zhang et al., 2009). Most of the vegetated lands are intensively degraded (Zhang et al., 2007). Agricultural lands, with only 0.07 ha/person, are often located in the mountainous region. Due to the low soil quality and extensive soil erosion, the massive use of fertilizers causes releases of large quantity of nitrates and phosphates, increasing their concentrations in the reservoir and consequently leading to eutrophication (Li et al., 2005; Liu et al., 2006a,b). Non-point source pollutants are increasingly becoming the primary pollutants of the reservoir (SEPA, 2009).

There are close to 1.4 million migrants who have been resettled due to the dam construction, and most of them have been moved to the steep hills of the TGRR. Relocation of towns, manufacturers, and temporary land usage for construction has cleared large areas of previously vegetated and agricultural lands. Land reclamation to compensate for the losses of productive agricultural lands to the impoundment has led the intensification of the human–land conflict, also compromising the reforestation efforts in the TGRR (Jackson and Sleigh, 2000; Heming et al., 2001; Zhang et al., 2007). Moreover, these activities will profoundly increase non-point source pollution into the reservoir (SEPA, 2009), and cause rampant soil erosion, riverbank collapses and landslides along the shores of the Yangtze's mainstreams and tributaries, leading further deterioration of the environment.

The TGRR has been one of the primary regions for national ecological restoration projects. The "Natural Forest Conservation Program", "Protective Afforestation along the Upper and Middle Reaches of the Yangtze River", and "Conversion of Cropland to Forest Program" have been implemented, and arable lands of 1810 $km^2$ have been transformed into forests between 1992 and 2002 (Zhang et al., 2007). Additionally, in partnership with local authorities and NGO's an experimental project in Yunyang County of Chongqing Municipality has been implemented as a demonstration of the "Green Belt" establishment in the TGRR since 2004 and that has successfully transformed over 400 ha of bare land into forest plantations. The effort has taken a traditional approach in terms of technology but the partnership with participation of various stakeholders has shown the model for the ecological restoration applicable for the entire TGRR.

Reforestation of large land areas has many obstacles, in particular resistance from local residents because of competition for land in the TGRR. Thus, a new concept known as "Ecological Shelter" has been developed for environmental restoration in the TGRR (Liu, 2007). While reforestation remains the primary objective, the effort will demonstrate sound practices both economically and environmentally for ecological restoration by planting native species with immediate economic values or/and abilities to absorb large quantity of nutrients and reduce soil erosion (Ng et al., 2008). It will also consider all the elements including vegetative lands, agricultural lands, townships in the landscape matrix and economic activities such as forestry and poultry for the ultimate objective of non-point pollution control. Additionally, integrative watershed management has implemented in the TGRR aiming at reducing nutrients into the reservoir from the upper streams into the reservoir.

## 6. Implications

Large-scale hydroelectric development has far-reaching social, economic and environmental implications (Rosenberg et al., 1997). As the TGRR is located in a rather ecologically fragile region and China's society and economy in a rapid transitional motion, the environmental changes in the TGRR would be dramatic. Due to the scale of the TGD, many changes are unprecedented such as formation of "Yellow Belt" with a total area of ca. 350 $km^2$ along the riverbanks in the TGRR. Thus, systematic monitoring on all aspects of the environment has been carried out since 1997 (http://www.tgenviron.org/).

Conservation of endangered and rare species in particular plants, aquatic mammals and fishes are of great concern surrounding the TGD. Known endangered plant species have been successfully preserved through *ex situ* programs and ongoing projects on the artificial breeding for fishes continuously increase their population in the Yangtze River. Yet, great challenge remains for the conservation of aquatic mammals. Establishment of nature reserve seems not quite effective, participation of international community with new approaches, ideas and technologies is urgently demanded.

In order to improve the water environment, there are great needs to reduce waste inputs from all sources into the reservoir. Yet, there lacks operational fund for sewerage treatment which can reduce industrial and domestic wastewater, and the reservoir filling will destabilize the river banks and increase the internal sources of pollutants due to sedimentation. Reduction of agricultural runoffs requires economic structure adjustment, such as transforming from land-based to knowledge-based economy, which will take decades, and waste materials from shipping and internal sources of pollutants from toxic industrial sediments will only increase by the improved navigation condition and periodic flooding in the reservoir, respectively. All those challenges will remain for the time being until more resources are allocated into the water conservation in the region.

Never a water-level-fluctuation-zone of a reservoir is as large as the one in the Three Gorges Reservoir. To restore the riparian ecosystem, revegetation is quite successful and the technology is capable of establishing vegetation in the novel habitat. Yet, unregulated agricultural activities and possible accumulation of wastes will degrade the environment in the WLFZ. Periodic flooding will destabilize the structure of soil and rocks, causing soil erosion and land sliding. It may take decades for the geological structure to reach a new stable state.

Due to all the constraints and challenges, the environment in the TGRR could only get worse in short term. Knowledge and new technology outside of China on the hydroelectric projects may provide reference to the TGD and help develop strategy for environmental conservation in the TGRR. Thus, building a partnership among TGD stakeholders, including local residents, Chinese government, and international communities is necessary to meet the mounting environmental challenge in the TGRR and finally demonstrate the capacity of humanity to reach sustainable development solutions.

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