American Fisheries Society Symposium 00:000–000, 2016

The Yangtze River Floodplain: Threats and Rehabilitation

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Abstract.—The Yangtze (Changjiang) River floodplain is one of the most important ecosystems in China, as well as in the world, but is seriously threatened by multiple factors. Thus, it is crucial and urgent to rehabilitate the river floodplain. This paper reviews ecological studies conducted on the Yangtze River floodplain and presents suggestions for conservation and rehabilitation. First, the Yangtze River system is briefly introduced. Formed 23 million years ago, the Yangtze River is ca. 6,300 km in length with a mean annual runoff of 9.6 × 10^{11} m^3. Thousands of floodplain lakes are distributed along the mid-lower Yangtze River, and the total area remains 15,770 km^2 at present. Such a river-lake complex ecosystem holds a unique and diverse biota, with ca. 400 hydrophytes and hygrophytes, ca. 170 mollusks, ca. 200 fishes, ca. 400 water birds, and endangered dolphins and porpoises. Second, main threats to the Yangtze River floodplain ecosystem are identified: (1) habitat loss, including river channelization, sharp shrinkage of lake area (ca. 10,000 km^2 since the 1950s), degradation of lakeshore zones, and sand overmining; (2) alternations of hydrological regimes, including construction of ca. 47,000 reservoirs and disconnection of most lakes from the main stem; (3) water pollution, including eutrophication, heavy metals, and organic pollutants; and (4) overexploitation of biological resources, including overfishing and intensive pen culture. Third, effects of river–lake disconnection on lake ecosystems are summarized on the basis of our studies in the past 20 years. It was found that (1) disconnection is one of the main causes of lake eutrophication; (2) species diversity, biomass, and production of macrophytes and macrobenthos reach maxima at some levels of intermediate river connectivity; (3) disconnection greatly reduces fish species richness of each habitat guild, and natural fish larvae is severely depleted; and (4) disconnection simplifies macroinvertebrate food web structure, and the trophic basis of the simplified food web is more heavily dependent on detritus in disconnected. Last, conservation strategies are proposed. Since the Yangtze River floodplain is a huge integrated system, the biodiversity conservation must be conducted on the whole basin scale. By establishing species–area models of fishes, the minimum protected area of Yangtze-connected lakes is estimated to be ca. 14,400 km^2. It means that at least 8,900 km^2 of disconnected lakes should be reconnected with the Yangtze main stem, and ecohydrological operation of dams and sluices is the feasible approach. Based upon our preliminary studies on environmental flow requirements, the following measures are suggested: (1) lower water levels during spring to improve germination of macrophytes, and control rising rates of water levels during spring–summer to ensure development of macrophytes; and (2)

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open sluice gates to restore migration routes for juveniles migrating into lakes during April–September and for adults migrating back to the Yangtze main stem during November–December.

Introduction

The Yangtze River floodplain is one of the most important ecosystems in China, as well as in the world, but is facing multiple stressors, such as habitat loss, alternations of hydrological regimes, pollution, and overexploitation. Therefore, it is crucial and urgent to rehabilitate the river floodplain. In this paper, we present a review of ecology and conservation of the Yangtze River floodplain. First, we briefly introduce the Yangtze River system. Second, we identify main ecological threats. Third, we summarize the effects of river–lake disconnection on lake ecosystems. Last, we propose holistic strategies for conservation and rehabilitation.

The History and Current Status of the Yangtze River Floodplain

Introduction to the Yangtze River Basin and Its Geological History

The Yangtze River is the longest river in Asia and the third longest in the world. Originating from Geladandong Peak, the main peak of the Tanggula Mountains on Qinghai–Tibet Plateau, the Yangtze River flows ca. 6,300 km from west to east and enters the East China Sea. The total catchment area is 1.8×10^6 km^2, being one-fifth of China's land territory. The terrain slopes downward stair-like from west to east, with a total fall of ca. 5,400 m. The upper reaches are the course above Yichang, being 4,504 km in length and 1×10^6 km^2 in catchment area; the middle reaches are between Yichang and Hukou, being 955 km in length and 6.8×10^5 km^2 in catchment area; and the lower reaches start from Hukou, being 938 km in length and 1.2×10^5 km^2 in catchment area (Yu and Lu 2005).

There are more than 10,000 tributaries in the Yangtze River system. Among them, there are 437 rivers, each with a catchment area of more than 1,000 km^2, and 22 rivers, each with a catchment area of more than 10,000 km^2. Numerous lakes are distributed on the plateaus and floodplains. Plateau lakes in the upper basin are mainly freshwater lakes, with a few saltwater ones. Floodplain lakes in the middle and lower basins are all freshwater ones (Yu and Lu 2005).

The mean annual runoff of the Yangtze River is 9.6×10^{11} m^3, being one-third of the total amount discharged into the sea by Chinese rivers and ranking forth in the world. Approximately 46% of the Yangtze runoff is from the upper basin, 18% from the Lake Dongtinghu drainage system, and 15% from the Lake Poyanghu system. Runoff of the main stem and tributaries is markedly different between flood and nonflood seasons in a year. The runoff of the main stem in the flood season (May–October) is 79–82% of the annual total in the upper basin, and 71–79% in the mid to lower basins (Yu and Lu 2005).

In the Early Cretaceous period, the Yanshan Movement turned the entire Yangtze River basin into land. However, the Paleo-Yangtze had not yet born until the Paleogene. From the Late Paleogene to the Early Neogene, the uplift of the Qinghai–Tibet Plateau altered the air circulation of lower atmosphere, turned the trade wind into the seasonal wind, and changed the climate from hot and dry to warm and humid. Since the precipitation and runoff sharply increased, the ancient Yangtze River started to develop in several regions. The water system of the upper reaches, including the Jinshajiang, Yalongjiang and Chuanjiang (Sichuan River) paleorivers, ran south into the South China Sea, and the rivers below Yichang drained into the Jianghan basin and others (Yu and Lu 2005). With regards to the age of the Yangtze River system, Zheng et al. (2013) argued that the connection through the Three Gorges must postdate 36.5 Ma (million years ago) and a river, much like the modern one, was in existence before 23 Ma.

During the Late Pleistocene (23–15 ka BP [thousand years before present]), the climate was dry and cold, and the level of the East China Sea was 130–160 m lower than the present level. The bed of the Yangtze River was intensely downcut, and headward erosion gradually moved up to Yichang, forming a deep narrow valley in the mid to lower reaches; compared to the present level, the riverbed was 5–25 m lower and the mean water level was 20–40 m lower. In the Early Holocene (13–12 ka BP), the climate became warmer, and the level of the East China Sea was uplifted to an altitude 50–100 m below the present level. In the Mid-Holocene (7.5–4 ka BP), temperature reached the highest level of the postglacial period; the mean annual temperature in the lower Yangtze basin was 3–4°C higher than the present one, and the sea level was 2–3 m higher. At that time, the Yangtze estuary was around Zhenjiang and Yangzhou. Due to large areas of forests and lakes, the amplitude of water level fluctuation in the river was relatively small (IGSNRRCAS et al. 1985; Yu and Lu 2005).

In the Late Holocene (4 ka BP to now), the climate fluctuated between cold-dry and hot-wet, the amplitude of temperature change was ca. 3.5°C (Zhu 1972), and the sea level was ±3 m around the present. Since the Western Jin Dynasty (265–317), large populations in the north were compelled to migrate to the south due to turmoil of wars, and they deforested for farming and reclaimed land from lakes. Due to climate change and aggravated soil water erosion, sand bars emerged in the river course and the Yangtze estuary kept expanding further east from Yangzhou, reaching somewhere near the present estuary in the Tang and Song dynasties (618–1279). For reasons such as the shifting of the main stem to the right and the construction of left banks, lakes along the left bank shrank gradually while lakes along the right expanded (IGSNRRCAS et al. 1985).

Distributions of Rivers and Lakes in the Mid to Lower Yangtze Plains

Downstream from the Three Gorges, the Yangtze River runs east through the Lake Dongtinghu Graben basin, Lake Poyanghu Graben basin, lower Yangtze Geosyncline belt, and Taihu–Wusong Graben basins, forming a series of fluvial-lacustrine plains along the mid to lower reaches by sedimentation. The plains (108–122°E, 24–34°N) lie east–west for 1,800 km with a total area of ca. 1.6×10^5 km^2. The terrain is flat and low, with altitudes mostly ca. 50 m above sea level (ASL). Plains along the middle reaches consist of the Jianghan plain, Lake Dongtinghu plain, Edong plain, and Lake Poyanghu plain; those along the lower reaches comprise the Chaohu–Wanjiang plain and the Yangtze River delta among the Jiangsu and Zhejiang provinces and Shanghai (Figure 1; Zhao and Chen 1999).

The mid to lower Yangtze main stem is 1,893 km, with a sinuosity of ca. 1.6 (Figure 1). The main channel pattern is braided reaches, being 70% of the mid to lower river in length. The river course is characterized by alternation of broad braided reaches and narrow single channels, resembling lotus roots. At bank-full level, the mean river width (B) is 1,168–3,332 m and the mean depth (H) is 13–20.4 m, with $B^{0.5}/H$ of 1.88–4.45, and the maximum depth of the thalweg reaches 90.5 m. The longitudinal profile of the mid to lower course has a total fall of 56.4 m, with a mean slope of 0.34 (0.05–0.85) $\times 10^{-4}$ (IGSNRRCAS et al. 1985).

Numerous lakes are distributed along the mid to lower Yangtze River (Figure 1), with a total area of 15,770 km^2. They are divided into the following lake clusters: (1) The Jianghan–Dongtinghu plains lakes, distributed between Zhijiang and Wuxue. In the Mid-Holocene, this region was the vast waters of the paleo-Yunmeng Lake. Afterwards, great quantities of sand brought by the Yangtze River and its tributaries were deposited in the lake. As a consequence, land areas expanded while water areas shrank. The lake was thus divided into thousands of

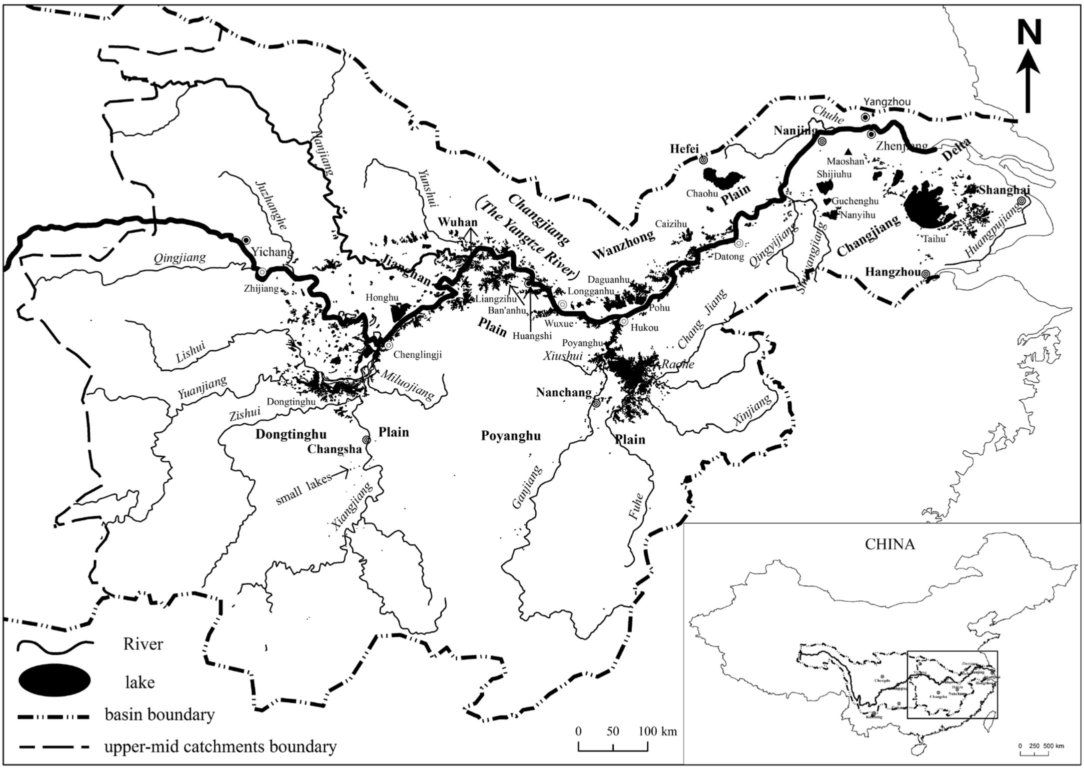

Figure 1. The mid-lower Yangtze River basin.

smaller lakes. At present, there remain more than 600 lakes, including Lake Dongtinghu, Lake Honghu, and Lake Liangzihu. (2) The Gan-Wan lakes, distributed between Wuxue and Datong. This group includes many lakes in eastern Hubei, southern Anhui, and the northern Jiangxi provinces, such as Lake Poyanghu, Lake Longganhu, Lake Bohu, and Lake Caizihu. (3) The Su-Wan lakes, distributed between Datong and Maoshan, including Lake Chaohu, Lake Nianyihu, Lake Shijiuhu, and Lake Guchenghu. (4) The Taihu plain lakes, distributed in the Yangtze River delta, including more than 200 lakes (Zhao and Chen 1999).

The origin of Yangtze lakes is roughly classified into five types (Rao 1956; Wang and Dou 1998): (1) Lakes formed by sedimentation in graben/depression basins. Since sedimentation rates are higher than subsidence rates, the lakes become shallower gradually. Typical ones are the Jianghan lakes, Lake Dongtinghu, Lake Poyanghu, and Lake Chaohu. (2) Lakes formed in abandoned channels. One type is formed by the mainstem migration, including the oxbow lakes along the middle reaches and the Yangtze-side lakes between Huangshi and Datong. Another type is irregular long lakes formed by obstruction of tributaries. (3) Lateral levee lakes, formed by overflowing narrow lowlands or valleys along floodplain boundaries. The outlets were blocked by sedimentation. Typical ones are Lake Luhu and Lake Liangzihu around Wuhan. (4) Scour lakes, deep pools scoured by floods after banks burst. (5) Lakes formed by river action on lagoons, such as Lake Taihu.

Climate and Hydrologic Features of the Mid to Lower Yangtze River Floodplain

The mid to lower Yangtze basin mostly belongs to the subtropical monsoon zone. The annual mean temperature is 13–20°C and the annual accumulated temperature (≥10°C) is

4,000–6,500°C. The mean temperature of the coldest month (January) is above 0°C, being 0–2°C in areas north of the main stem, 2–10°C in areas south of the main stem, and 10–12°C in the Nanling mountainous areas. The freezing duration is short, and the frost-free season lasts for ca. 285 d. The annual precipitation is 800–1,600 mm. It decreases from southeast to northwest, being 1,200–1,800 mm in east hill areas, ca. 1,500 mm in mountainous areas south of the Yangtze main stem, and 1,000–1,200 mm in the Yangtze plains. Seasonally, precipitation ranks first in summer, being 40% of the annual total in June–August; second in spring; third in fall; and least in winter (but also >10%) (Zhao and Chen 1999).

In the mid to lower Yangtze main stem, the multiyear mean discharge is from 13,900 m^3/s at Yichang to 28,700 m^3/s at Datong, and the mean annual runoff is from 4.38×10^{11} m^3 at Yichang to 9.60×10^{11} m^3 in the estuary. The runoff in May–October is more than 70% of the annual total, with a peak in July. The multiyear mean water level is from 43.8 m ASL at Yichang to 8.7 m ASL at Datong. The water level is highest in July–September and lowest in December–February, with annual fluctuation amplitude of 13.5–18.4 m. The water table slope is $(0.193–0.579) \times 10^{-4}$ in the middle main stem and $(0.097–0.0203) \times 10^{-4}$ in the lower. The sediment content of water is moderate. The multiyear mean sediment concentration is from 1.14 kg/m^3 at Yichang to 0.48 kg/m^3 at Datong, and the mean annual sediment runoff is from 5.0×10^8 metric tons (mt) at Yichang to 4.3×10^8 mt at Datong (Yu and Lu 2005).

As a consequence of human disturbance, hydrological regimes of the Yangtze floodplain lakes have been altered to various extents. According to water level fluctuations (WLFs), three lake types can be identified (Table 1). The first WLF type is quasi-natural. It is similar to the WLF of the Yangtze main stem, with large fluctuation amplitude. This type includes all Yangtze-connected lakes and some disconnected ones. The second WLF type is intermittent. This type includes lakes connected to rivers or Yangtze-connected lakes only during the high-water level period, with moderate fluctuation amplitude. Water levels are low and stable during the low-water level period. The third WLF type is reservoir-like WLF. It mainly includes Yangtze-disconnected lakes, with small fluctuation amplitude. Before the flood season, lakes are drained to the lowest water levels for flood control. After the flood season, sluice gates are shut to store water and lakes are kept at high water levels.

Environments and Biological Resources of the Yangtze River Floodplain

The Yangtze floodplain lakes are characterized by their shallow, flat, and large basins. The mean water depth of these lakes is generally ca. 2 m and rarely over 4 m. There are 18 lakes each with an area larger than 100 km^2. Because of these characteristics, interaction between water and sediments happens frequently in the lakes under the influence of monsoon climate. Moreover, the lakes are characterized by high levels of nutrients. Thus, the transparency is quite low (Table 2). In the main stem, total nitrogen was lower, but total phosphorus was higher (Table 2).

The nutrient levels of the lakes were found to be high (ca. 50 μg/L) back in history, according to a palaeolimnological research (Yang et al. 2006). With a combination of high nutrients and good water-heat conditions, a unique and diverse biota has been evolved in the Yangtze River and lakes complex ecosystems. There are ca. 400 recorded species of hydrophytes and hygrophytes (Zhang 2013), 167 mollusk species with 92 endemic to China (Shu et al. 2009), ca. 200 fish species with 50% endemic to China (Yu et al. 2005; Liu and Wang 2010), ca. 50 reptile species, ca. 400 water bird species, and more than 60 mammal species, including endangered river dolphin *Neophocaena phocaenoides* and finless dolphin *Lipotes vexillifer* (Fang et al. 2006a).

The abundances of plankton, macrophytes, and macroinvertebrates are rather high in the lakes, but very low in the main stem (Table 2). Fishes are abundant in the

Table 1. Hydrological features of typical lakes on the Yangtze floodplain.

Lake	Connectivity with Yangtze	Water level fluctuation (WLF) type	Lake area (km^2)	Catchment area (km^2)	Mean depth (m)	Maximum depth (m)	WLF amplitude (m)	Lake volume (m^3)	Annual water turnover
Dongtinghu	Connected	Quasi-natural	2,432.5	257,000	6.39	23.50	13.35	178.00	18.30
Honghu	Disconnected	Quasi-natural	344.4	10,352	1.91	2.20	2.13	6.58	1.92
Liangzihu	Disconnected	Reservoir-like	304.3	3,265	4.16	6.20	2.82	12.65	1.17
Poyanghu	Connected	Quasi-natural	2,933.0	162,000	5.10	29.19	13.31	249.00	6.40
Dahuchi (sublake of Poyanghu)	Seasonally connected	Intermittent	36.7		4.55	6.00	3.50	1.67	
Shahuchi (sublake of Poyanghu)	Seasonally connected	Intermittent	14.0		0.45	3.96	3.40		
Shengjinhu	Disconnected	Quasi-natural	78.5	1,554	1.26	3.50	6.98	0.99	
Chaohu	Disconnected	Reservoir-like	769.6	9,258	2.69	3.77	2.46	19.00	2.17
Taihu	Disconnected	Reservoir-like	2,338.1	36,895	1.90	2.60	1.26	44.28	1.18

Table 2. Basic limnological characteristics of lakes and the Yangtze main stem in the mid to lower Yangtze River basin (reanalyzed from Wang et al. 1999, 2005, 2006, 2007, 2008, 2014; Feng 2005; Pan et al. 2009, 2011a, 2011b, 2014; Wang and Wang 2009; Zhao 2010). Ind = individuals; "–" = no data.

Parameters	Lakes				Yangtze main stem
	Mean	Median	Min	Max	(mean)
Secchi depth, m	1.1	0.9	0.3	3.3	0.41
Total nitrogen of water, mg/L	2.02	0.94	0.07	13.7	0.66
Total phosphorus of water, mg/L	0.11	0.04	0.005	0.76	0.13
Phytoplankton chlorophyll *a*, µg/L	16.5	4.4	0.8	139	1.69
Density of phytoplankton, 10^4 ind/L	947	361	16	6,615	–
Biomass of phytoplankton, mg/L	6.3	2.3	0.2	35.3	–
Density of zooplankton, ind/L	2,032	1,518	233	16,145	17.5
Biomass of zooplankton, mg/L	2.2	1.5	0.4	8.3	0.07
Biomass of submersed macrophytes, wet mass, g/m^2	931	295	0	9,484	Rare
Biomass of emergent macrophytes, wet mass, g/m^2	406	82	0.4	1,728	–
Density of macroinvertebrates, ind/m^2	864	259	8	23,194	91
Biomass of macroinvertebrates (mollusks with shells), wet mass, g/m^2	30.0	16.1	0.005	313	0.17

river floodplain, and the fish yield of natural lakes was 75–135 kg/ha (Wu and Jao 1958).

Main Threats to the Yangtze River Floodplain Ecosystem

Habitat Loss

River channelization.—Embankments along the mid to lower Yangtze River was initiated between 345 and 356 during the Eastern Jin Dynasty and began to take shape during the Ming and Qing dynasties (1368–1911). Discrete dikes had been gradually connected together by that time, and the total length was ca. 3,600 km, forming a huge system (Wang 1959). Prior to 1950, the river course was changed frequently due to the weakness of embankments. Since then, embankment engineering along the Yangtze main stem has been conducted on a large scale and the river regime has been stabilized, resulting in serious channelization. The work includes three major engineering projects (Yu and Lu 2005). The first one is dykes reinforcement, especially along the reaches with bank caving. Over more than 50 years, the total volume of enrockments is 8.9 × 10^7 m^3, the total area of sunken fascine mattress 4.9 × 10^6 m^2, the number of spur dikes 685, and the total length of longitudinal dikes 20 km. The total length of reinforced bank is ca. 1,400 km. The second one is cut-off of meanders. In 1966–1972, three meanders were cut off from the lower Jingjiang in the middle Yangtze. The river length was shortened by 78 km, with sinuosity reduced from 2.83 to 1.93, and the slope was increased. As a result, the riverbed was severely eroded and the water level was lowered, reducing river water flowing into Lake Dongtinghu. The third one is blockage of secondary channels. Since the 1970s, secondary channels in 7 of 41 braided reaches were blocked. After blockage, flow regimes were simplified and main channels were deepened. With regard to ecological effects of channelization along the mid to lower Yangtze, no systematic studies have been conducted. The probable impacts are habitat loss, environmental heterogeneity decrease, and biodiversity decline.

Sharp shrinkage of lake area.—Since the Western Jin Dynasty (265–317), large fluxes of northern Chinese have migrated to the Yangtze basin many times. Due to land reclamation from lakes and sedimentation caused by deforestation, the area of Yangtze lakes began to decrease (IGSNRRCAS et al. 1985). Land reclamation reached a considerable scale in the Southern Song Dynasty (1127–1279), rapidly increased during the Ming Dynasty (1368–1644), and peaked in the middle of the Qing Dynasty (1644–1911) (Du et al. 2011). In 1949, the total area of lakes was 25, 828 km^2 (CWRC 1999). From the 1950s to 1970s, the reclaimed area sharply increased, and the area of remaining lakes is only 15,770 km^2 at present.

In the Jianghan and Dongtinghu plains of the middle basin, the total lake area was reduced by 5.2% between the 1930s and 1950s, by 46.4% between the 1950s and 1970s, and by 17.5% between the 1970s and 2000 (Du et al. 2011; Figure 2). The major cause is land reclamation, and the second is sedimentation. Historically, forest coverage of the Yangtze basin was 50–60%, but it decreased to 30–40% in the 1950s and to 10% in 1986 (cited from Wei et al. 2007). This resulted in increased soil erosion, and the rate of sediment accumulation reached 1.6–3.4 mm/year in three lakes of the Jianghan plain, and 10–30 mm/year in Lake Dongtinghu (cited from Du et al. 2011). The siltation in lakes further stimulated the reclamation process.

Degradation of lakeshore zones.—In many Yangtze lakes, shore zones have degraded or even disappeared due to human activities such as land reclamation, urbanization, and road construction. Natural shorelines have been artificially replaced by hard banks

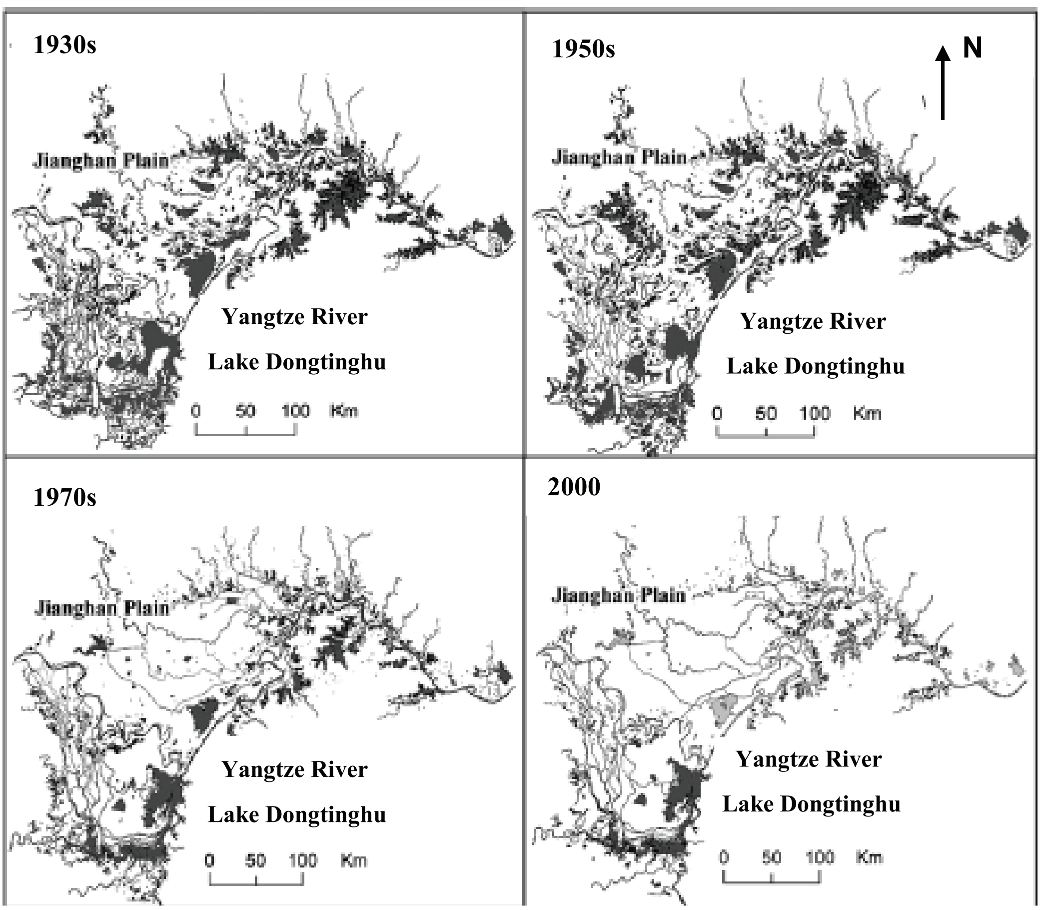

Figure 2. Lakes from the Jianghan Plain and the Dongtinghu Plain in the 1930s, 1950s, 1970s, and 2000. (From Du et al. 2011.)

(rocks and concrete). For example, in Lake Chaohu along the lower reaches, stone bank is 129.0 km long, cement revetment is 40.7 km long, and both are 90% of the whole shoreline length (Wang et al. 2012). Meanwhile, a vast area of the riparian zone has become impermeable ground. Degradation of lakeshores results in deterioration of aquatic and terrestrial vegetation along shorelines, diminution of capabilities to intercept external pollution and to reduce internal loading, and loss of lake-ecosystem integrity.

Sand overmining.—Sand mining in the Yangtze main stem began in the 1950s, and limited amounts of cobbles were collected from the Jinjiang reaches during low-water periods. Since the 1980s, the amount and extent of sand mining by machines increased gradually and the ship number reached thousands, but most of these activities were unauthorized. Due to serious damage of sand overexploitation, the State Council enacted a regulation on sand mining in the Yangtze River, which has been in force since 2002. Up to now, sand mining in the main stem has been controlled (Wu and Li 2010). However, large-scale sand mining moved quickly to Lake Poyanghu and Lake Dongtinghu, and their tributaries afterwards. Taking Lake Poyanghu as an example, mining ships increased from 140 in 2001 to 450 in 2005; after 2010, mining area enlarged from the north to the middle, and more than 90 additional ships were added (Cui et al. 2013). Recently, local governments began to issue relevant rules to control the serious situations of unauthorized sand mining.

Sand overmining should have very serious impacts on river floodplain ecosystems, but no systematic studies have been conducted. According to some reports (Zhang and Huang 2008; Wu and Cui 2008; Ma and Xu 2013), the negative effects may include five aspects. First, large amounts of sediment are pumped out and habitats of benthic animals and aquatic plants are destroyed. Second, suspended substance dramatically increases. For example, in northern Lake Poyanghu, suspended substance reached 0.35 kg/m^3, and Secchi depth in the summer dropped from 1.5 to 0.1–0.5 m. Turbid water affects plankton directly and inhibits plant growth. Third, pollution of wastewater, oil, garbage, noise, light, and so forth from mining ships is produced, and probably release of sediment pollution due to disturbance is enhanced. Fourth, feeding, breeding, migration, communication, and other activities of fishes, finless porpoise, water birds, and so forth are affected. Fifth, hydrogeomorphology and related processes are changed, resulting in bank collapse and decrease of lake and wetland area.

Alternations of Hydrological Regimes

Cascade reservoirs in the main stem and tributaries.—By 2009, ca. 47,000 reservoirs had been built in the Yangtze basin. The total storage capacity was 2.5 × 10^{11} m^3, and the usable capacity was 1.2 × 10^{11} m^3, being 25% and 2% of the multiyear mean surface runoff of the Yangtze River. Among them, there were 166 large reservoirs, with 38 in the upper basin, 114 in the middle basin, and 14 in the lower basin (Chen 2012). Moreover, many new reservoirs are being constructed or planned, and the South–North Water Diversion Projects are being implemented.

Due to multiple factors, such as hydraulic projects, water use for industry and agriculture, climate changes, and land-use changes, hydrological regimes of the mid to lower Yangtze main stem and floodplain lakes have been greatly altered. Next, we take the changes after impoundment of the Three Gorges Reservoir (TGR) as an example. First, the mean annual runoff below the dam after the impoundment was reduced by 6–10% during 2003–2007 (CAE 2010). The water release from TGR was decreased greatly from mid-September to November to store water, but it increased from January to June; during the major flood season, it was reduced only at risk of serious flooding (Wang and Chen 2010; Zhang et al. 2013). Second, the mean annual sediment discharge below the dam after the impoundment was greatly reduced by 63–86% during 2003–2007, and the sediment released from TGR became much finer. This resulted in riverbed erosion, even down to the Datong reach in the lower basin, and the water level at equal discharge during the flood season was decreased by 0.1–1 m. The most serious erosion occurred in the Yichang–Chenglingji reach, with scour depth in the thalweg up to more than 10 m. The amount of sediment flowing into Lake Dongtinghu from the Yangtze main stem was greatly reduced, and the mean annual sedimentation rate in 2003–2006 was reduced by 90.7%, thus prolonging the lifetime of Lake Dongtinghu (CAE 2010). Third, water storage in TGR and riverbed scour downstream changed water levels of the main stem and Yangtze-connected lakes and their fluctuation rhythms. It was estimated that the water level in the middle reaches decreased by 2–3 m while storing water and increased by 0.6–0.8 m in January–March (Wang and Chen 2010). During 2003–2007, the water level of Lake Dongtinghu (at Lujiao station) increased by 0.5–1 m in January–March but deceased by 1.2–1.4 m in July–August and by 1.5–2.2 m in October–November; the water level of Lake Poyanghu (at Hukou station) increased by 0.9–1.4 m in January–March but decreased by 0.1–0.2 m in July–August and by 1.3–1.5 m in October–November (Shi et al. 2011). Fourth, water temperature was changed. During 2003–2008, the water temperature at Yichang gauging station of the main stem increased by 0.5–2.3°C in October–January but decreased by 0.3–1.8°C in March–May (Li et al. 2013).

The alterations of hydrological regimes exert great impacts on the river floodplain ecosystem along the mid to lower Yangtze River. First, the drop of water levels in the Yangtze main stem during summer and autumn blocks the exchange of matter and energy with the floodplain, decreasing floodplain area, habitat heterogeneity, and species diversity (Poff and Hart 2002; Shi et al. 2011). Second, alternations of water level fluctuation rhythms affect wetland vegetation. The rise of water levels in spring can retard germination of hygrophytes and emergent macrophytes, and the drop of water levels in autumn can kill submersed macrophytes, and invertebrates such as bivalves by drought (Xu and Chen 2013; Zhang 2013; Zhang et al. 2014). Since vegetation can provide important habitats and food bases, wildlife resources, including water birds and fishes, were affected seriously (CAE 2010). Third, the lowering of flood peaks and water temperature from spring to early summer retards fish spawning, and fish resources declines seriously. After the impoundment of TGR, the initiation of the spawning season was delayed ca. 1 month, early growth and development was suppressed, and the eggs and larvae were reduced by 90% (Xie et al. 2007; Zhang et al. 2011). Also, the earlier drop of water levels in autumn may disturb fish migration (Ru and Liu 2013).

River–lake disconnection.—From the mid-1950s to 1960s, most lakes were disconnected from the Yangtze main stem by embankments and sluice gates, leaving few connected lakes, including Lake Dongtinghu, Lake Poyanghu, and Lake Shijiuhu, at present. After disconnection, water level fluctuations in the lakes became reservoir-like. Taking Lake Chaohu (777 km^2) as an example (Figure 3), before damming the water level reached a maximum in summer and dropped to a minimum in early spring, with fluctuation amplitude of over 2 m; afterwards, the amplitude was only 1 m and water level dropped to a minimum before the flood season. Ecological effects of river–lake disconnection will be discussed in detail later in this paper.

Water pollution.—The discharge of wastewater and sewage in the Yangtze River basin has been continuously increasing since the 1970s. The total amount increased from 9.5×10^9 mt/year in the late 1970s through 1.5×10^{10} mt/year in the late 1980s and 2.0×10^{10} mt/year in the mid to late 1990s to 4.4×10^{10} mt/year in 2012 (Figure 4; MWR 2004–2013). More than 80% of the wastewater is discharged into the mid to lower basins.

Lake eutrophication is one of the severe impacts of excessive wastewater and sewage. More than 40% of the lakes were in eutrophic–hypertrophic states (Figure 5). Two of the four largest lakes herein, Lake Taihu and Lake Chaohu, have suffered very severe

Figure 3. Alteration of water levels before (1956–1960) and after (2007–2011) building sluices in Lake Chaohu. (From Zhang et al. 2014.)

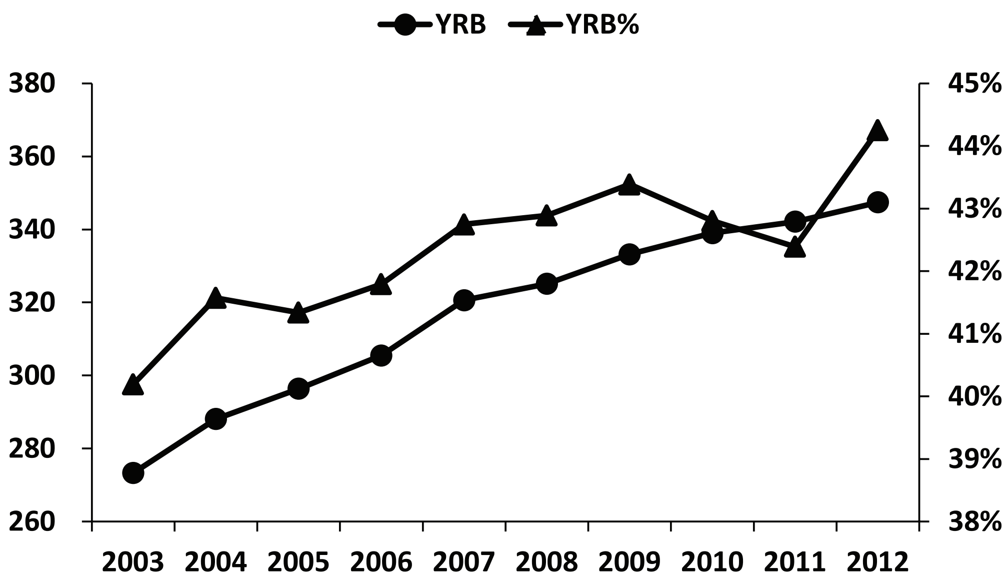

Figure 4. Amount of wastewater and sewage discharged in the Yangtze River basin (YRB) between 2003 and 2012 (108 metric tons) and its percentage of the total amount in China (YRB%). (Data from MWR 2004–2013.)

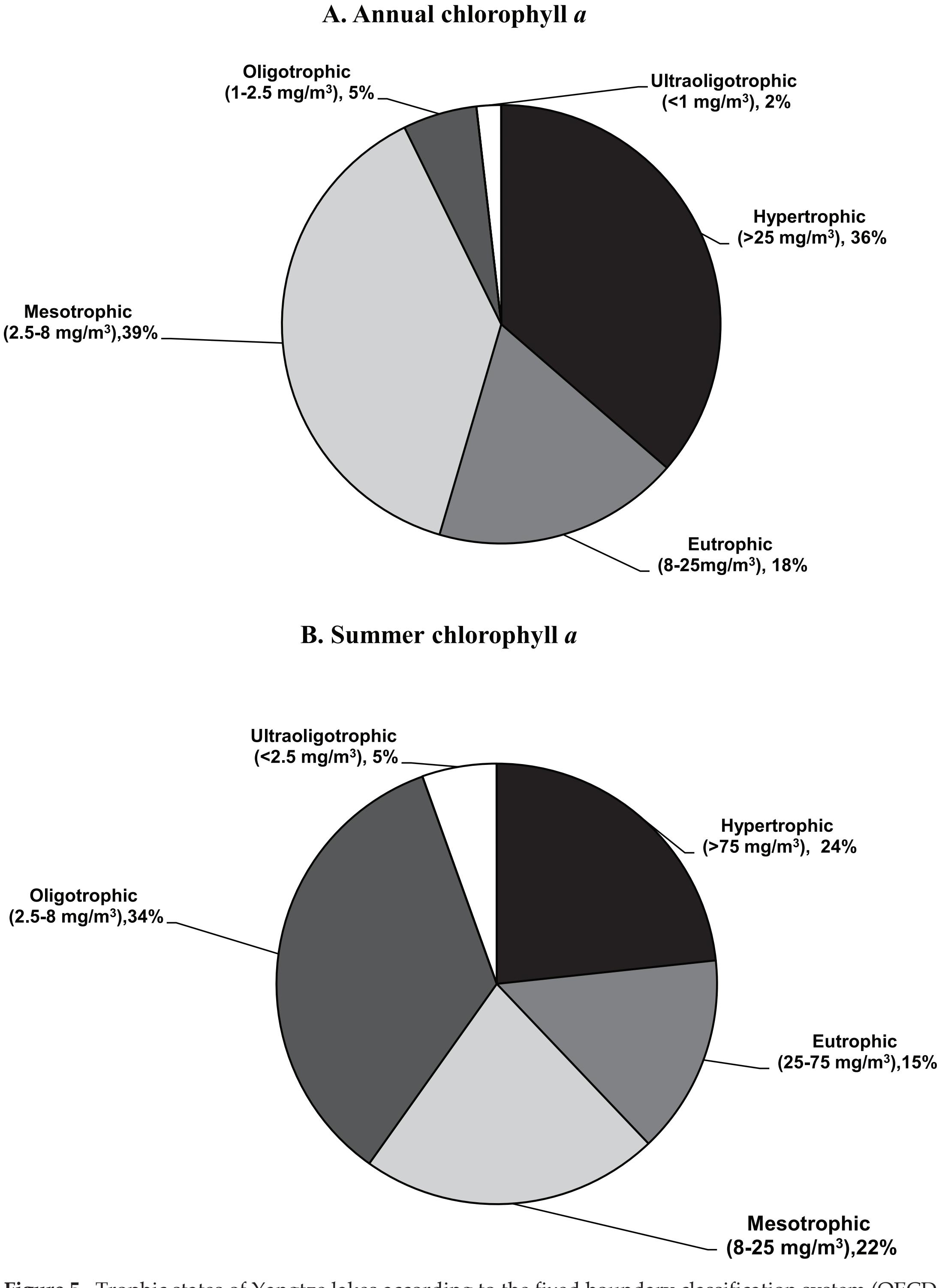

Figure 5. Trophic states of Yangtze lakes according to the fixed boundary classification system (OECD 2006). (From Wang 2007.)

cyanobacteria blooms for decades (Zhu 1996; Lin 2003; Xie 2009).

Pollution of heavy metals and organic pollutants are among other impacts on the lakes. In the main stem (Wuhan, Hubei), ca. 64% of sediment sites were polluted by heavy metals to a medium level of ecological hazard; contents of eight metal species were higher than the background soil levels (Shen et al. 2008). In lakes (Wuhan, Hubei), heavy metals pollution in the sediment was more severe. The contents of four out of eight metal species were more than twice as much as the background levels, and the average content of zinc was as high as 297 μg/g in Lake Donghu, Lake Longyanghu, and Lake Moshuihu (Shen et al. 2008). Concentrations of persistent organic pollutants were higher than the standards in many lakes (Wuhan); 19 species of organo-chlorine pesticides were detected in Lake Honghu (Fang et al. 2006b).

Overexploitation of biological resources.— Biological resources in the Yangtze River floodplain have been seriously overexploited. In the main stem and connected lakes, eletrofishing boats and fine-meshed (0.5–1 cm) fish traps are the main direct threats to fish resources (Cao 2011). Due to overfishing as well as reservoirs construction, river-lake disconnection, and pollution, fish yield in the whole river-lake system has decreased from 4.3×10^5 to 1.0×10^5 mt/year between the 1950s and 2000s (cited from Liu and Wang 2010). The famous Reeves Shad *Tenualosa reevesii* has disappeared from the Yangtze River; Tapertail Anchovy *Coilia ectenes* and pufferfish have become rare, and natural populations of the four major domestic Chinese carps have sharply decreased (Cao 2008, 2011). Meanwhile, mollusks and other organisms have been also overused as human and fish food or for other purposes.

In disconnected lakes, pen culture has become the dominant fishery model in the past 20 years, overstocking Chinese mitten crab *Eriocheir sinensis* in most cases. Although useful for production and management, pen culture can have severe negative effects on ecosystems. In Lake Biandantang (Hubei), after years of continuous intensive crab culture, submersed macrophytes declined from coverage of ca. 90% in 1991 to less than 5% in 2002 and disappeared in the end; Secchi depth was only 1.1 m, being around half of the original state. Under the stocking density of 1 kg/ha of crab larvae or juveniles, the density and production of macroinvertebrates were reduced by more than 60% (Xu et al. 2003). Besides, fish culture using chemical fertilizer is also common, especially in small to medium-sized lakes, thus worsening eutrophication in this region.

Ecological Effects of River–Lake Disconnection on Yangtze Floodplain Lakes and the Mechanisms

We focused upon this issue in the past 20 years, and the results are summarized as follows.

Plankton

The mean species number of phytoplankton in Yangtze-connected lakes was 25% higher than that of disconnected lakes while the total density of the former was 42% lower (Wang and Wang 2009). The dominant taxon of connected lakes was cryptophytes while that of disconnected lakes was cyanobacteria. Densities of cyanobacteria, chlorophytes, and bacillariophytes in connected lakes were obviously higher than those of disconnected lakes, while those of cryptophytes and euglenophytes were in reverse. The mean species number of zooplankton (rotifers, cladocerans, and copepods) in connected lakes was ca. 30% lower than that of disconnected lakes, and densities of the total and each group in the former were much lower.

Phytoplankton chlorophyll *a* (Chl *a*) of disconnected lakes (30 μg/L) ranked first, lentic area of connected lakes second (5.0 μg/L), and lotic area of connected lakes third (2.1 μg/L), while total nitrogen (TN) and total phosphorus (TP) of lake water were in different order (TN: 2.6 mg/L, 1.2 mg/L, and 1.5 mg/L; TP: 0.2 mg/L, 0.06 mg/L, and 0.13 mg/L) (Wang and Wang 2009). This means that the highest abundance of phytoplankton in disconnected lakes cannot be explained by nutrient alone. A further analysis showed that TP is the limiting factor of Chl *a* in disconnected lakes as well as in lentic areas of connected lakes, but the slope of the TP-Chl *a* regression in the former was about twice as great as that in the latter (Figure 6). This disparity may mainly be attributed to the different residence times. In lotic areas of connected lakes, the limiting factor of Chl *a* is water current. Chl *a* had a parabolic relationship with surface velocity, reaching a vertex at the velocity of 0.12 m/s. When current is slow, Chl *a* tends to increase with velocity, due to the fact that higher flow is closely linked to greater input of external nutrient sources. When current is fast, Chl *a* tends to decline, suggesting that current inhibition has prevailed over nutrients effects on growth of algae. Fast current may cause high concentrations of suspended substance, resulting in light limitation on algal growth. The above analyses demonstrate that river–lake disconnection makes lake water more still, and then phytoplankton propagate in large numbers. Similarly, due to stable environment and plentiful food of phytoplankton, zooplankton develops well in disconnected lakes.

Macrophytes

There was no significant difference in the mean species number of the total as well as floating and submerged species between Yangtze-connected and disconnected lakes (Wang and Wang 2009). The species number of emergent macrophytes in disconnected lakes was 40% higher than that of connected lakes while that of hygrophytes was 8% lower in the former.

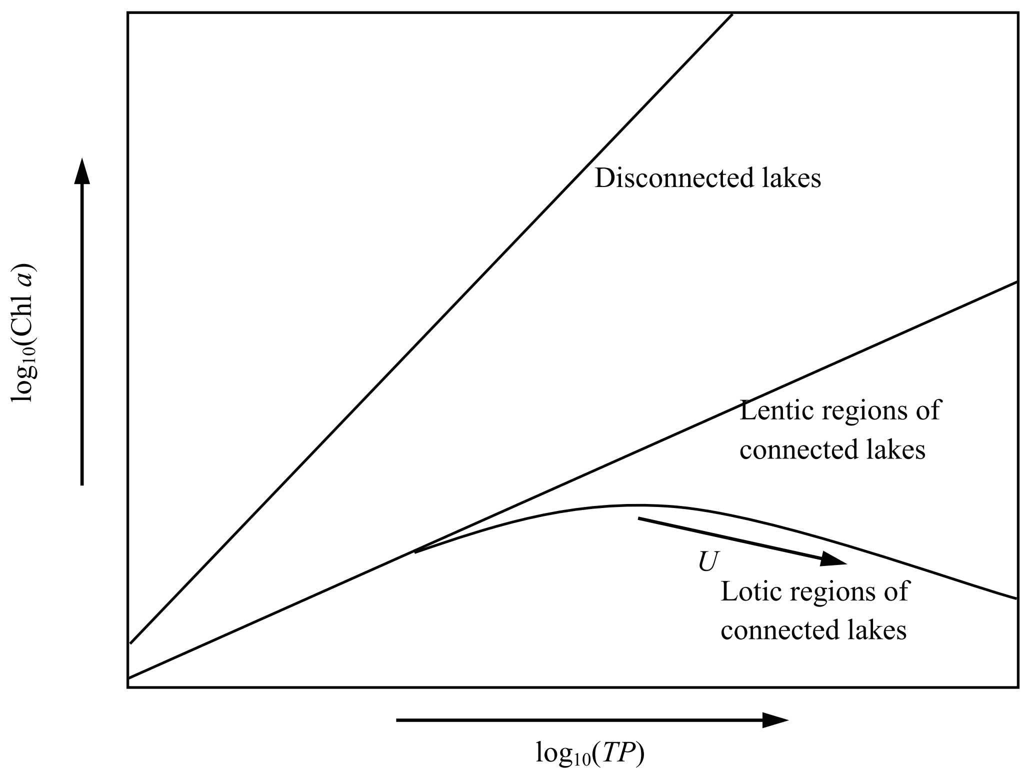

Figure 6. Comparison of phosphorus–chlorophyll *a* regression lines from Yangtze-connected and disconnected lakes. TP = total phosphorus of lake water; Chl *a* = phytoplankton chlorophyll *a*; *U* = water velocity. (From Pan et al. 2009.)

Hygrophytes develop very well in the Yangtze-connected lakes, with coverage up to 15% and biomass up to 1,500 g/m^2, but develop poorly in disconnected lakes. Emergent macrophytes can grow well in connected and disconnected lakes, with biomass up to 2,000 g/m^2 but coverage lower than 10%. Freely floating macrophytes occur more frequently in disconnected lakes, but coverage and biomass are very low. Floating-leaved macrophytes may cover large areas in the two lake types, but biomass is relatively low. Submerged macrophytes develop better in disconnected lakes than in connected ones, with coverage up to 80% and 40%, respectively, and biomass up to 2,600 and 1,200 g/m^2, respectively (Wang and Wang 2009).

In terms of dominant species, hygrophytes are dominated by the genus *Carex* in connected lakes and *Cynodon dactylon* in disconnected lakes. Emergent macrophytes are dominated by *Phragmites australis* and *Triarrhena lutarioriparia* in connected lakes and by *P. australis* and *Zizania latifolia* in disconnected lakes. For submerged macrophytes, the dominant species in connected lakes are *Potamogeton malaianus*, *Hydrilla verticillata*, *Ceratophyllum dermersum*, and *Vallisneria spiralis*. Among them, *P. malaianus* prefers waters with larger water level fluctuation amplitude while the others prefer areas with lower connectivity. The dominant submerged species in disconnected lakes are *P. maackianus*, *H. verticillata*, *C. dermersum*, and *V. spiralis*. Among them, *P. maackianus* dominates the climax community. The dominant submerged species usually shifts from *P. malaianus* to *P. maackianus* after river–lake disconnection.

There are two mechanisms for disconnection to change macrophytes. First, water level fluctuations (WLFs) are altered (e.g., Figure 3). Water level fluctuation amplitude is closely correlated with diversity and biomass of all macrophytes. Species richness maximizes at an intermittent level of fluctuation amplitude (ca. 5 m; Figure 7). Biomass of hygrophytes increases with fluctuation amplitude while that of submerged macrophytes decreases (Figure 7; Zhang 2013). The fluctuation amplitude is decreased in disconnected lakes, thus resulting in decreased coverage and biomass of hygrophytes and increased submerged macrophyte biomass. After disconnection, the reduced rate of water-level change is also harmful to hygrophytes development. If WLF type is changed as reservoir-like, this can lead to degradation of all vegetation. For example, vegetation coverage in Lake Chaohu has decreased from 30% before disconnection to less than 1% at present (Zhang et al. 2014). Second, other habitat conditions are changed. In disconnected lakes, water velocities decrease so sediment concentrations of water decrease, and the lake bottom is covered with more silt, thus favoring freely floating and submerged macrophytes.

Macrobenthos

Compared with those of the Yangtze main stem and disconnected lakes, macrozoobenthos of the Yangtze-connected lakes are characterized by higher diversity (Wang et al. 1999, 2007; Pan et al. 2011a). This pattern of species richness conforms to the theory that α diversity of macrobenthos in floodplain waters reaches a maximum at an intermediate level of connectivity (Amoros and Bornette 2002). Mollusks in connected lakes were especially species-rich, and the total number of species was about four times as high as that in disconnected lakes; the total number of insect species in connected lakes was about 1.5 times as high as that in connected lakes; the total number of oligochaete species and other animals in connected lakes was about twice as high as that in connected lakes. This result seems attributable to habitat heterogeneity within such a large lotic-to-lentic area. For example, bottom structures of connected lakes range from silt to sand and to gravel, but in disconnected lakes, sediment is primarily with silt. Also, river–lake disconnection can indirectly affect macrobenthos by changing vegetation types.

River–lake disconnection affects standing crops of macrobenthos to a considerable extent (Pan et al. 2011a). Although total

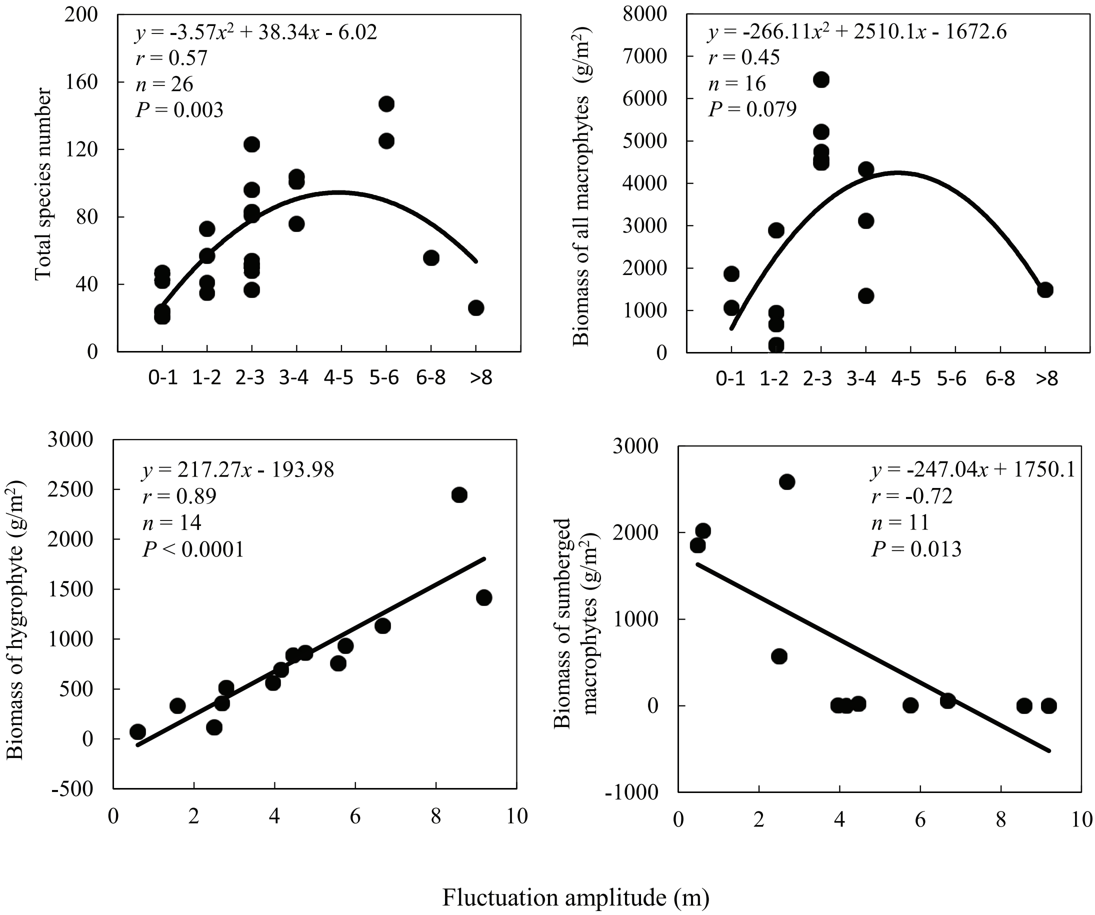

Figure 7. Relationships between water level fluctuation amplitude, and species richness and biomass of macrophytes in Yangtze floodplain lakes. (From Zhang 2013.)

densities had no much difference, connected lakes had abundant bivalve filters such as the genus *Corbicula*, which was more than eight times denser than that in disconnected lakes. Oligochaetes and insects were more abundant in disconnected lakes, and the density of each was 4.6 times and 4.5 times as high as that of connected lakes, respectively.

Along the river connectivity gradient, the change patterns of functional groups of macrobenthos in Yangtze lakes could be classified into three types (Pan et al. 2011a). First, density, biomass, and production of shredders, collector-filterers, and predators show unimodal changes. Shredders (e.g., the genus *Stictochironomus*) feed on coarse particulate organic matter, such as decaying leaves. Therefore, their abundance should increase due to more external organic matter brought by increased river inflow but may be inhibited in case of overdisturbance. At an intermediate level of river connectivity, the substrate is hard and sandy in general (Figure 8C), and suspended organic particles are relatively abundant (Figure 8C). Thus, the substrate favors filterers (mainly bivalves). At a high level of river connectivity, the substrate becomes unstable and water is full of inorganic particles so that filterers would not be supported. The increase of predators (e.g., the family Dytiscidae) at the initial stage may be the result of reduction in macrophytes because plants can provide refuges for zoobenthos and impede predation. The decrease of predators at later stages seems to be caused by high turbidity and habitat instability. High turbidity may prevent predators from seeing prey (Figure 8C). Second, density, biomass, and production decrease when river connectivity increases. This pattern is represented by collector-gatherers (mainly the families Tubificidae and Chironomidae). Collector-gatherers mainly consume fine particulate organic matter, so their decrease probably is caused by the fact that the organic-rich silt diminishes with increasing river connectivity (Figure 8C). Third, density decreases with increasing river connectivity, whereas biomass and production change unimodally. Scrapers exhibit this trend. The decrease of scrapers density could be ascribed to the reduction of macrophytes, which small-sized gastropods prefer (Figure 8C). The increase of biomass and production at the initial stage could be ascribed to the replacement of small-sized epiphytic gastropods (mainly the family Bithyniidae) by large-sized bottom dwellers (mainly the genus Bellamya), and the decrease at later stages may result from the increase of sand fractions. Because of instability and detritus shortage, sandy bottoms in the Yangtze-connected lakes should not be suitable for scrapers, which feed mainly on detritus there. In terms of total benthos, density decreases with increasing river connectivity (Figure 8A), showing the same pattern with the dominant groups in density (i.e., scrapers and collector-gatherers). Biomass and production change unimodally (Figure 8B), showing the same pattern with the dominant groups in biomass (i.e., scrapers and collector-filters).

Fishes

By comparing species–area relationships of fishes in Yangtze-connected and disconnected lakes (Figure 9), our study shows that river-lake disconnection reduced the total species number in lakes on the Yangtze River floodplain by 38.1% on average. In terms of habitat guilds in disconnected lakes, river–sea migratory fishes was reduced by 87.5%, riverine fishes by 71.7%, river–lake migratory fishes by 40.6%, and lake resident fishes by 25.4% (Figure 9A–D). The reduction in fish diversity after river-lake disconnection should be attributed mainly to the blockage of migration routes, the loss of fluvial environments in which some species spend parts of their life cycle, and decreased habitat heterogeneity.

The resource of eggs and larvae of four domestic Chinese carps in the Yangtze main stem was estimated to be 1×10^{11} in 1964 (Yi et al. 1988) but was reduced to only 1.7×10^{10} in 1981 (STSGDFCR 1982). River–lake disconnection is one of the main causes for the observed decline in fish larvae.

Food Webs

As stated above, river–lake disconnection changes lake communities completely, thus affecting the food web structure. For example, macroinvertebrate food web structure differs greatly between Yangtze-connected and disconnected lakes, and the food web of the latter is much simplified (Figure 10; Liu et al. 2006; Liu and Wang 2008). The numbers of total species, macroinvertebrate species, functional groups, predators, and total links are much higher in connected lakes than in disconnected ones. By contrast, connectance and connectivity are much lower in connected lakes, indicating that the species interaction strength is weaker in these lakes than that of disconnected ones. Connected lakes have more heterogeneous habitats and wider range of food resources, and this can decrease the interaction strength among species. Also, the greater seasonal fluctuations of physical environments such as water levels can decrease the frequency that animal species meet each other, and thus the interaction strength. Although the trophic basis of macroinvertebrate food web is detritus in both connected and disconnected lakes, the latter is more heavily based on detritus (70%) than the former (40%). In terms of energy flow, the total energy flowing through the food web is much higher (by orders of magnitude) in connected lakes.

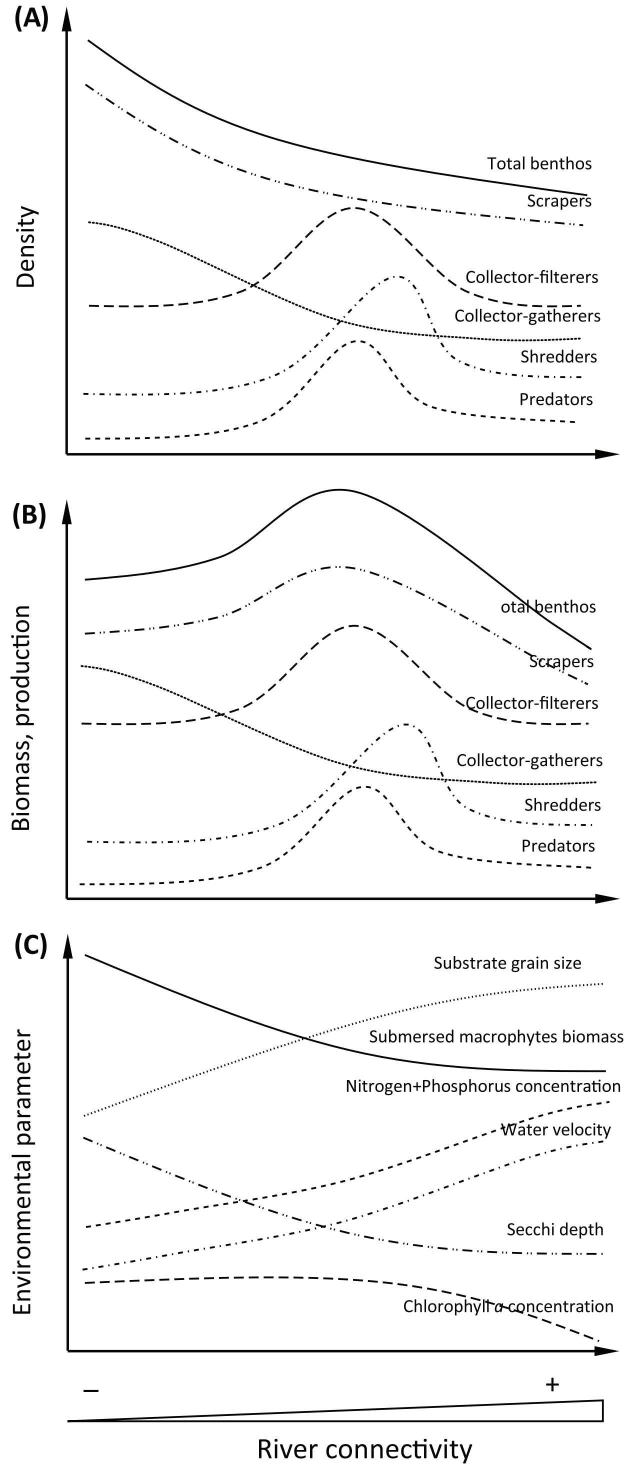

Figure 8. Tendency diagrams to illustrate responses of (A) density of different functional feeding groups, (B) biomass and production of different functional feeding groups, and (C) environmental parameters to river connectivity in the Yangtze floodplain. (From Pan et al. 2011b.)

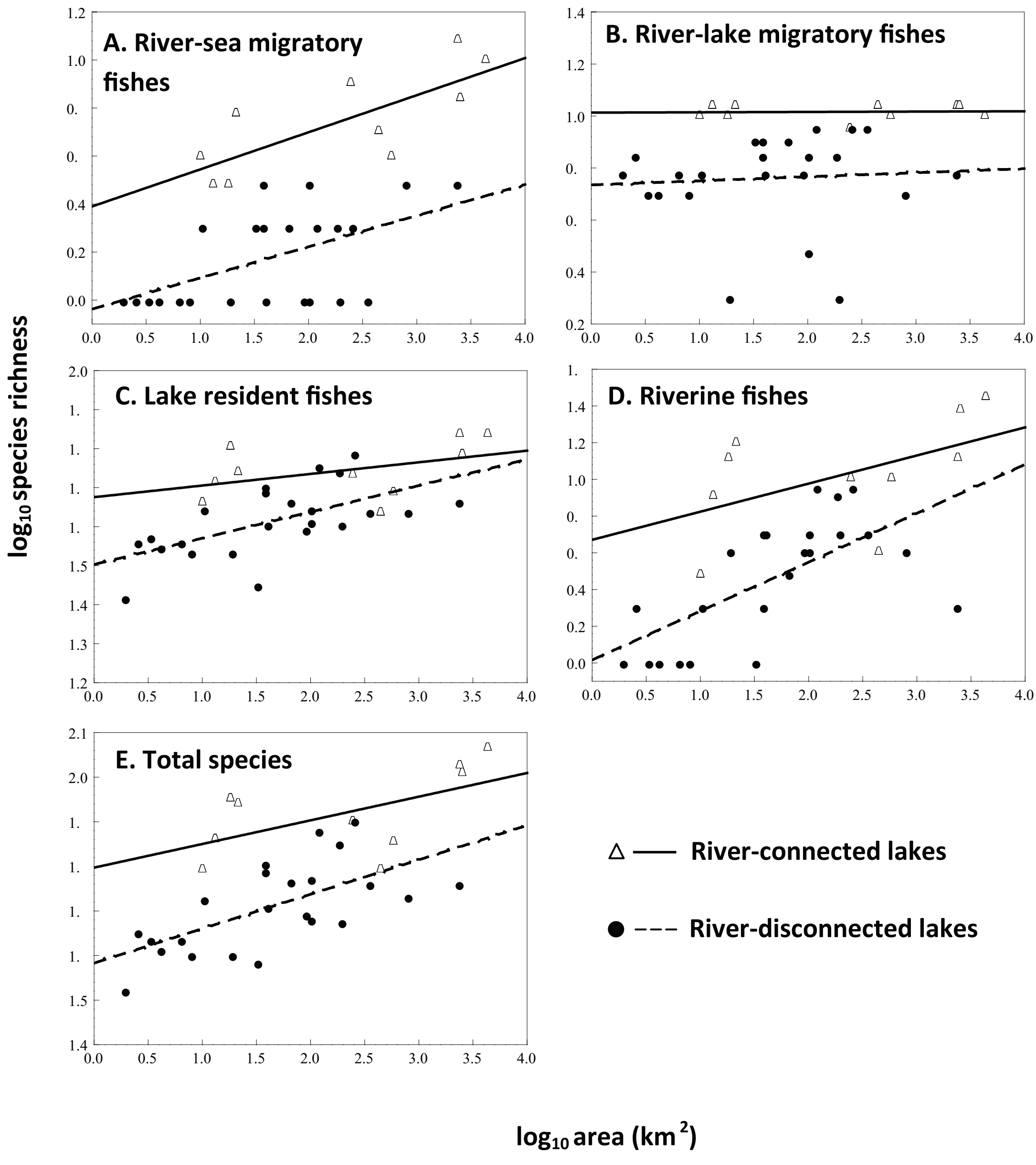

Figure 9. Species–area relationships of fishes in Yangtze-connected and disconnected lakes in the Yangtze floodplain. (From Liu and Wang 2010.)

Mechanisms for Effects of River–Lake Disconnection on Lake Ecosystems

We have systematically revealed the relationships between river connectivity and lake ecosystems (Figure 11). The main findings are as follows: (1) river–lake disconnection is one of the main causes of lake eutrophication, increasing the conversion efficiency of nutrient into phytoplankton biomass to a large extent; (2) species diversity, biomass, and production of macrophytes and macrobenthos reach maxima at some levels of intermediate river connectivity; (3) river–lake disconnection greatly reduces fish species richness of each habi-

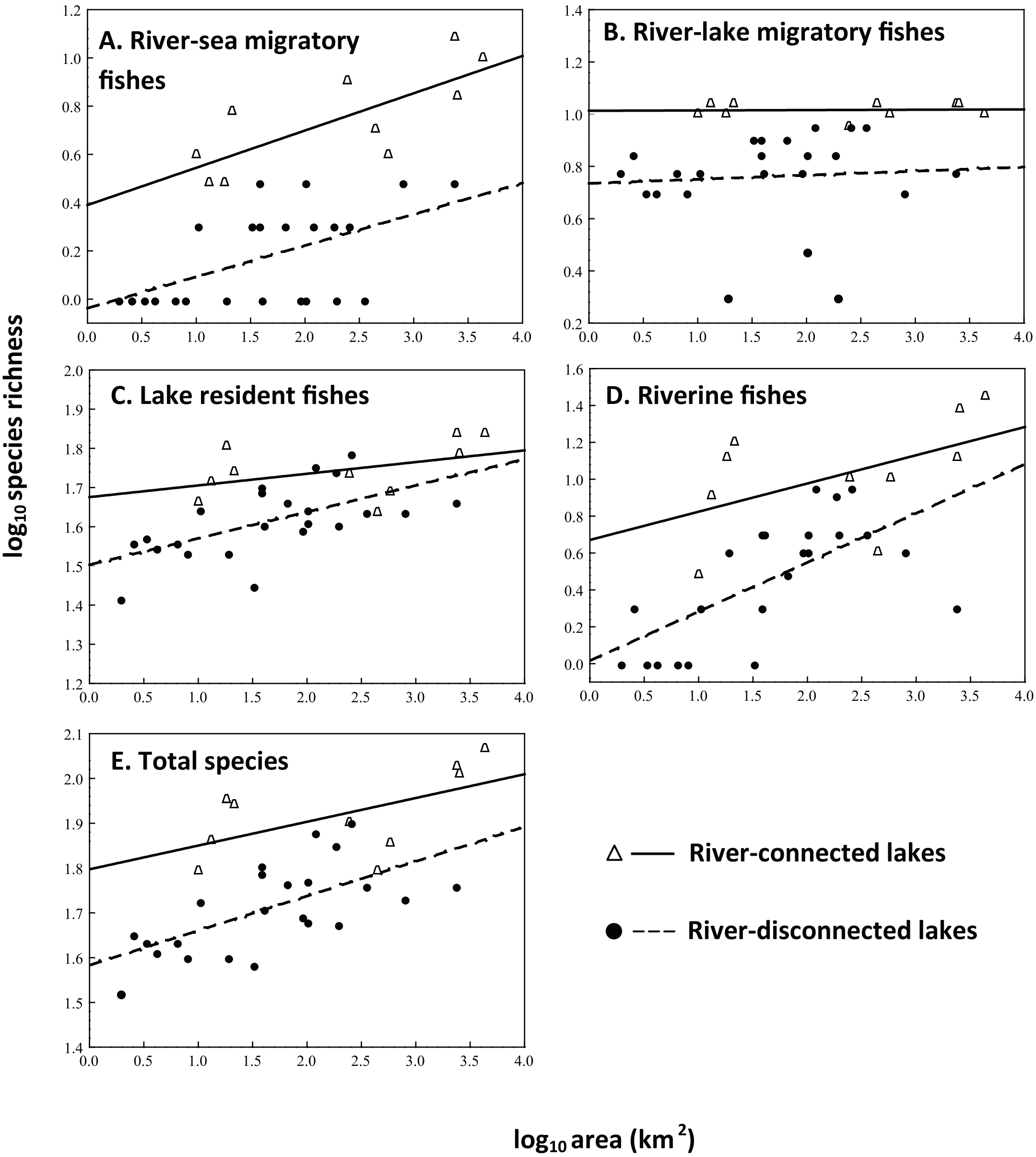

Figure 10. Comparison of niche overlap web (summary web) of Yangtze-connected Lake Dongtinghu with two disconnected lakes. IS = insect shredders, GS = gastropod scrapers, ACG = annelid collector-gatherers, ICG = insect collector-gatherers, BCF = bivalve collector-filterers, ICF = insect collector-filterers, SIP = small insect predators (mainly chironomids), and LIP = large insect predators (mainly odonates). The line thickness in each ellipse shows the dietary overlap of species within the functional feeding group. (From Liu and Wang 2008.)

tat guild, and natural resource of fish larvae is severely depleted; and (4) river–lake disconnection simplifies macroinvertebrate food web structure in disconnected lakes and increases the connectance and degree of dietary overlaps, and trophic basis is more dependent on detritus.

River–lake disconnection disturbs the natural flow regimes, decreasing the species diversity of lakes sharply and changing the

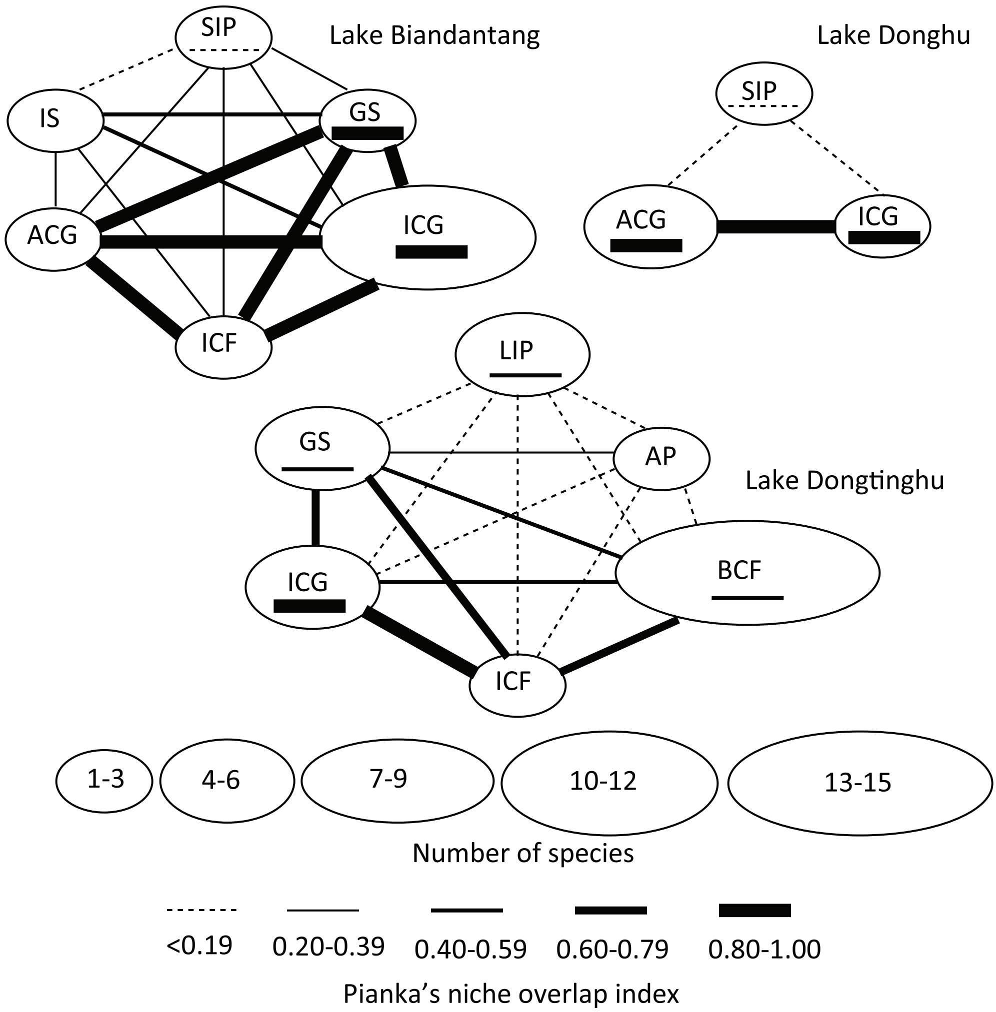

Figure 11. Relationships between hydrological connectivity and different ecological groups in the Yangtze floodplain.

community structure substantially. It has been revealed that natural flow regimes are the main mechanisms by which river floodplain ecosystems have quite rich species and very high production (Mahoney and Rood 1998; Amoros and Bornette 2002; Lytle and Poff 2004; Junk 2005; Rood et al. 2005). Over evolutionary time, all species have developed life history strategies adapting to predictability of water regimes, and thus hydrological alternations will exert great effects on any organisms. In summary, obstruction of river–lake hydrological connectivity affects Yangtze lake ecosystems via three mechanisms (Ward 1997; Amoros and Bornette 2002; Ward et al. 2002). First, block the exchange of water, sediment, nutrients, and organic matter between the Yangtze main stem and lakes, disturb periodicity of hydrological fluctuations, and hinder/delay growth and development of organisms. Free connection is of particular importance to organisms with habitat shifts in life histories. Second, lessen hydrogeomorphological dynamics, and decrease spatiotemporal heterogeneity of habitats. Hydrological processes create various landscape elements and environmental gradients, which are changing over time. Third, stop or weaken natural disturbance by hydrological dynamics, which interrupts successions of various communities and keeps them in different successional stages, thus forming mosaics of community patches.

According to situations in the Yangtze floodplain, Figure 12 shows how river–lake connection works on lake ecosystems:

In winter (Figure 12A), water levels in the Yangtze main stem and lakes are the lowest and some areas are dry. Hygrophytes on lakeshore and some submerged macrophytes in shallow waters begin to germinate, invertebrates such as mollusks winter in sediment and other habitats, and river–lake migratory fishes stay in deep pools of the main stem.

In spring (Figure 12B), the main stem floods, and river water containing large amounts of sediment and nutrients flows into lakes. Hygrophytes and hydrophytes grow well, invertebrates revive and breed, and migratory and resident fishes spawn and then larvae migrate/drift into lakes.

In summer (Figure 12C), the water level in the main stem reaches a maximum. Lakeshore is submerged and then hygrophytes degenerate gradually, but hydrophytes flourish; fishes and invertebrates assemble and forage in vegetation.

In autumn (Figure 12D), the water level in the main stem goes down and lake water flows back into the river. Lakeshore emerges from water and hydrophytes decline; migratory fishes swim to the main stem.

Holistic Conservation of the Yangtze River Floodplain Ecosystem and Strategies of Ecohydrological Rehabilitation

Conservation Principles and Key Scientific Questions

At present, species diversity in the Yangtze floodplain is continually decreasing and water quality is continually degrading. Therefore, the ecosystem protection should be oriented to resolve these two problems. Since pollution control has been discussed extensively, we focus upon biodiversity conservation in this paper. According to our studies and related literatures, we propose the following two principles concerning biodiversity conservation in the Yangtze River floodplain.

The principle of holistic conservation Since the Yangtze River is a huge integrated system formed before 23 Ma, biodiversity conservation must be conducted on the whole water system scale. The Yangtze River floodplain covers a large geographical region and holds diverse subsystems such as the main stem, tributaries, lakes, ponds and ditches, hyporheic zones, riparian zones, and estuary. All the subsystems are interconnected and interact with each other. Apparently, any single/local reserve is not enough to realize biodiversity conservation of the whole river floodplain. Therefore, it is of great importance to conserve the huge ecosystem from a holistic perspective.

The principle of free hydrological connectivity The principle concerns free water exchange among water bodies of the river floodplain. There are four dimensions of hydrological connectivity (i.e., longitudinal, lateral, vertical, and temporal). Free connection can increase temporal-spatial heterogeneity of habitats, and thus species diversity, and can help to prevent overgrowth of some species and thus reduce ecological disasters (e.g., blue-green algal blooms). Migratory species shift habitats in different stages of life history, and connection is of particular importance to them. To avoid habitat fragmentation, it is also necessary to maintain internal connection in a single water body.

To implement the above principles, two scientific questions should be answered. First, what is the minimum protected area of Yangtze-connected lakes for biodiversity conservation of the Yangtze River floodplain? Estimating reserve size is a key step for effective conservation of biodiversity. At present, only a few connected lakes maintain free connection with the Yangtze main stem. Do they meet the requirement of biodiversity conservation for the entire floodplain? Second, what are the environmental flow requirements of the Yangtze River floodplain?

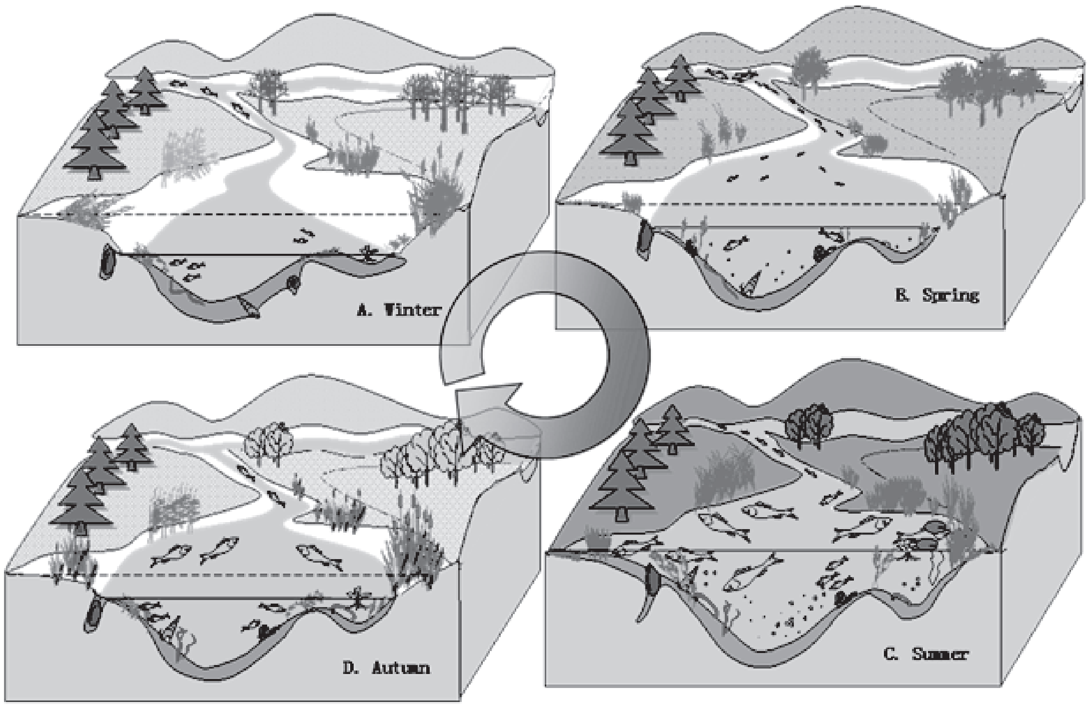

Figure 12. Diagram of ecosystem dynamics of the Yangtze River floodplain. (From Wang and Wang 2009.)

The hydrological regimes of the floodplain waters have been altered by river damming and river–lake disconnection, leading to ecosystem degradation to various degrees. Therefore, it is urgent to understand the hydrological requirements of these ecosystems so as to provide the scientific basis for ecohydrological operation of dams and sluices.

Minimum Protected Area of Yangtze-Connected Lakes

Species–area relationship is regarded as one of the general laws in ecology and can be used to calculate the minimum protected area. Targeting fish conservation, we estimated the minimum protected area of the Yangtze-connected lakes. The reasons to choose fish are (1) fish species are sensitive to hydrological connectivity, especially migratory ones; (2) fishes are K-strategists and position at higher trophic levels in general, and it is reasonable to assume that most organisms can be conserved if fishes are under protection; and (3) fish data are most abundant.

Based on collected fish diversity data of the past 50 years, the cumulative species–area model has been constructed (Liu and Wang 2010; Figure 13). Given that the total number of fish species is 173 in this region, the minimum protected area is estimated to be 14,400 km^2 according to the model. Since the total area of existing Yangtze-connected lakes is 5,500 km^2, at least 8,900 km^2 of disconnected lakes need to be reconnected.

Ecohydrological Operation of Dams and Sluices

Our research shows that the existing Yangtze-connected lakes do not meet the area requirement of biodiversity conservation in the Yangtze floodplain. Therefore, we must reconnect enough disconnected lakes with the main stem. The feasible approach is to operate dams and sluices in ecohydrological ways, and this should be based on the assessment of environmental flow requirements (EFRs).

In terms of macrophytes EFRs, we focused on WLFs. Macrophyte distributions

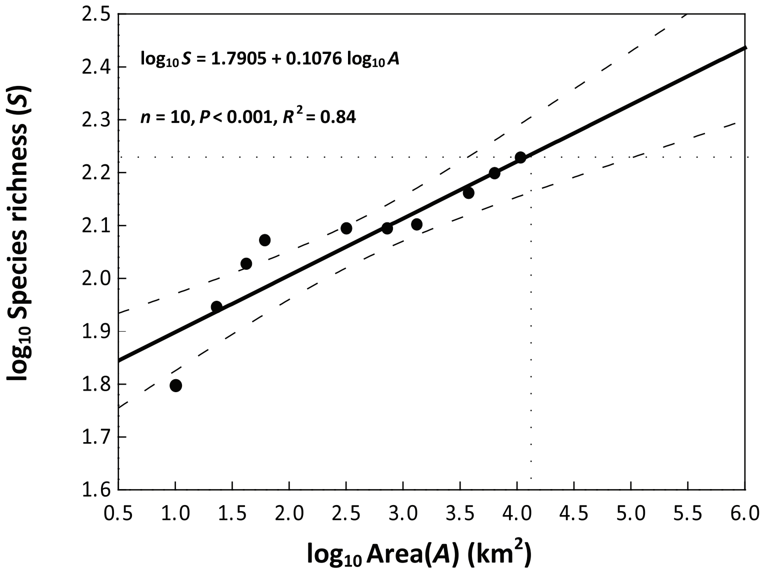

Figure 13. Estimation of minimum protected area of Yangtze-connected lakes for fish diversity conservation in the Yangtze floodplain. (From Liu and Wang 2010.)

show clear zonation along elevation gradients, and the life histories are closely correlated with lake WLFs (Keddy and Reznicek 1986). Hygrophytes are distributed at the highest elevations and adapt to environments with large fluctuation amplitude. For example, biomass of *Carex* in lakes with large amplitude (e.g., Lake Dahuchi) is about 10 times as much as those with small amplitude (e.g., Lake Yandonghu) (Zhang 2013). Hygrophytes germinate near lakeshore in low water level periods, and the seedlings cannot tolerate submergence. During growth, hygrophytes prefer stable water levels and cannot survive if water levels rise too fast. Most hygrophytes mature before June, and thus the suitable submergence time is June–July. Emergent macrophytes grow at lower elevations than hygrophytes and are distributed at a wide range of fluctuation amplitude. Also in low water level periods, they germinate in places from 1 to 7 m above lake surfaces to shallows. Taking the common reed *Phragmites australis* as an example, root-sprouting is obviously prevented at 20 cm under water and absolutely fails beyond 30 cm (Cao 2007). The sprouts can resist submergence to a certain degree, but fast rising of water levels beyond the growth rate has detrimental effects on their growth, even leading to death. The suitable submergence time is July–August, and biomass is much higher in areas submerged in July–August than June (Zhang 2013). Submerged macrophytes prefer lakes with small fluctuation amplitude. Underwater light is the key factor affecting their growth, and the ratio of Secchi depth to mean depth should be more than 0.5 during March–June in order to enable a normal growth (Wang et al. 2005). A certain increase in water levels can promote the growth of macrophytes (Zhang et al. 2013), but fast rising of water levels can inhibit the growth or kill the plants (e.g., Keddy and Reznicek 1986).

With regards to fishes, we analyzed the migration pattern of river-lake migratory fishes (the four Chinese carps, i.e., Black Carp *Mylopharyngodon piceus*, Grass Carp *Ctenopharyngodon idella*, Silver Carp *Hypophthalmichthys molitrix*, and Bighead Carp *Hypophthalmichthys nobilis*; Figure 14; Ru and Liu 2013). Between late spring and early summer, the adults breed in the main stem when the water level rises sharply, and the eggs drift downstream and develop in the main stem.

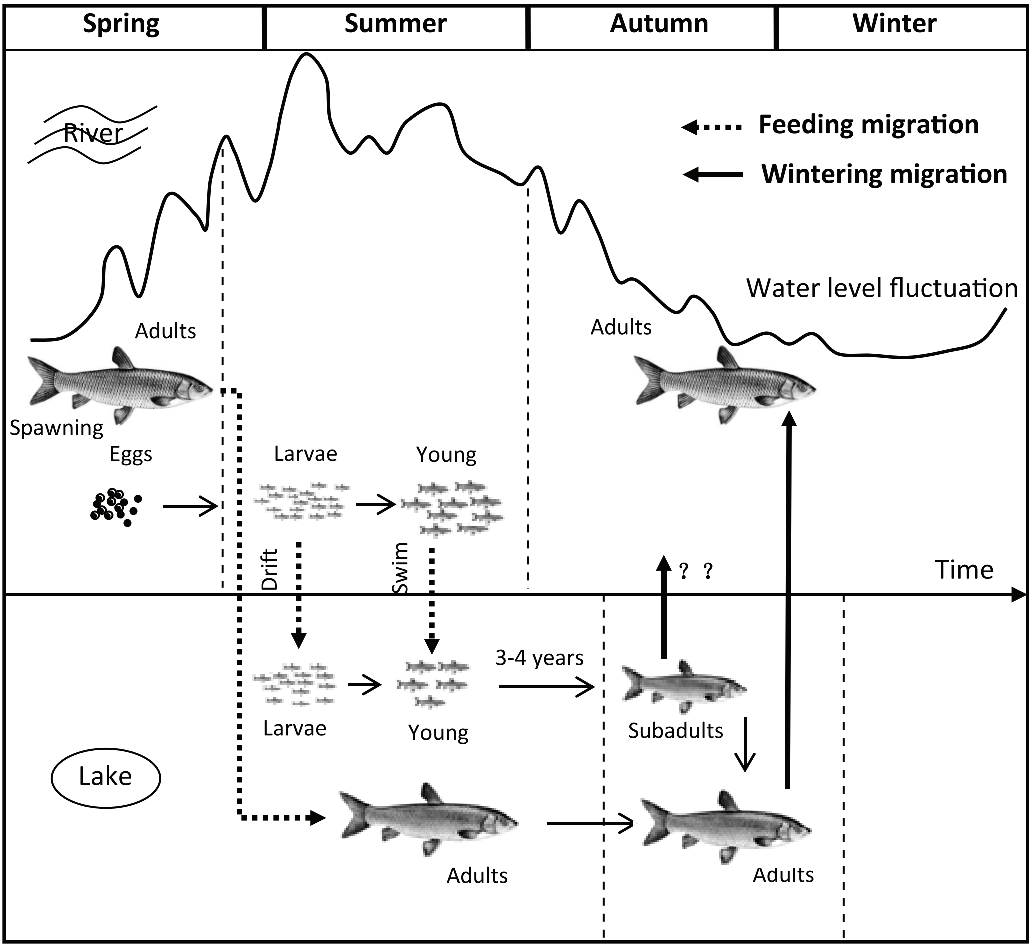

Figure 14. Migration diagram of four major Chinese carps in the Yangtze floodplain. (From Ru and Liu 2013.)

After spawning, adults will migrate into floodplain lakes to feed. Some larvae and juveniles then move passively into lakes along with the flow. Others feed in backwaters of the river and migrate later into floodplain lakes. They grow and mature in the lakes for 3–4 years. When the water recedes in late autumn, the adults again return to the main stem. The subadults may also leave if the lake water is not deep enough.

According to the above results, we propose the following ways to operate dams and sluices to meet ecohydrological requirements: (1) lower water levels during spring to improve germination of macrophytes, and control rising rates of water levels during spring–summer to ensure development; and (2) open sluice gates to restore migration routes for juvenile fishes migrating into lakes during April–September and for adults migrating into the Yangtze main stem during November–December.

Strategies for Holistic Conservation

Based on conservation principles and our researches, we propose the following strategies to conserve the Yangtze biodiversity.

First, establish a holistic nature reserve to protect the entire Yangtze River ecosystem. In the mid to lower river floodplain, the reserve should include (1) the main stem and connected lakes, and (2) the rehabilitation of at least 8,900 km^2 of disconnected lakes.

Second, strengthen conservation actions in the main stem and connected lakes. The existing connected lakes include only two large-sized lakes, Lake Poyanghu and Lake Dongtinghu, and one medium-sized lake, Lake Shijiuhu (see Figure 1). They are biodiversity hotspots. However, fishes and other organisms in these lakes are facing multiple threats, such as overfishing, sand overmining, water pollution, and unusually low water levels in dry seasons because of flow regulations by upstream reservoirs and climate change. Although the Chinese central government has banned fishing in spring in the Yangtze main stem and connected lakes since 2002, the protection achieved appears to be rather limited. Numerous juvenile fish are being caught during open fishing seasons with illegal fishing gears. We propose that commercial fishing in the Yangtze main stem and connected lakes be banned all year round, and a core protected area where all human activities are forbidden should be demarcated. In addition, it is necessary to reoperate the upstream dams to meet the ecohydrological requirements and connectivity of the connected lakes.

Third, rehabilitate disconnected lakes. Those with good conservation potentials are of first consideration, such as oxbows, Honghu and Liangzihu lakes along the middle reaches, and Anqing lakes along the lower reaches. Ecohydrological operation of dams and sluices had better be based on EFR assessments of key organisms (e.g., macrophytes, benthos, fishes, water birds, and dolphins) and ecosystem services (e.g., clean water, food production, and scenery). As stated above, we have done some works in this aspect, but more studies are needed. To meet the urgent need of conservation at present, ecohydrological operation must be implemented as much as possible, even if knowledge is limited. Additionally, enclosures for aquaculture spread over many disconnected lakes, leading to vegetation degradation and then eutrophication. Therefore, these enclosures should be removed completely or only confined to small areas.

Acknowledgments

This work is financially supported by the State Key Laboratory of Freshwater Ecology and Biotechnology (2011FBZ14), the National Natural Science Foundation of China (30900194 and 41371054), the Chinese Academy of Sciences (KZCX1-SW-12), 973 Programs (2008CB418006 and 2002CB412309), and WWF China. The map and area data of Yangtze lakes are from the Scientific Data Sharing Platform for Lake and Watershed made by the Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences. We thank Shu-Ran Wang, Ya-Jing He, Sai-Bo Yuan, Yu Peng, Qing Yu, Xiao-Peng Shi, and Xiao-Ke Zhang for their help.

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