Chapter 3
Environmental Impacts of Dams in China: Focusing on Biological Diversity and Ecological Integrity

3.1 An Overview of Environmental Problems Caused by Dams in China

With the growing awareness concerning the environmental impacts of coal-fired power plants, China has shifted to exploiting hydropower, a cleaner energy resource. China has become the world's largest hydropower producer having built some 87,000 dams and reservoirs, about one-third of which are for hydroelectricity production. According to an estimate by the Chinese Government, the Three Gorge Dam can generate the equivalent amount of electricity as burning 50 million tons of coal annually, thus reducing greenhouse gas emissions by100 million tons of carbon dioxide, 1.2–2 million tons of sulfur dioxide, and 10,000 tons of carbon monoxide as well as eliminating the release of large quantities of particulate matter (Xinhua News Agency 2007). However, many argue that hydroelectric power should not be considered a renewable energy source because of the irreversible environmental damages caused by these projects. The environmental debate concerning the construction of large dam is not new in China and has been ongoing for decades since the first large Soviet-style dam, Sanmenxia Dam, was built in 1957 on the main channel of the Yellow River. As Shapiro (2001) states about the Chinese hydraulic engineer, Huang Wanli, who fought against dams, "Many years of his own practical research conducted on the Yellow and other major rivers had shaped his conviction that damming the main streams of large waterways ran contrary to the laws of nature."

The environmental impacts caused by large dams in China are no different than those that occur in other parts of the world (see Sect. 1.3). China also has some additional environmental concerns, such as an increased danger of landslides and earthquakes in areas of high seismicity, such as Western China. More than 130 large dams are being built in western China with 98.6 % of these located in moderate to very high seismic hazard zones (Probe International 2012). Here, we synthesize the key environmental impacts caused by large dams constructed along eight major

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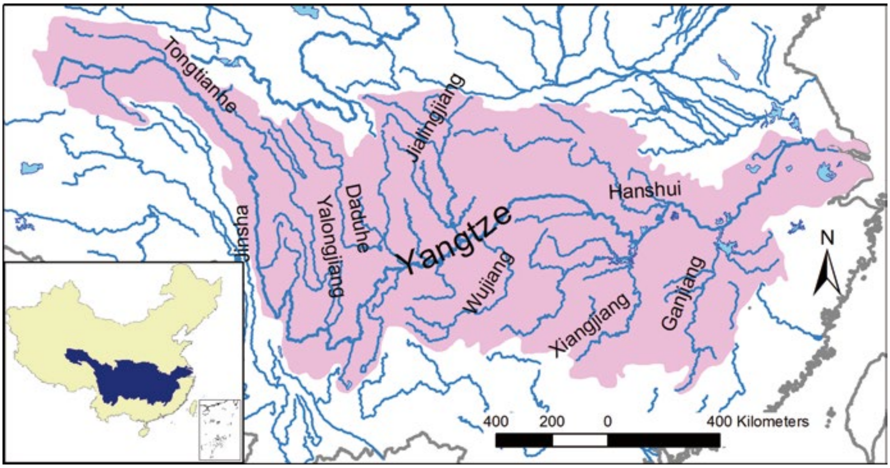

Fig. 3.1 Map of the Yangtze River Basin

river basins in China, with particular focus on ecological impacts. In the following Sect. 3.2, we specifically discuss the effects of large dams on biological diversity and ecological integrity to support a case study presented in Sect. 3.3.

3.1.1 The Yangtze River Basin

The Yangtze (also called Chang Jiang) is the longest river in China and all of Asia, and the third longest in the world. It originates in the glaciers on the Qinghai-Tibetan Plateau and flows 6,418 km south and then eastward across southwest, central, and eastern China before emptying into the East China Sea at Shanghai, one of China's largest cities (Fig. 3.1). The basin is home to 400 million people, making it one of the most densely populated river basins anywhere on earth—with an average population of 214 people per km^2 (WRI et al. 2003). The Yangtze River Basin is already highly fragmented by a significant number of dams over 15 m high, including one of the world's largest, the Three Gorges Dam. The additional 46 dams planned or under construction will put further pressure on an already stressed basin (WWF 2004).

Alteration of the flow regime is one of the biggest environmental issues associated with dam construction along the Yangtze River. Building of the Three Gorges Dam has been widely criticized since the most severe drought in Yangtze River Basin in the history was recorded in 2011 (Lu et al. 2011), although the debate of "to build or not to build" has lasted for decades (Dong 2005). Soon after the droughts, torrential rains triggered floods and landslides causing massive economic loss and environmental damage (Xinhua News Agency 2011). While it was believed that the Three Gorges Dam was built to control floods, generate clean energy, and improve irrigation capacity, the severe downstream flood and drought have put a question mark on its flood control objectives (Ran et al. 2012). The Chinese Government conceded that there were some problems associated with the Three Gorges Dam project in their statement, "Although the Three Gorges Dam project provides huge comprehensive benefits, urgent problems must be resolved regarding the smooth relocation of residents, ecological protection and geological disaster prevention" (New York Times 2011).

Siltation in the reservoir is another problem associated with dams in the Yangtze River Basin. For example, an estimated 530 million tons of silt already has accumulated in the reservoir of the Three Gorges Dam due to the reduced flow velocity behind the dam (Mount Holyoke College 2007). The rising silt levels could potentially block the sluice gates that are essential for controlling water levels behind the dam, which could cause more flooding to occur upstream in the event of a heavy rainfall (Mount Holyoke College 2007). Also, reduced downstream sediment flows may negatively impact downstream floodplains, such as the Jianghan (Yangtze River and Hanjiang River) Plain and Dongting Lake Plain (Li et al. 2000), threatening these floodplain areas.

The reservoir acts as a trap for debris, pollutants, and toxins being carried by the river contaminating the water (Mount Holyoke College 2007). Approximately ten million tons of plastic bags, bottles, animal corpses, trees, and other detritus that would have otherwise flowed downstream and out to sea have accumulated behind the Three Gorges Dam. The reservoir itself flooded 1,600 abandoned factories, mines, dumps, and potential toxic waste sites. More than 265 billion gallons of raw sewage are dumped into the Yangtze River leading to frequent algal blooms and eutrophication throughout the basin (People's Daily 2007). The untreated wastes, together with other nonpoint pollutants from agriculture and point pollutants from industries (Sichuan Daily, 2004), have already made the Yangtze River one of the most polluted rivers in the world (Fig. 3.2). In addition, the decomposition of vegetation and organic materials accumulated in the dam's reservoir is source of greenhouse gases. Although the methane emission rate in the Three Gorge reservoir is relatively low (0.26 ± 0.38 mg CH4 m^2/h) compared with other hydropower reservoirs (Chen et al. 2011), the total amount released is high due to the large surface area of the reservoir.

Increased risk of landslides and earthquakes are current environmental concerns associated with the Three Gorges Dam. Since construction of the dam, a total of 36 km of shoreline in 91 locations has collapsed with some landslides triggering 50 m-high waves on its reservoir (Mount Holyoke College 2007). In Fengjie County, upstream of the Three Gorges Dam, there are more than 800 disaster-prone areas and the potential for geological catastrophe is threatening the lives of millions of residents (Mount Holyoke College 2007). Additionally, in the upper Yangtze River Basin, an area of high seismicity in Western China, reservoir-induced seismicity is likely to increase the frequency and perhaps magnitude of earthquakes (Probe International 2012). In the event of an earthquake or dam collapse, over 360 million people who live within the watershed of the Yangtze River will be in danger (Mount Holyoke College 2007). For example, the Zipingpu Dam built in a moderate seismic zone in the upper Yangtze River Basin is now thought to have triggered the

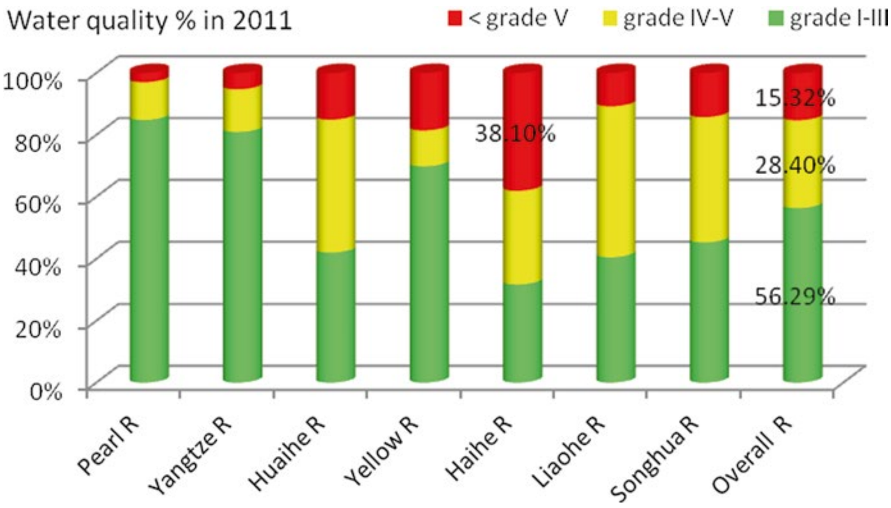

Fig. 3.2 Fresh water quality in China: an overall grim situation of water quality in major rivers in 2011 (Adopted from http://asianfootprint.blogspot.com/2012/11/fresh-water-environment-in-china.html). *Note*: China uses a six-grade classification scheme for water quality. Grade I and II are the best. Water no worse than grade III can be used for drinking. Grade V can be used for irrigation. Water less than grade V cannot be used for irrigation

magnitude 7.9 Sichuan earthquake in 2008 that killed an estimated 80,000 people (Mount Holyoke College 2007).

The Yangtze River Basin has a biologically rich terrestrial and freshwater flora and fauna that originated from tropical, subtropical, and temperate zones (Wu et al. 2004). Environmental alterations associated with large dams may result in a number of regional changes in terrestrial and aquatic biodiversity as well as ecosystem structure and functioning (Wu et al. 2004). With the completion of the Gezhouba Dam in 1981, 40 km downstream from the Three Gorges Dam site, there was a rapid and sharp decline in the populations of three of China's most famous ancient and endangered fish species, the Chinese sturgeon (*Acipenser sinensis*), the river sturgeon (*Lipotes vexillifer*), and Chinese paddlefish (*Psephurus gladius*) (Xie et al. 2003). Below the two high head dams, Xinanjiang Dam (Qiantang River) and Danjiangkou Dam (Han River), fish spawning has been delayed for 20–60 days due to lower water temperatures (Zhong and Power 1996). Changes in the flow regime resulted in the extinction of *Macrura reevesii*, a highly valued fish, in the Qiantang River. The Three Gorges Dam marked the upper limit in the distribution of the Yangtze River dolphin or Baiji dolphin (*Lipotes vexillifer*), which is the most threatened cetacean in the world (IUCN 2002). The construction of the Three Gorges Dam and other large dams on tributaries in the middle reaches of the basin are exacerbating pressures on the remaining population of these dolphins (Revenga 2003). In 2006, scientists exploring the Yangtze River failed to find a single Baiji dolphin prompting fears that mankind may have killed off its first species of cetacean (The Guardian 2007).

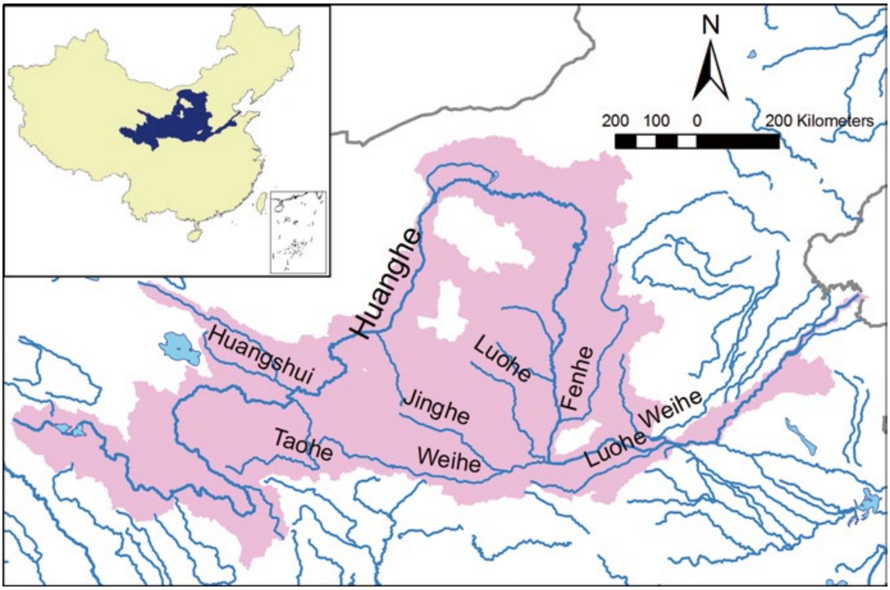

Fig. 3.3 Map of the Yellow River Basin

Waterfowl also are impacted by large dam construction in the Yangtze River Basin. For example, the rich mudflats of Poyang Lake are the major wintering sites of the Siberian crane (*Grus leucogeranus*), with 95 % of the population overwintering there. However, habitat loss in the lake associated with the construction of the Three Gorges Dam now poses a major threat to this endangered bird species (WWF 2004). In addition, dams can alter the riparian zone along a river leading to the destruction of riparian vegetation and degradation of waterfowl habitats. As a consequence, riparian biodiversity can be lost. For example, 400–770 vascular upstream plant species will be flooded when the Three Gorges Dam reaches its planned maximum water level (Wu et al. 2004). Two plant species, *Myricaria laxiflora* and *Adiantum reniforme* var. *sinese* likely became extinct due to inundation (Xie et al. 2006); two other species, *Securinega wuxiensis* and *Neyraudia wushanica*, lost critical habitat (Huang 2001).

3.1.2 The Yellow River Basin

The Yellow River (also called Huang He) originates in the Bayan Har Mountains in Qinghai Province in western China and is the second longest river in China and the sixth longest in the world (Fig. 3.3). It flows through nine provinces and empties into the Bohai Sea, with an estimated length of 5,464 km. The Yellow River is called “China’s Mother River” or “the Cradle of Chinese Civilization” as its basin was the birthplace of ancient Chinese civilizations and the most prosperous region in early Chinese history. This river already is heavily dammed and an additional eight large dams are planned or under construction, which will put further pressures on the basin (WWF 2004).

Like the Yangtze River, alteration of the flow regime is one of the biggest environmental issues associated with dam construction along the Yellow River. Ouyang and colleagues' (2011) study of the Longliu section (from Longyangxia to Liujiaxia) of the upper reaches of the Yellow River showed that after the construction of eight cascade dams (Longyangxia, Nina, Lijiaxia, Zhiganglaka, Kongyang, Gongboxia, Suzhi, and Liujiaxi) between 1977 and 2006, peak streamflow shifted from June to May and October. Furthermore, the maximum monthly streamflow velocity difference between the inlet and outlet of the Longliu Section decreased from 430 to 115 m^3/s (Ouyang et al. 2011). Such dramatic changes in the natural flow regime of the river can have important consequences on water availability downstream. Water diversion for irrigation and other uses combined with dams and their operation have resulted in the lower reaches of the Yellow River drying up. The river has dried up 30 times since 1972 with the longest period of no-flow lasting for 230 days in 1997 (He et al. 2012). Timely releases of reservoir water have prevented the river from drying up since 2000.

Sedimentation is a serious problem in the Yellow River Basin. The river gets its name from the yellow silt it picks up in the Shaanxi Loess Plateau and it has a naturally high sediment load. Because of these high sediment loads, the river is prone to flooding; silt is deposited on the riverbed causing the river levels to rise. Levees have been built along the lower 800 km of the river to contain the water, but the riverbed continues to rise and the river is now elevated above the surrounding landscape (Wang et al. 2007b). The levees along the "suspended river" have to be continuously raised and consolidated to constrain water flow within the channel (Ran et al. 2012), and any breach in a levee will result in massive flooding. The first major water control project on the Yellow River was the Sanmenxia Dam constructed in 1957–1960 in the middle reaches of the Yellow River. As discussed earlier, the dam was poorly designed and did not account for the high sediment loads carried by the river, and the reservoir silted up 2 years after it began operation causing floods in upstream areas and threatening river navigation (Wang et al. 2005). To mitigate the negative impacts of sedimentation on reservoir storage capacity and downstream flow regimes, the dam has been reconstructed to provide high sediment releasing capacity, and dam operation has achieved a balance between sediment inflow and outflow (Wang et al. 2005). Subsequently, the Xiaolangdi Dam, China's second largest dam, was built downstream of the Sanmenxia Dam to control flooding by slowing the dangerous build-up of silt on the lower reaches of the river (Hays 2009).

Dams are having a negative impact on the water quality of the Yellow River Basin as pollutants accumulate behind dams instead of being flushed downstream (Hays 2009). The Yellow River travels through major industrial areas including thousands of petrochemical plants, large population centers, and China's major coal producing area. Over 30 % of water samples taken from the Yellow River in various places registered worse than Level 5, meaning the water was unfit for drinking, agriculture, or industrial use (Fig. 3.2). Four billion tons of wastewater, which is 10 % of the river's volume, flows annually into the Yellow River (Hays 2009), making it the most polluted river in the world.

Reduced water flow, severe pollution, dams blocking fish migration routes, and overfishing are threatening fish diversity in the Yellow River Basin. An unnamed agriculture ministry official in China said, "The Yellow River used to be host to more than 150 species of fish, but a third of them are now extinct, including some precious ones" (The Guardian 2007). According to a survey conducted by the People's Daily, catches of fish have fallen 40 % from an annual average of 700 tones (The Guardian 2007). In addition, terrestrial plants and animals in the basin also can be impacted by land use/cover changes associated with the construction and operation of dams. Large dam projects in the Yellow River Basin threaten four critical habitats for endemic birds and one wetland of international significance according to the Ramsar Convention on Wetlands (WWF 2004). Construction of the cascade of dams in the Longliu Section (from Longyangxia to Liujiaxia) of the upper reaches resulted in the loss of large areas of grassland (Ouyang 2011).

3.1.3 Lancang River Basin

The Lancang (Upper-Mekong) River situated in southeastern Eurasia with a length of 4,909 km originates as Guyong-Pudigao creek near the foot of Mt. Jifu on the Qinghai-Tibet Plateau and discharges into the South China Sea (Liu et al. 2007). It is a famous transboundary river and is commonly divided into two parts: the Upper-Mekong River Basin, including portions in China (called Lancang River in Chinese) and Myanmar; and the Lower-Mekong Basin, including portions in Laos, Thailand, Cambodia, and Vietnam (MRC 2010). This river remains mostly undammed on the mainstream, except for eight cascading hydropower dams constructed along the Upper-Mekong River in China (Nilsson et al. 2005; Grumbine and Xu 2011) (Fig. 3.4). Another 11 dams have been proposed on the Lower-Mekong River in Laos as of September of 2010 (Grumbine and Xu 2011).

Alteration of the flow regime has been widely documented as a major environmental impact of large dams in the Upper-Mekong River Basin. Recent research shows that the overall degree of hydrologic alteration associated with dam construction and precipitation variation is 25.2, 25.3, and 29.1 %, respectively, for the upstream, midstream, and downstream areas of the Manwan Dam (located in middle reaches of Lancang River) (Zhao et al. 2012a). He et al. (He et al. 2007) found that the Manwan and Dachaoshan dams can influence the downstream flow regime of the Mekong River, but their impacts are insignificant in scale compared to changes in natural daily flow stages and is limited geographically to the narrow channel north of Vientiane. He et al. (2007) further stressed that the water flow below the Yunjinghong hydrologic station (located in lower reaches of the Lancang River) is only 15.4 % of total flow in the Mekong River, and the primary factor changing the flow volume in the Lower-Mekong River is climate variability rather

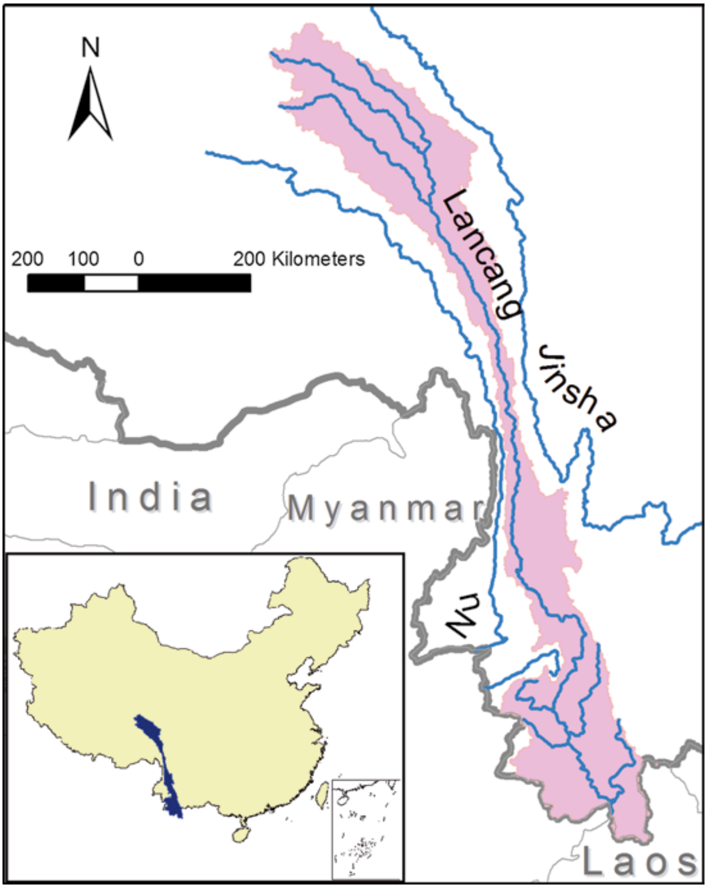

Fig. 3.4 Map of the Lancang (Upper-Mekong) River

than upstream dam construction and operation. Li et al. (2006) reported that the normal operation of the cascading dams of Manwan, Dachaoshan, and Jinghong in the upstream reaches of the Lancang River has minor interim effects on downstream monthly and annual water levels, but may have major impacts on short-term daily water levels.

Sedimentation of the dams in the Lancang River Basin has also been well studied. Fu et al. (2008) found that over the 11 years since the Manwan Dam started to store water in 1993 when the Dachaoshan Dam began to store water in 2003, the annual mean sediment storage in the Manwan Reservoir was about 26.9–28.5×10^6 tons, equivalent to a loss of 21.5–22.8 % of the reservoir's total storage capacity. Liu et al. (2012) reported a remarkable reduction in annual sediment load at the Gajiu hydrological station (located downstream of the Manwan Dam) after the Manwan hydropower station was put into operation in 1995, declining to over

60 % of the mean pre-dam value. Both Fu et al. (2008) and Liu et al. (2012) found there were poor correlations between upstream and downstream sedimentation at the dammed sections of the river, indicating that a large dam in the upper reaches of a river may have little effect downstream sedimentation.

Water pollution associated with the large dams in the Lancang River Basin has not been well studied. However, recent research has shown that there is the potential risk of heavy metal contamination in the sediments of the reservoir of the Manwan Dam due to the accumulation of As, Cd, Cr, Cu, Pb, and Zn in sediments that were measured at levels above the threshold established by both the United States and Canada. Moreover, the concentration of Hg in the Manwan Reservoir exceeded recommended levels of water quality standards in China, indicating that the dam may be impacting the water quality through the accumulation of heavy metals in the reservoir's water (Zhao et al. 2012c).

Habitat degradation and biodiversity loss in both aquatic and terrestrial ecosystems are another major environmental cost of constructing dams in the basin. This region is characterized as a biodiversity hotspot and a fragile ecoregion (Zhao et al. 2012c). Altered flow regimes, sedimentation, and pollution will degrade the feeding and breeding habitats of fish along the Mekong River (Kummu and Sarkkula 2008; Kang et al. 2009). Moreover, the dams are physical barriers for fish migrations. As many as 40–70 % of the fish species in the Mekong River migrate long distances along the mainstream and into its tributaries (Barlow et al. 2008; Baran and Myschowoda 2009; Kang et al. 2009). Although the impacts of dams on the upper reaches (Lancang River) of the river basin and on individual tributaries will be restricted to the fish populations that use these reaches, these populations contribute substantially to fish production along large stretches of the river (Poulsen et al. 2002). Dugan and colleague's (2010) review showed that current moves towards dam construction on the Mekong River will not stop; therefore, innovative technology and conservation strategies are needed to reduce the loss of fish diversity and ecosystem services provided by the river. For example, two tributaries of the upper reaches of the Lancang River, the Buyuan and Nanla rivers, are important feeding and spawning habitats for upstream migrant fish species and should be protected (Kang et al. 2009).

Dam construction and operation has led to land use/cover changes, alterations in water levels, thermal stratification, and water quality deterioration, all of which may influence the structure and function of riparian vegetation (Li et al. 2012a). The series of hydropower dams can induce habitat fragmentation, reduce the distribution ranges of primary vegetation, reduce the complexity of the vegetation types along the river, and potentially lead to the loss of primary vegetation in the whole watershed (Li et al. 2012c). Two endangered shrub species, *Homonoia riparia* and *Phoenix roebelenii*, are currently threatened by the dam impoundment (Li et al. 2012a), and one aggressive exotic species with extremely strong invasion capabilities, *Eupatorium adenophorum*, has spread rapidly along the riparian corridor below the Manwan Dam when the water level drops in association with the operation of the dam (Li et al. 2012d).

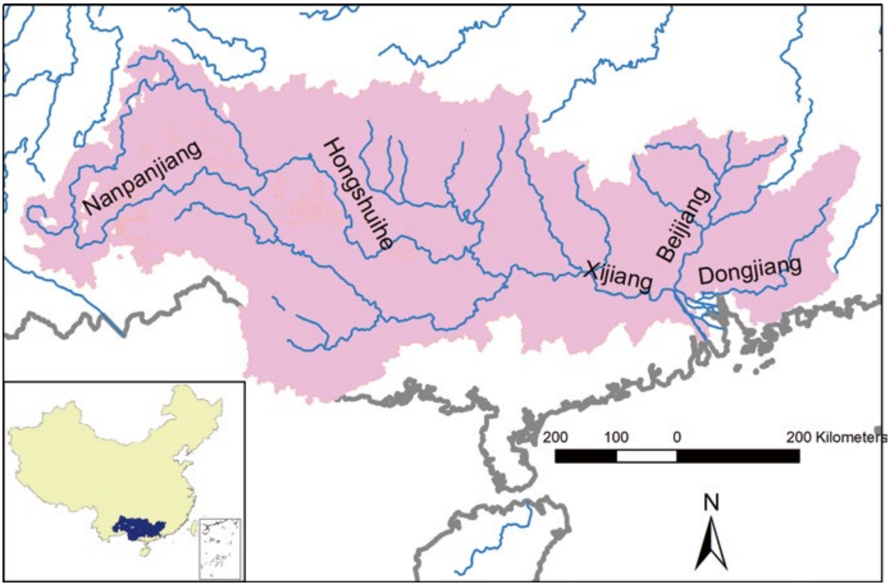

Fig. 3.5 Map of the Pearl River Basin

3.1.4 Pearl River Basin

The Pearl River (also called Zhu Jiang) is China's third longest river (2,400 km, after the Yangtze River and the Yellow River), and second largest by volume (after the Yangtze). It is the largest river in southern China, flowing to the South China Sea between Hong Kong and Macao (Fig. 3.5). The river basin drains the majority of south central China, as well as parts of southwestern China and northeastern Vietnam (The Ministry of Water Resources 2013). There are a large number of existing dams and another ten are under construction (WWF 2004).

Similar to other large dam projects in the major river basins of China, the dams in the Pearl River Basin have similar environmental impacts of flow regime alteration, sedimentation, pollution, ecosystem degradation, and loss of biodiversity. Since the 1960s, increased dam building and water extraction through diking have changed land use and land cover affecting the surface runoff pattern in the basin with a gradual rise in the water table, especially in the estuary areas (Weng 2007). In addition, unregulated sediment mining associated with dam building and dike linking has changed the longitudinal profiles of the river channels affecting flood discharge and causing the penetration of saline water (Qian 2005; Wang et al. 2005). The third largest dam in China, the Longtan Dam, was completed in 2009 on the Hongshui River, a tributary of the Pearl River. Siltation is a concern and local officials stated "deforestation in the area has caused severe erosion and power stations downstream are already facing serious problems because of silting" (BBC 2001).

Although the impacts of dams on the water quality of the Pearl River Basin are poorly known, the river suffers from serious water pollution. According to the National Marine Environmental Monitoring Centre, the Pearl River dumps 8,655 tons of heavy metals, 65,637 tons of nitrates and ammonia, and 59,853 tons of petrol into the sea each year (AsiaNews 2005). As reported by China Daily (2011), China's Fishery Eco-environment Report tallied 165 pollution incidents in the Pearl River in 2009, leading to economic losses totaling 56 million yuan (US$8.6 million). Undoubtedly, as seen elsewhere, pollutants can accumulate in the sediments and water behind large dams. As a consequence, the Pearl River is becoming one of the most polluted waterways in China.

The basin has a rich amphibian diversity with 127 recorded species, and a large bird population with four endemic bird areas that host migratory species which traverse the East Asian Australasian flyway (WRI et al. 2003). There is concern that these populations might be negatively impacted by the dams. In addition, two endemic fish species, the Chinese gizzard shad (*Clupanodon thrissa*) and Reeve's shad (*Tenualosa reevesii*), have disappeared altogether from the regulated parts of the river, and the populations of major carp species (such as *Cirrhinus molitorella*) no longer sustain a viable fisheries industry. A China Daily (2011) interview reported that, "Anadromous fish, which live in the sea but swim upriver to reproduce, have been forced to spawn before arriving at the best sites … because traditional grounds are blocked by hydro projects; as a result, their young have slimmer chances of surviving, largely because their migration routes back to the ocean are not long enough to allow them to mature." It was also noted that "there have been no recorded catches of Chinese sturgeon in recent years, although about 400,000 kg of the sturgeon were produced each year in the 1930s in the Xi Jiang alone" (China Daily 2011).

3.1.5 Huai River Basin

The Huai River originates in the Tongbai Mountains in Henan Province and is located about midway between the Yellow and Yangtze Rivers. It flows through southern Henan, northern Anhui, and northern Jiangsu, entering the Yangtze River at Jiangdu, Yangzhou (Fig. 3.6). The river has a length of 1,078 km and a drainage area of 174,000 km^2 (The Ministry of Water Resources 2013). As the river does not flow all the way to the sea, it is notoriously vulnerable to flooding. Therefore, many dams, including 16 large dams, have been built on the river primarily for flood control, but also for irrigation and power generation (Jiang et al. 2009).

Similar to other large dams in major rivers worldwide (Liu and Xia 2004; Stone and Jia 2006; Wang et al. 2006), the large dams in the Huai River Basin have greatly changed the flow regime, water–sediment properties, and habitats of organisms living in or along the river, which has affected the natural ecosystem and environment (Jiang et al. 2009). The most serious environmental problem in the Huai River Basin is water pollution causing massive social, ecological, and economic losses. As reported by the People's Daily (2006), "almost all the tributaries of the Huaihe

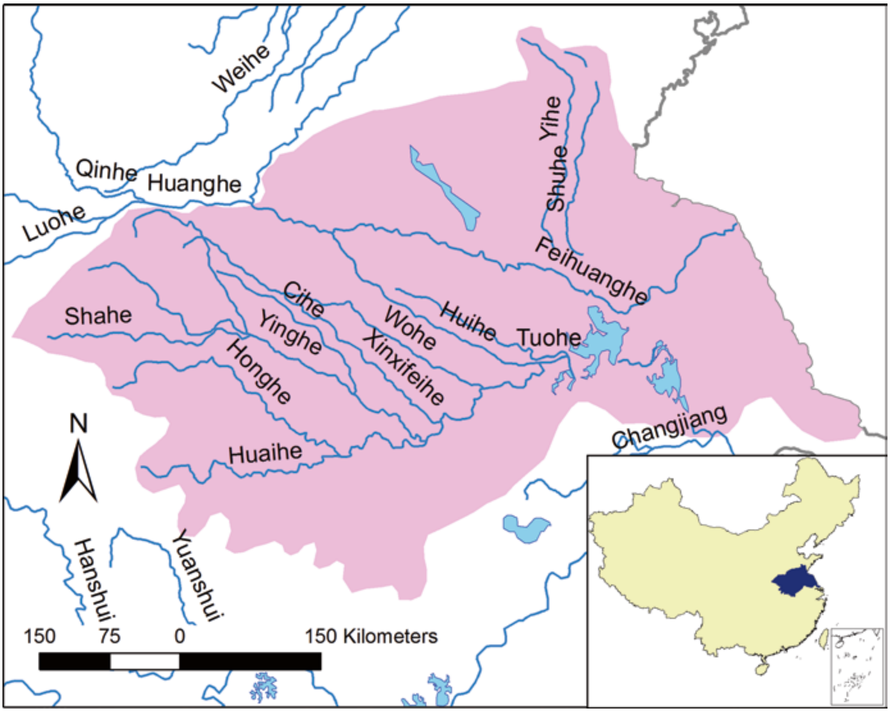

Fig. 3.6 Map of the Huai River Basin

River don't have any fish or anything alive and 70 % of the water quality is under class V, very poisonous and can not be used for any purpose." Although many scholars assume these environmental disasters to be highly related to the large dam construction and operation, a simulation modeling conducted by Jiang and colleagues (2009) showed that the increasing discharge at Hengpaitou Dam brings about significant improvement in the water quality of the Pihe River (a tributary of the Huai River) downstream from Lu'an City. Thus, good design and operation of large dams have to some extent mitigated water pollution in the Huai River Basin.

3.1.6 Hai River Basin

The Hai River flows through Beijing and Tianjin in northern China before emptying into the Yellow Sea at the Bohai Gulf. This river has nine large tributaries including the Zhangwei, Ziya, Daqing, Yongding, Chaobai, Beiyun, Jiyun, Tuhai, and Majia Rivers. The total length of the river, originating from the source of the longest tributary, is 1,329 km and the length of the mainstream of the Hai River in Tianjin is about 70 km (Fig. 3.7). Its annual flow is only half that of the Yellow River, or 1/30

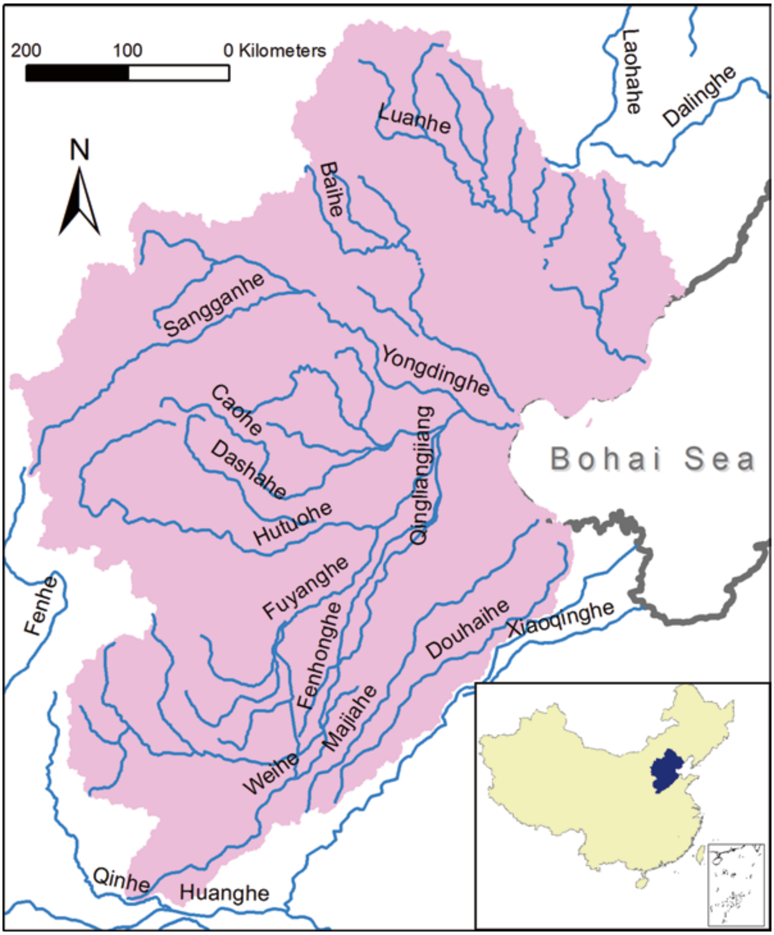

Fig. 3.7 Map of Hai River Basin

that of the Yangtze River (The Ministry of Water Resources 2013). The Hai River Basin has an area of approximately 319,000 km^2. The major tributaries of the Hai River can be divided into three reaches: the mountainous, transitional, and plains. Among them, the Yongding River is the most sediment-laden tributary, and Beijing (the capital of China) is located on this tributary. Sedimentation in the Yongding River channel in the past turned it into a perched river, making flood control for downstream cities such as Beijing very difficult. In1954, Guanting Dam was built in the upper reaches of the Yongding River for flood control and water supply. Since then, a great number of large dams have been built in the tributaries to control floods following the principle to build dams "to impound flood water in the reservoirs in the mountainous regions, to harness river channels in the middle reaches, and to discharge floods rapidly in the lower reaches" (IRTCES 2004).

However, construction of large dams in the Hai River Basin has caused serious sedimentation in the downstream river channels and estuaries. Due to water storage in the upstream reservoirs, the low water flow does not move sediments through the downstream river channels and estuaries, leading to heavy sedimentation which causes them to dry up (IRTCES 2004). Moreover, large dams have changed the flow regimes downstream, resulting in flooding or drought problems. For example, in August of 1963, a large flood in the Hai River Basin inundated 107 counties belonging to seven prefectures, destroyed the Beijing–Guangzhou Railway, Beijing–Dezhou Railway, and Shijiazhuang–Taiyuan Railway, damaged six medium-sized dams, collapsed 330 small dams, and destroyed 62 % of the irrigation systems and 90 % of the drainage systems in the basin (IRTCES 2004). Moreover, the accumulation and magnification of pollutants by the dam have reduced the water quality, threatening the quality of water sources stored in large reservoirs such as Miyun Reservoir (Wang et al. 2001, 2002; Wang and Cao 2006; Xie et al. 2003), which is the primary source for drinking water for about 3,000,000 residents in Beijing City.

3.1.7 Liao River Basin

The Liao River, flowing through Hebei, Jilin, and Liaoning Provinces and the Inner Mongolia Autonomous Region with a length of 1,345 km, is an important river in Northeast China (IRTCES 2004). The river has two main branches. The western branch (Xi Liao He) is formed by the confluence of the Shara Muren River flowing from Inner Mongolia Autonomous Region in the west and the Laoha River flowing from Hebei Province in the south. The eastern branch (Dong Liao He) rises from the low mountains in Jilin Province in the east (Fig. 3.8). The confluence of these two branches flows across a vast plain in central Liaoning Province to the Bohai Gulf (The Ministry of Water Resources 2013). Like the Yellow River, the Liao River has an exceedingly high sediment load because the river flows through many parts of the loess plains. Similarly, high sedimentation in the river makes flood control in downstream areas very difficult. Therefore, most dams were built to control flooding with the first dam completed in 1942 and the last one in the 1980s. At present, there are 688 dams of various sizes with a total reservoir storage capacity of 13.8 billion m^3, but the 17 are large reservoirs hold most of the water (13.2 billion m^3) (IRTCES 2004)

Dams in the Liao River Basin work better in flood control in contrast to those in the Hai River Basin. Runoff and flood peaks have been reduced by one half and the sediment load reduced by 16 % (IRTCES 2004). However, large dams have changed the flow regime and sediment loads of the river below the reservoirs (IRTCES 2004), which may impact downstream ecosystems. Moreover, the dams may block and accumulate pollutants in the reservoirs negatively affecting water quality. A GIS-based analysis showed that over 60 % of the pollution loading by nonpoint sources is concentrated in the mainstream of the Liao River (Wen et al. 2011) and the densely dammed areas in the Liao river Basin. Although it is not clear how much

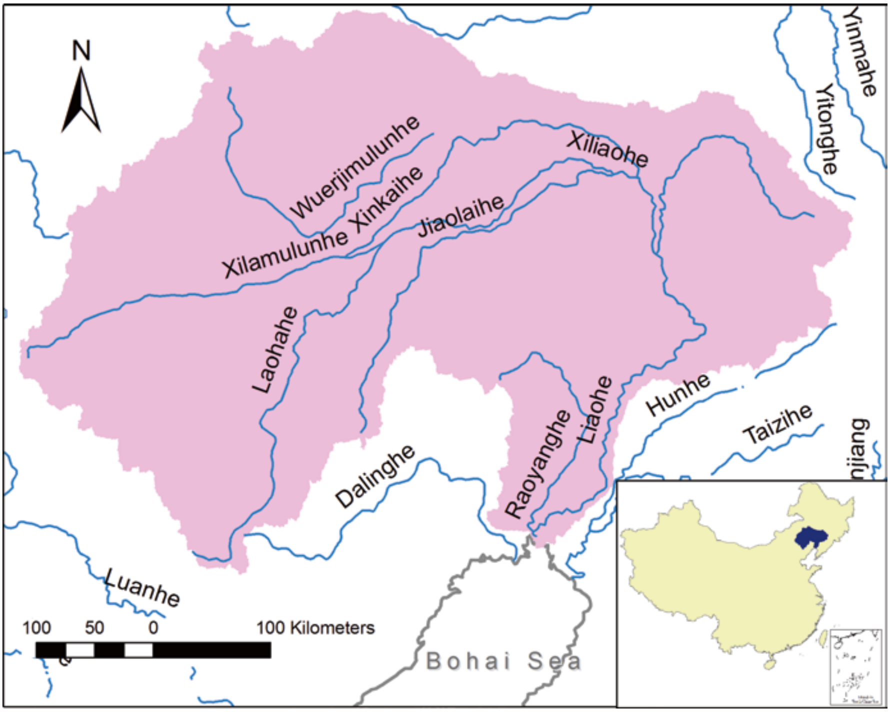

Fig. 3.8 Map of the Liao River Basin

the poor water quality is related to the large dams, serious water pollution has turned the Liao River, "Mother River" of Liaoning Province into a "sewage ditch." (Xinhuanet News Domestic 2009).

3.1.8 Songhua River Basin

The Songhua River, flowing about 1,434 km from the Changbai Mountains through Jilin and Heilongjiang Provinces, is the largest tributary of the Amur River (Heilong Jiang in Chinese) (Fig. 3.9). It joins the Amur River at the town of Dongjiang. It is another important river in Northeast China, with a basin area of about 1,443,100 km^2. The largest tributary of this river, Second Songhua River, has three dams, the Baishan, Hongshi, and Fengman Dams, which are used for the production of hydroelectricity (The Ministry of Water Resources 2013).

The impacts of large dams on the flow regime, water quality, and river ecosystems in the basin are poorly recorded. However, one study found that nonpoint source pollutants, such as nitrogen and suspended solids from agriculture and urban runoff, have increased from 1990s to 2000s, as compared to heavy metals and toxic

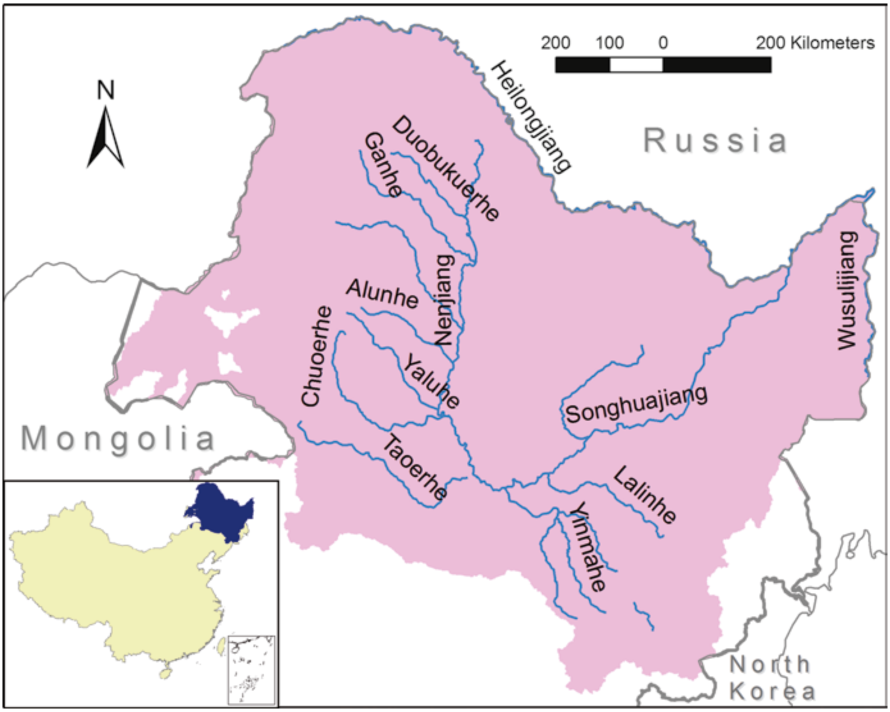

Fig. 3.9 Map of the Songhua River Basin

organic chemicals (Yu et al. 2003). This dynamic may be partially related to the effects of dams on the downstream flow regime, sedimentation, and storage capacity of the reservoir. Most importantly, the contamination of benzene in the river in November, 2005 led to a shutdown of Harbin's water supply and threats of a Russian lawsuit against China (People's com 2005).

3.2 Effects of Large Dams on Biological Diversity and Ecological Integrity

As we have discussed, it is well documented that dams can cause diverse environmental problems such as changes in the flow regime of a river, increased sedimentation in the reservoir, reduced water quality, habitat degradation, and losses in biodiversity. However, few studies have examined the impacts of the large dams on biological diversity at watershed scale and ecological integrity at the ecosystem level. In fact, biological diversity and ecological integrity are the most important indicators to reflect the environmental impacts at ecosystem or watershed levels (Li et al. 2012a, c). Below, we present frameworks for assessing the impacts of dams on the biological diversity at watershed scale and impacts on ecological integrity of rivers at ecosystem scale. In Sect. 3.3, we present case studies that assess the impacts of dams on the biological integrity and ecological integrity of the Upper-Mekong River.

3.2.1 Assessing Biological Diversity at Watershed Scale

Loss of biodiversity associated with dam construction and operation is a growing environmental concern. Although a lot of research has focused on mitigating the negative impacts of large dams on biodiversity, these studies have focused mostly on endangered, endemic, or economically valuable fish species and rarely on other aquatic and terrestrial species. In most cases, these studies have investigated the impacts of dams on biodiversity at the species level and have overlooked the impacts on biodiversity at ecosystem and watershed/landscape levels. Indeed, assessment of large-scale biodiversity losses associated with dam construction and operation is very important if upstream–downstream relationships and biological interactions are considered.

In Article 2 of the Convention on Biological Diversity, biological diversity is defined as "variability among living organisms from all sources including inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems." Hence, biodiversity is not only the sum of all ecosystems, species, and genetic material, but also includes the variability within and among them. Biological diversity is often understood at three levels: genetic, species, and ecosystem diversity. All three levels of diversity are necessary for the continued survival of all life including humans (Primack 2012).

Previous studies (Whittaker 1972; Colwell 2009; Wilson 1988) have developed various indices to assess biological diversity. Although these indices are appropriate in disturbed or natural environments, few indicators have been created for assessing the impacts of large dams on the biological diversity at a landscape or region level. Recently, we developed the Vegetation Impact Index (VII) for assessing the impacts of large dams on plants at the community level (Li et al. 2012a). The VII was developed as a quantitative index to predict the degree to which vegetation types would be affected by rising water levels and inundation calculated as follows:

$$Riparian\,vegetation: VII = R_\mathrm{a} \,/\, R_\mathrm{r}$$

$$Upland\,vegetation: VII = R_\mathrm{b} \,/\, R_\mathrm{u}$$

where R_a is the riparian vegetation distribution range (the boundary at which the vegetation cannot be affected by the backwater) after dam construction, R_r is the riparian vegetation distribution range before dam construction; R_b is the upland vegetation distribution range (altitude) above normal water level in the reservoir region, and Ru is the upland vegetation distribution range (altitude) in the area far from dam. The values of VII are divided into five classes: (1) <0.20 is grade 5, representing

Table 3.1 Ecological risk categories for species derived from the changes of the summed dominance ratio (SDR)

Changes of species dominance (%)	Level of ecological risk at species level	
	Dominant species	Nondominant species
100	IV	III
>64	IV	II
34–64	II	I
<34	I	0

Note: 0:, no ecological risk/extremely low ecological risk; I, low ecological risk; II, medium ecological risk; III, high ecological risk; IV, Extremely high ecological risk

severe impact; (2) $0.20 < 0.40$ is grade 4, representing heavy impact; (3) $0.40 < 0.60$ is grade 3, representing moderate impact; (4) $0.60 < 0.80$ is grade 2, representing light impact; and (5) > 0.80 is grade 1, representing little or no impact.

We also developed an indicator of ecological risk (ER) of plant species using changes in the summed dominance ratio (SDR) to evaluate impacts of large dams at the species level (Li et al. 2012a). The SDR is calculated based on the relative coverage (C) and relative frequency (F) of a species as follows:

$$SDR(\%) = \frac{C' + F'}{2}, \quad C'(\%) = \frac{C_i}{C_\mathrm{I}} \times 100, \quad F'(\%) = \frac{F_i}{F_\mathrm{I}} \times 100$$

where the variables C' and F' are a species cover ratio and species frequency ratio. C_i and C describe species i cover and maximum species cover in the plant community, and F_i and F_I are species i frequency and maximum species frequency in the plant community, respectively. The ER of the species is categorized into four levels for both dominant and nondominant species based on changes in the SDR of that species (Table 3.1).

3.2.2 *Assessing Biological Integrity at Ecosystem Scale*

The concept of biological integrity originated in the US Federal Clean Water Act of 1972, which addressed concerns about the integrity of the nation's waters. Integrity refers to an unimpaired condition, and biological integrity is defined as how "pristine" an environment is by examining the biological composition, structure, and function relative to the potential or original state of an ecosystem before human disturbances were introduced (Angermeier and Karr 1994; Karr 1991).

The widely accepted definition of biological integrity is adapted from Frey (1977): "the capability of supporting and maintaining a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of the natural habitat of the region." The implications of this definition are that living systems have a variety of scales relative to which they exist, that one can quantify the parts that sustain or contribute to a

Table 3.2 Selected metrics for the modified fish index of biological integrity (F-IBI) in the middle reaches of the Upper-Mekong River

Categories	Selected metrics	Abbreviation	RE
Species composition and richness	Number of species	SM_1	+
	Number of native species	SM_2	+
	Proportion of native species	SM_3	+
	Proportion of endemic species	SM_4	+
Trophic guilds	Proportion omnivorous	SM_5	–
	Proportion invertivorous	SM_6	+
	Proportion herbivorous	SM_7	+
	Proportion planktivorous	SM_8	–
Habitat	Proportion of lotic habitat (includes water column and benthic habitat)	SM_9	+
Tolerance	Proportion of tolerance individuals	SM_{10}	-

Note: RE means response to environmental condition; “+” means positive correlation to pristine environmental conditions; “–” means negative correlation)

system’s functioning, and that all systems must be seen within the context of their environments and evolutionary histories.

Karr (1981, 1986) created the index of biological integrity (IBI) as a means for resource managers to quantify the biological integrity of aquatic systems. After that, many different indices have been developed for various organisms and ecosystems, but none have been developed specifically to assess the impacts of dams on the biological integrity of rivers. As such, we developed a modified fish-IBI (F-IBI) for evaluating the health of the aquatic ecosystem disturbed by large dams in the middle reaches of the Upper-Mekong River. We used ten metrics that can be grouped into four categories: species composition and richness, trophic guilds, fish habitat, and tolerance to disturbance. Species composition and richness included four vectors: the number of species, number of native fish, proportion of native fish, and proportion of endemic fish. The trophic guilds of fish assemblages were classified into four vectors: omnivorous, invertivorous, herbivorous, and planktivorous. Fish habitat was classified as the proportion of the total habitat that is a lotic system; this was selected as the key vector because most fish in this section of the Upper-Mekong River live in rapid flowing waters. For tolerance, the proportion of tolerant fish was used as the key vector as tolerant species are more adaptable to varying environmental condition, e.g., insensitive to changes of flow regimes and water quality associated with dam inundation and operation (Li et al. 2013).

Changes in the F-IBI at both temporal and spatial scales reflect ecological variation from pristine to degraded aquatic ecosystems induced by dam impoundment and flow regulation (Li et al. 2013). The index value of each sampled site can be normalized on a scale of 0–100 based on the ten selected metrics (SM1–SM10).

When the response to environmental conditions (RE in Table 3.2) is positive, the SM can be normalized as follows:

$$SM = \frac{V - V_{\min}}{V_{\max} - V_{\min}} \times 100$$

Table 3.3 Categories of aquatic ecosystem health derived from modified F-IBI scores

F-IBI score	Level	Assessment	Character
81 ≤ 100	I	Excellent	Relative pristine condition, diverse native fish species
61 ≤ 80	II	Good	Decreased native fish species, low disturbance from human activities
41 ≤ 60	III	Fair	Dramatically decrease in native species, moderate disturbance from human activities
21 ≤ 40	IV	Poor	Few native fish species, fish habitats highly impacted by impoundment and flow regulation
1 ≤ 20	V	Bad	Dominance by exotic fish species, no native fish species.
0	VI	No fish	No fish caught in the waterways.

When the response to environmental conditions (RE in Table 3.2) is negative, the SM can be normalized as follows:

$$SM = 100 - \frac{V - V_{\min}}{V_{\max} - V_{\min}} \times 100$$

The score of the modified F-IBI for each site is then calculated as the average of the 10 SM values:

$$Modified\ F - IBI = \sum_{i=10}^{i=1} SM_i \,/\, 10$$

where V is the value of a sampled site, $V_{\min}$ is the minimum value of all sampled sites, $V_{\max}$ is the maximum value of all sampled sites, SM_i is the score of the sampled metric, i. The final modified F-IBI scores range from 0 to 100, which reflects different levels of aquatic ecosystem health (Table 3.3).

Similarly, we currently are developing a modified phytoplankton IBI for evaluating the health of the phytoplankton communities impacted by the large dams in middle reaches of the Upper-Mekong (Li et al. 2012b).

3.3 Case Study: Environmental Impacts of Dams on the Upper-Mekong River

3.3.1 Impacts on Biological Diversity

3.3.1.1 Vegetation Impacts

We conducted field surveys to study the impacts of the large dams on vegetation distribution patterns in riparian and upland areas along the middle-lower reaches of the Upper-Mekong River during the dry seasons from 2004 to 2010. In total, 24 transects perpendicular to the river channel were set up to sample the riparian and

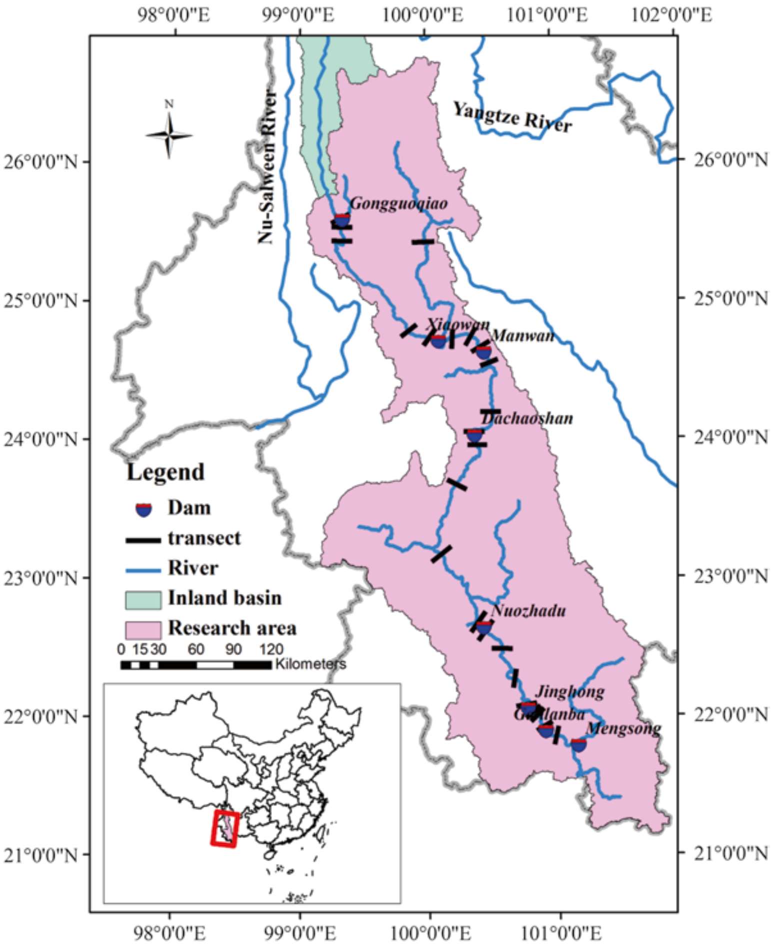

Fig. 3.10 Map of cascading dams along the middle-lower reaches of the Upper-Mekong River and location of transects used to sample vegetation

upland vegetation on the upstream impoundment banks and downstream river banks of eight cascading dams, the Gongguoqiao, Xiaowan, Manwan, Dachaoshan, Nuozhadu, Jinghong, Ganlanba, and Mengsong dams (Fig. 3.10). Along each transect, 5–6 × 10 m^2 quadrats were arrayed along the elevational gradient and a total of 126 quadrats were used to sample the vegetation in the study area. Using the reservoir water level as a reference, the number of quadrats that were inundated or will be inundated was recorded on each sampling transect, and the percentage of inundation calculated. The vegetation impact index (VII) at different sampling sites was calculated using the methods introduced in Sect. 3.2.

The vegetation was classified into 21 community types (Table 3.4). The upland vegetation was dominated by trees and shrubs whereas the riparian areas supported

Table 3.4 Vegetation types along the middle-lower reaches of the Upper-Mekong River Basin measured before dam construction

	Vegetation types	Dominant plant species	Coverage	Habitat	Quadrats		
			Mean ± SD		T	I	Per. I. (%)
TC	I	*Dendrocalamus strictus*	90.0 ± 0.0	Upland	4	1	25.00
	II	*Ficus semicordata*	55.0 ± 7.1	Upland, Riparian	2	0	0.00
	III	*Ficus semicordata*, *Phyllanthus emblica*	75.0 ± 21.8	Upland, Riparian	9	3	33.33
	IV	*Dalbergia obtusifolia*, *Wendlandia scabra*	76.6 ± 16.3	Upland	19	5	26.32
	V	*Pinus khasya* var. *langbianensis*, *Dalbergia obtusifolia*	81.0 ± 16.7	Upland	15	0	0.00
	VI	*Engelhardtia colebrookiana*, *Phyllanthus emblica*	71.1 ± 24.0	Upland	14	5	35.71
	VII	*Pinus yunnanensis*, *Castanopsis delavayi*	70.0 ± 12.6	Upland	7	0	0.00
	VIII	*Pinus yunnanensis*, *Schima wallichii*	83.3 ± 11.6	Upland	3	0	0.00
	IX	*Pinus yunnanensis*, *Woodfordia fruticosa*	71.3 ± 15.5	Upland	4	0	0.00
	X	*Pinus yunnanensis*, *Phyllanthus emblica*	67.8 ± 27.6	Upland	13	1	7.69
SC	XI	*Bauhinia acuminata* var. *candida*	80.0 ± 17.3	Upland	3	3	100.0
	XII	*Homonoia riparia*	68.8 ± 16.5	Riparian	4	2	50.00
	XIII	*Woodfordia fruticosa*, *Homonoia riparia*	50.0 ± 0.0	Riparian	1	1	100.0
	XIV	*Picrasma quassioides* var. *quassiodes*, *Broussonetia papyrifera*	91.3 ± 2.5	Upland	4	1	25.00
	XV	*Dendrocalamus strictus*, *Broussonetia papyrifera*	73.3 ± 28.9	Upland	3	2	66.67
	XVI	*Buddleja asiatica*	55.0 ± 12.9	Upland	4	3	75.00
	XVII	*Rapanea neriifolia*, *Ficus tikoua*	65.0 ± 16.6	Riparian	5	2	40.00
GC	XVIII	*Vernonia patula*, *Digitaria sanguinalis*	67.5 ± 35.2	Riparian	4	2	50.00
	XIX	*Equisetum diffusum*	25.0 ± 0.0	Riparian	1	1	100.0
	XX	*Buddleja* sp., *Eupatorium odoratum*	66.7 ± 20.8	Riparian	3	2	66.67
	XXI	*Phragmites* sp.	48.8 ± 11.8	Riparian	4	1	25.00
					126	35	27.78

TC tree community, *SC* shrub community, *GC* grass community, *T* total number of quadrats sampled for each vegetation, *I* the number of quadrats that will be inundated, *Per.I.* percentage of inundated quadrats

Table 3.5 Vegetation impact index (VII) associated with dam construction

Reservoir areas	Vegetation type	VII	Grade	Vegetation type	VII	Grade
GGQ	VII	0.0723	5	XVIII	0.0000	5
XW	XVI	0.5503	3	XVIII	0.0079	5
	IV	0.5059	3	VII	1.0000	1
	III	0.0972	5	VIII	1.0000	1
	VI	0.0769	5	X	0.5543	3
MW	IV	0.8358	1	VIII	1.0000	1
	VI	0.7295	2	X	1.0000	1
	V	0.6489	2	IX	1.0000	1
DCS	IV	0.8770	1	VI	0.8117	1
	III	0.8145	1	V	0.7680	2
NZD	III	0.6847	2	II	0.2553	4
	XV	0.0000	5	VI	0.7385	2
	XXI	0.0141	5			
JH	II	1.0000	1	XX	0.0000	5
	I	0.3057	4	XII	0.0000	5
	XIV	0.5000	3	XIII	0.0000	5
	XV	0.8072	1	III	0.9552	1
	XIX	0.0000	5	IV	1.0000	1
	XXI	0.0000	5	V	1.0000	1
GLB	XI	0.0000	5			
	XIV	1.0000	1	XXI	0.1538	5
	XII	0.1538	5	V	1.0000	1
	XVIII	0.1538	5	XX	1.0000	1
	XXI	0.0833	5	I	1.0000	1
MS	XII	0.0833	5			

GGQ GongGuoqiao Dam, *XW* Xiaowan Dam, *MW* Manwan Dam, *DCS* Dachaoshan Dam, *NZD* Nuozhadu Dam, *JH* Jinghong Dam, *GLB* Ganlanba Dam, *MS* Mengsong Dam

grasses and shrubs. Eight of the ten tree communities identified in our analysis were distributed in upland areas whereas two were found on upland and riparian areas. Of the shrub communities, three of the seven were distributed in riparian areas and the other four in upland sites. All of the grass communities were distributed in riparian areas (Table 3.4). The vegetation has the potential to be greatly impacted by the rising water levels following dam operation. When the water levels increase with dam operation, 36 out of 126 quadrats were/will be inundated by the reservoirs (Table 3.4). The grass and shrub layers were/will be more seriously affected than the tree layer (Li et al. 2012c).

The calculated vegetation impact index (VII) of each community type associated with dam construction shows that Gongguoqiao Dam severely impacted vegetation type VII, *Pinus yunnanensis*, *Castanopsis delavayi* and type XVIII, *Vernonia patula*, *Digitaria sanguinalis* (Table 3.5). The Xiaowan Dam severely affected vegetation type III, *Ficus semicordata*, *Phyllanthus emblica*, type VI, *Engelhardtia colebrookiana*, *Phyllanthus emblica,* and type XVIII, *Vernonia patula*, *Digitaria sanguinalis* and moderately impacted vegetation type XVI, *Buddleja asiatica*, and type IV, *Dalbergia obtusifolia*, *Wendlandia scabra*. The Manwan Dam only lightly impacted vegetation type V, *Pinus khasya* var. *langbianensis*, *Dalbergia obtusifolia* and type VI, *Engelhardtia colebrookiana*, *Phyllanthus emblica*. The Dachaoshan Dam lightly affected vegetation type V, *Pinus khasya* var. *langbianensis*, *Dalbergia obtusifolia*. The Nuozhadu Dam severely impacted vegetation type XV, *Dendrocalamus strictus*, *Broussonetia papyrifera*, and type XXI, *Phragmites* sp., heavily impacted vegetation type II, *Ficus semicordata*, and lightly impacted vegetation type III, *Ficus semicordata*, *Phyllanthus emblica*, and type VI, *Engelhardtia colebrookiana*, *Phyllanthus emblica*. The Jinghong Dam severely affected vegetation type XIX, *Equisetum diffusum*, type XXI, *Phragmites* sp., type XI, *Bauhinia acuminata* var. *candida*, type XX, *Buddleja* sp., *Eupatorium odoratum*, type XII, *Homonoia riparia*, and type XIII, *Woodfordia fruticosa*, *Homonoia riparia*, heavily affected vegetation type I, *Dendrocalamus strictus*, and moderately affected vegetation type XIV, *Picrasma quassioides* var. *quassiodes*, *Broussonetia papyrifera*. Ganlanba Dam severely affected vegetation type XII, *Homonoia riparia*, type XVIII, *Vernonia patula*, *Digitaria sanguinalis*, and type XXI, *Phragmites* spp. The Mensong Dam severely affected vegetation type XXI, *Phragmites* sp. and type XII, *Homonoia riparia* (Li et al. 2012c).

3.3.1.2 Ecological Risk of Plant Species

We conducted surveys of key species in the Manwan and Xiaowan reservoir areas in 1997, before construction of the Xiaowan Dam, and in 2011, after the Xiaowan Dam was constructed to quantify species dominance and their ecological risk imposed by the dams. Three plots were established along a 10 km section from the Xiaowan to Manwan dam: 15 × 10-m^2 quadrats, five per plot, were used to sample trees; the dominant shrub species were sampled in three 5-m^2 sub-quadrats in quadrat; and dominant herbs species were recorded three 1-m^2 sub-quadrats placed in each quadrat. The number and total cover of the dominant species in each subquadrat were recorded (Fig. 3.11).

The results indicated that at sampling site No. 1 that, before the construction of Xiaowan Dam in 1997, *Phyllanthus emblica* and *Woodfordia fruticosa* were the dominant tree and shrub species but were replaced by *Engelhardtia colebrookeana* after dam construction in 2010. The disappearance of the herb *Heteropogon contortus* and appearance of *Capillipedium assimile* and *Ageratina adenophora* were the major changes in the herbaceous vegetation at this site. At sampling site No. 2, the dominant tree species were *Castanopsis delavayi* and *Castanopsis fleuryi* before dam construction, but *Pinus yunnanensis* became the dominant species post dam construction and *Castanopsis fleuryi* vanished. In the shrub and herb layers, *Glochidion daltoni* and *Pogonatherum paniceum* became the dominant species after construction of the Xiaowan Dam. At sampling site No. 3, the dominant species were crops, such as *Bauhinia acuminata*, *Dalbergia obtusifolia,* and *Oplismenus compositus*, before the dam, and the invasive plants, *Ageratina adenophora* and *Chromola enaodoratum*, became dominant when farmland was abandoned (Table 3.6).

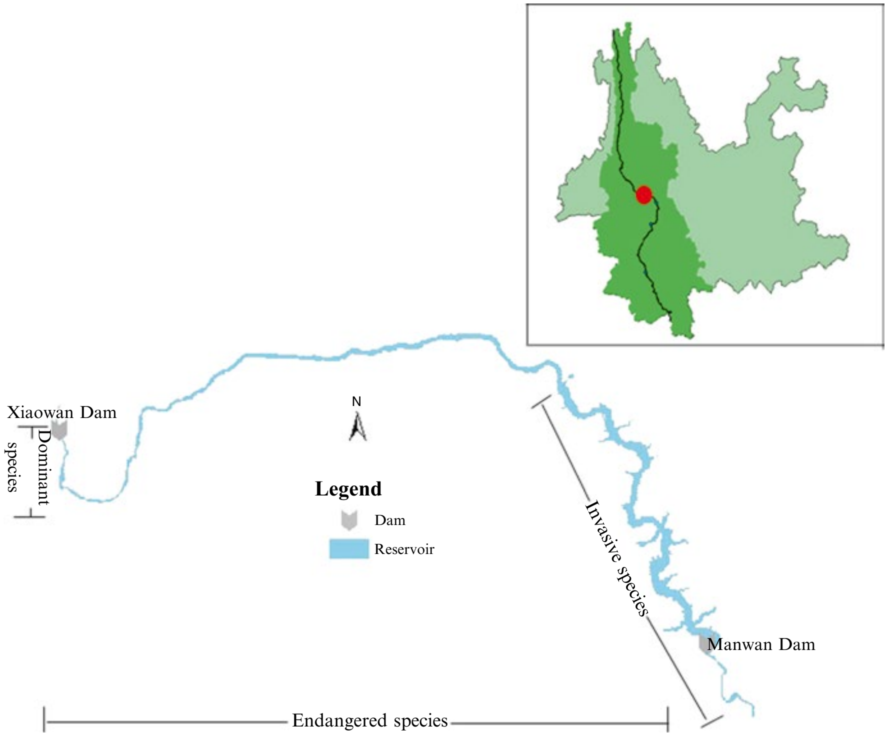

Fig. 3.11 Map of sampling sites for assessment of ecological risk of vegetation along the Xiaowan and Manwan reservoirs in the middle reaches of the Lancang River

Table 3.6 Changes in key species of riparian vegetation at three sampling sites before (1997) and after (2010) construction of the Xiaowan Dam

			SDR (mean ± SE)	
Sample site	Vegetation layer	Plant species	1997	2010
1	Tree	*Phyllanthus emblica*	100 ± 1	79 ± 4
		Engelhardtia colebrookeana	13 ± 10	100 ± 1
	Shrub	*Woodfordia fruticosa*	100 ± 1	52 ± 24
	Herbs	*Heteropogon contortus*	100 ± 10	0
		Capillipedium assimile	39 ± 9	67 ± 25
		Eupatorium adenophorum	0	75 ± 25
2	Tree	*Castanopsis delavayi*	55 ± 15	69 ± 19
		Castanopsis fleuryi	100 ± 20	0
		Pinus yunnanensis	0	100 ± 0
	Shrub	*Melastoma normale*	88 ± 9	29 ± 4
		Glochidion daltoni	85 ± 15	100 ± 24
	Herbs	*Pogonatherum paniceum*	43 ± 4	65 ± 0
3	Tree	*Dalbergia obtusifolia*	77 ± 5	0
		Bauhinia acuminate	100 ± 4	0
	Herbs	*Ageratina adenophora*	16 ± 3	79 ± 12
		Chromolaena odoratum	0	100 ± 12
		Oplismenus compositus	100 ± 25	0

Table 3.7 Ecological risk of plant species at sampling sites of No. 1, 2, and 3 before (1997) and after (2010) the construction of Xiaowan Dam

Sample site	Vegetation layer	Dominant species	Risk level
1	Tree	*Phyllanthus emblica*	I
		Engelhardtia colebrookeana	III
	Shurb	*Woodfordia fruticosa*	II
	Herbage	*Heteropogon contortus*	IV
		Capillipedium assimile	I
		Ageratina adenophora	IV
2	Tree	*Castanopsis delavayi*	I
		Castanopsis fleuryi	IV
		Pinus yunnanensis	IV
	Shurb	*Glochidion daltoni*	I
		Melastoma nrmale	III
	Herbage	*Pogonatherum paniceum*	I
3	Tree	*Dalbergia obtusifolia*	IV
		Bauhinia acuminate	IV
	Herbage	*Chromolaena odoratum*	IV
		Ageratina adenophora	II
		Oplismenus compositus	IV

Note: 0, no ecological risk/extremely low ecological risk; I, low ecological risk; II, medium ecological risk; III, high ecological risk; IV, extremely high ecological risk

It is evident from these results that dam construction can have major impacts on the vegetation and biodiversity leading to a decrease or even loss of the dominant species and an increase in nondominant and invasive plants in the riparian zones (Li et al. 2012a).

The ecological risk analysis presented in Table 3.7 indicates that at sampling site No. 1, the tree species, *Engelhardtia colebrookeana,* was at high ecological risk (III), the shrub species, *Woodfordia fruticosa* and *Eupatorium adenophorum*, were at medium (level II) and extremely high risk levels (level IV), respectively, and the herbaceous species, *Phyllanthus emblica* and *Capillipedium assimile*, were at low ecological risk (level I). At sampling site No. 2, the tree species *Castanopsis fleuryi* and *Pinus yunnanensis* were at extremely high ecological risk (level IV), and the herb, *Pogonatherum paniceum*, was at low ecological risk (level I). At sampling site No. 3, the tree species *Dalbergia obtusifolia*, *Bauhinia acuminata,* and *Oplismenus compositus* were at the extremely high risk (level IV), the herb species, *Ageratina adenophora* and *Chromolaena odoratum*, were at moderate (level II) and extremely high levels of ecological risk (level IV). These results indicate that each plant species responded differently to dam construction and were at different levels of risk. The dominant species in some of the plant communities were at risk of being completely lost from the system whereas exotic species were poised to become dominant in some sites (Li et al. 2012a).

3.3.2 Impacts on Ecological Integrity

3.3.2.1 Impacts on the Biological Integrity of Fish Assemblages

We monitored changes in the fish assemblages at the Xiaowan Dam at both temporal and spatial scales. The surveys were conducted in 2008, 2010, and 2011 that corresponded to the periods of before dam impoundment, during water storage and after dam operation. Because the Xiaowan Dam is far upstream from the Manwan Dam and there were no dams further upstream from the Xiaowan Dam, the 2008 fish survey was regarded as the baseline sample that represented pristine conditions. The 2010 survey assessed the impacts of water storage (as the reservoir began filling) on fish assemblages, and the 2011 survey was the impact of the fully operational dam on the fish communities. We selected four sampling sites to monitor the fish populations (Fig. 3.12). Sample site S1 was located below the reservoir and could assess the impacts of flow regulation on the fish communities. Site S2 was located at the head of the reservoir in static water with a maximum depth 252 m after dam impoundment; S3 was located in static water in the middle reach of the mainstream reservoir region; and S4 was located in a tributary reservoir region of the lower Heihuijiang River, representing the effects of dam impoundment and operation on fish populations in tributaries.

The sampling sites were selected to represent a range of habitat and hydrological conditions that would be differentially impacted by the dam and its operation. The fish index of biological integrity (F-IBI) was calculated at each site at each time period to assess changes in the health of the river ecosystem before and after the dam became fully operational.

The calculated F-IBI for the different sites shows that before dam impoundment in 2008, the F-IBI score decreased from 99.83 (level I) in the upstream site, S3, to 70.59 downstream at site S2 (level II). The F-IBI score at S4 in the tributary of was 48.86 (level III), much lower than that of the mainstream. With the impoundment of the Xiaowan Dam in 2010, the scores of F-IBI decreased sharply to level V at all sites. When the dam was operational and generating power in 2011, the F-IBI at S2, S3, and S4 all decreased slightly whereas S1 increased (Table 3.8). These results clearly show that the construction and operation of large dams can have negative impacts on fish assemblages. The major causes of decreased biological integrity of the river were due to loss of lotic habitat, habitat fragmentation, migration blockage, loss of native fish species, and an increase in nonnative fish species (Li et al. 2013).

3.3.2.2 Impact on the Biological Integrity of Plankton

We conducted surveys of the phytoplankton assemblages in 1988, 1997, and 2011 at nine sites (Fig. 3.13). In 1988 and 1997, the phytoplankton assemblages were sampled in the dry season only (April) whereas they were sampled twice in 2011 during both the dry and rainy season (October). The 1984 survey represents the natural pristine state of the river unaffected by dams. The 1997 survey is after the

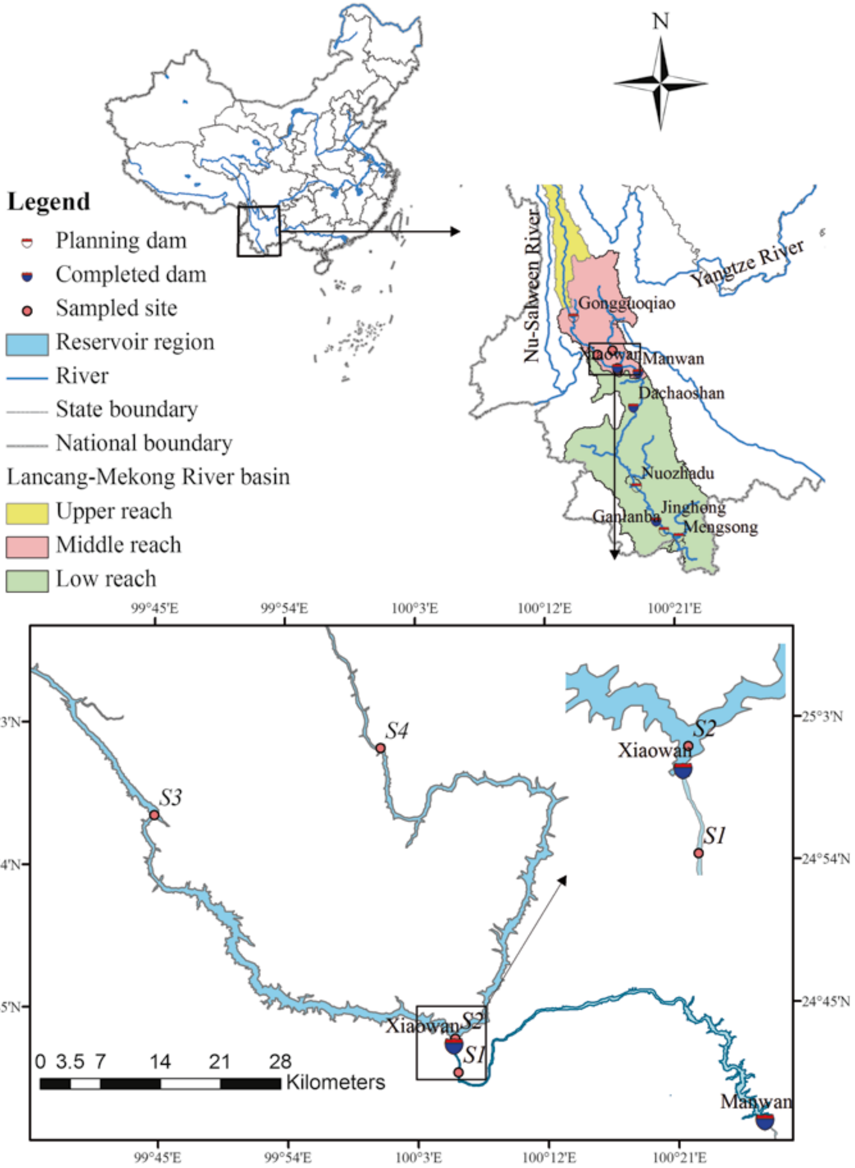

Fig. 3.12 Sampling sites for monitoring fish assemblages in the Xiaowan reservoir area

Table 3.8 Modified F-IBI scores in the Xiaowan reservoir and middle reaches of the Upper-Mekong River before (2008) and after (2010, 2011) dam construction

F-IBI	S1	S2	S3	S4	S1–S2/km	S2–S3/km	S2–S4/km
2008	NA	70.59 (II)	99.83 (I)	48.86 (III)	NA	0.53	0.33
2010	17.59 (V)	19.77 (V)	19.84 (V)	16.74 (V)	0.56	0.00	0.05
2011	26.14 (IV)	14.21 (V)	15.50 (V)	12.36 (V)	3.09	0.02	0.05

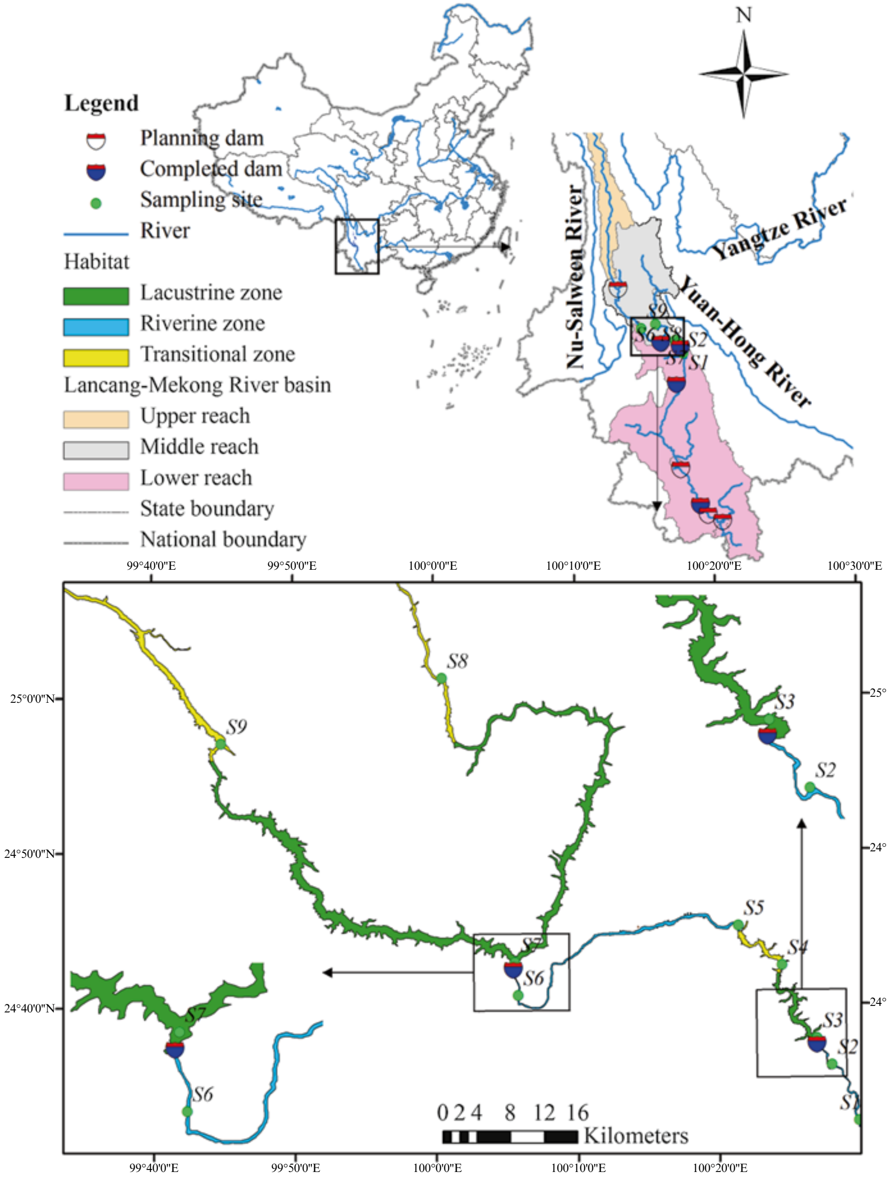

Fig. 3.13 Sampling sites for plankton assemblages in the reservoirs of three cascading dams, the Xiaowan, Manwan, and Dachaoshan dams

Manwan Dam was completed and became operational in 1995. Thus some but not all of the sampling sites were affected by dam impoundment and flow regulation in 1997. In 2011, both the upstream dam of Xiaowan (2010) and downstream dam of Dachaoshan (2003) were completed and operational, and all sampling sites were impacted by the dams. In 1984, seven sites were sampled (S1, S3, S4, S5, S7, S8,

Table 3.9 The P-IBI in the middle reaches of the Upper-Mekong River measured at four time periods: before the dams were built (April 1984), after the first dam became operational (April 1997), and after all three dams were fully operational during the dry season (April 2011) and rainy season (Oct 2011)

Sampling years	DM			MR				DX	XR			
	S1	S2	Mean ± SD	S3	S4	S5	Mean ± SD	S6	S7	S8	S9	Mean ± SD
2011.4	2.6	3.0	2.8 ± 0.3	2.6	2.8	2.4	2.6 ± 0.2	3.6	2.4	3.2	2.8	2.8 ± 0.4
2011.10	3.4	2.8	3.1 ± 0.4	2.6	2.6	2.4	2.5 ± 0.1	3.0	2.8	2.4	2.0	2.4 ± 0.4
1997	2.4	3.0	2.7 ± 0.4	2.2	2.2	3.6	2.7 ± 0.8	NA	4.0	3.8	4.0	3.9 ± 0.1
1988	4.6	NA	4.6	3.6	4.8	4.0	4.1 ± 0.6	NA	4.4	4.0	3.0	4.1 ± 0.3

DM downstream of Manwan hydropower dam; *MR* Manwan reservoir region; *DX* downstream of Xiaowan hydropower dam, *XR* Xiaowan reservoir region; *NA* not available

and S9), eight sampling sites in 1997 (S1, S2, S3, S4, S5, S7, S8, and S9) and all nine sites were sampled in 2011. After the dams became operational, S3 and S7 represented the lacustrine zone of each reservoir region; S4, S8, and S9 represented the transitional zone; S5 and S6 represented the riverine zone of the Manwan reservoir region; S1 and S2 represented the riverine zone of the Dachaoshan Dam and the downstream region below the Manwan Dam (Fig. 3.13). The planktonic index of biological integrity (P-IBI) was structured and calculated following the same procedures used for the F-IBI.

The results of P-IBI show that in 1988, before the dams had been constructed, the P-IBI in the mainstream ranged from 4.0 to 4.8 with the exception of site S3 which was lower which might have been associated with the early phases of construction of the Manwan Dam which began in 1986 (Table 3.9). After the Manwan Dam became operational in 1995, the first large dam on the mainstream of Langcang River, the P-IBI decreased both downstream and in the reservoir the Manwan Dam. In contrast, the P-IBI upstream of the Manwan reservoir increased slightly to 3.9. After all three cascading dams became operational in 2011, the P-IBI decreased sharply in the Xiaowan reservoir area during both the rainy (2.4) and dry (2.8) seasons. The P-IBIs downstream of each dam were higher than those in the impoundment areas; however, all values decreased over time as compared to the pre-dam measurements (Table 3.9). These results indicate that the health of aquatic ecosystems both upstream and downstream from large dams will be negatively affected by the construction and operation of dams due to changes in the flow regime, the loss of lotic habitat, and nutrient accumulation in the reservoirs (Li et al. 2012b).

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