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PROCESSES AND ENVIRONMENTAL QUALITY IN THE YANGTZE RIVER SYSTEM

Conservation and ecofriendly utilization of wetlands associated with the Three Gorges Reservoir

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Abstract The Three Gorges Dam on the Yangtze River in China has created a major reservoir in which the water level fluctuates annually by about 30 m, generating a drawdown zone of up to 350 km^2 in summer. Since construction of the dam, there has been scientific and public interest in how to use the drawdown zone resources in environmentally sustainable ways. To this end, and with government support, an international conference was held in Chongqing Municipality (China) in October 2011 on the subject of conservation and ecofriendly utilization of wetlands in the Three Gorges Reservoir. The conference proceedings were subsequently published in the Journal of Chongqing Normal University. The proceedings reports are reviewed here in the context of other relevant literature. The proceedings included papers on ecology, ecodesign and ecological engineering, erosion control, plant production and carbon sequestration, phytoremediation of pollution, hydrosystem management, and others. Several of the reports derive from experimental work conducted at a research field station on the Three Gorges Reservoir situated in Kaixian County, Chongqing Municipality. Plant communities in the drawdown zone are declining in diversity and evolving. Experimental plantings of flood-tolerant edible hydrophytes in a dike–pond system reveal their potential to provide economic returns for farmers, and flooding-tolerant trees, such as cypresses, also show promising results for stabilizing soils in the drawdown zone. Flood-tolerant natural plant communities vary strongly with depth and their composition provides useful indicators for revegetation strategies. In the region surrounding the reservoir, remnant natural broad-leaved evergreen forests are most effective in sequestering carbon, and within the drawdown zone, carbon is mostly stored below ground. There is strong interest in the potential of aquatic plants for removal of pollutants, notably N and P, from the reservoir water by means of floating beds. Other examples of applying ecodesign and ecological engineering strategies for restoration and management of rivers and lakes are also given. Scientific studies have provided valuable advice for ecofriendly utilization of the reservoir drawdown zone and further studies of the evolving condition of the reservoir can be expected to pay additional practical dividends.

Keywords Three Gorges Reservoir · Wetland · Drawdown zone · Hydrophytes · Ecological engineering · Ecodesign · Phytoremediation · Revegetation

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Introduction

The Three Gorges Dam on the Yangtze River has created a significant reservoir in China that was recently filled. Most of the reservoir lies within Chongqing, a large municipality in southwest China that is administered by the central government. There are four such municipalities in China: Beijing, Tianjin, Shanghai, and Chongqing, of which Chongqing is the largest in terms of area and population.

The dam provides the economic and social benefits of flood control, power generation, improved river transportation, and improved freshwater access (Fu et al. 2010). The hydroelectric project itself is among the largest in the world, but the area flooded by the reservoir has a relatively modest surface area of 1,080 km^2 as a result of the mountainous terrain and steep slopes that surround it (Fig. 1). Nevertheless, there have been very significant socioeconomic impacts because the reservoir lies in a densely populated region of China and many riverside towns and other settlements were flooded by the rising water resulting in the need to resettle hundreds of thousands of residents (Stone 2008; Fu et al. 2010). The region affected sociopolitically by the reservoir is about 58,000 km^2 in area and has come to be known as the Three Gorges Reservoir Area (Zhang and Lou 2011).

In order to optimize the benefits provided by the dam, the water level in the reservoir fluctuates considerably, with a target height of 175 m above sea level during winter and 145 m above sea level during summer. The large fluctuation is necessary for flood control purposes in light of the heavy rains associated with the summer monsoon (Ding and Chan 2005). The water level is lowered so that floodwater can be retained and released in a planned manner, thereby avoiding the most severe flood peaks in the lower reaches of the Yangtze River which have historically experienced catastrophic floods (Challman 2000). This pattern of water management is described as "counter seasonal" because water levels in rivers in southwest China are relatively high in summer and low in winter, but the reservoir has the opposite hydrological condition.

In addition to the Yangtze River itself, many smaller rivers also feed into the reservoir such as the Pengxi, Daning, and Wujiang rivers, all of which now have drawdown zones resulting from the hydrological management regime. The drawdown zone of the Three Gorges Reservoir is commonly called the "water level fluctuating zone" (Zhang and Lou 2011) or the "hydrofluctuation belt" by Chinese authors. It has also been called the "littoral zone" because it is somewhat analogous to seashore tidal zones. These terms all refer to the same thing. The reservoir surface area is reduced by about one third when the reservoir is fully drawn down in summer, resulting in a total drawdown zone of about 350 km^2 when the water level is at its lowest (Chen et al. 2009; Yuan et al. 2012). The total length of shoreline is more than 1,300 km (Wang et al. 2005).

Fig. 1 Slopes around the Three Gorges Reservoir are commonly very steep, as shown in the Qutang Gorge near the town of Fengjie which lies in the middle section of the reservoir. The reservoir is almost full in this image taken in November 2009 with water surface about 170 m above sea level

Given the economic needs of the many communities that live around the reservoir and their loss of access to land that they have traditionally used, there are strong pressures to find uses for the drawdown lands, particularly given that these lands are exposed during the peak summer growing season. Furthermore, large areas of the reservoir surface have the potential to be used for agriculture if suitable floating bed technologies can be developed for use with marketable crops.

The reservoir has created some new environmental problems, such as increased erosion, sediment deposition, and water-borne pollution, all of which are well-known consequences of the construction of dams and impoundments (Baxter 1977; Zhang and Lou 2011). Within the drawdown zone, the combination of an altered hydrological regime and new patterns of erosion and sedimentation are causing ecological changes such as loss of vegetation and invasion of new species (Wu et al. 2004; New and Xie 2008). These negative environmental and ecological consequences need to be minimized.

For the reasons outlined above, the municipal government of Chongqing held a symposium on the subject of "Conservation and eco-friendly utilization of wetland in the Three Gorges Reservoir" in October 2011. The symposium was supported by several Chinese government agencies and was attended by 40 scientists from China, Germany, USA, UK, and Canada (Fig. 2). The challenge presented to the scientists attending the conference was to examine ways to provide all of the following: economic benefits, reduced environmental hazards, and improved living conditions for the local and regional inhabitants (Yuan et al. 2011). The conference participants responded by examining the problem from several perspectives including: wetland ecology, plant community ecology, restoration ecology, pollution control, ecological engineering, carbon sequestration, as well as the management of wetlands, rivers, and lakes.

The proceedings of the conference were subsequently published in the May 2012 issue of the Journal of Chongqing Normal University (Natural Science). Sixteen papers appeared in this focus issue of the journal which was published in both Chinese and English. The English version is freely available online (Journal of Chongqing Normal University 2012). The findings reported in this journal issue are integrated and put in context in the current paper.

Fig. 2 Scientific participants who attended the international symposium titled "Conservation and eco-friendly utilization of wetland in the Three Gorges Reservoir" held in October 2011. The photograph was taken during a visit to the field research station at Laotudi Bay on Baijia Stream, a tributary of the Pengxi River which drains into, and is part of, the Three Gorges Reservoir

Ecology of the drawdown zone

Flooding resulting from the regulation of the water level has caused marked ecological changes in the littoral zone of the Three Gorges Reservoir (Yuan et al. 2012). These ongoing changes create difficulties for many of those who live around the reservoir, but also provide exciting opportunities for the discovery of novel "ecofriendly" engineering and management responses to the emergent environmental challenges. If used properly, the hydrofluctuation belt has great potential for plant production, water purification, and other direct economic benefits, but only if attention is paid to sustainability. In light of this, Yuan and his colleagues have established an experimental field station at Laotudi Bay on Baijia Stream (a tributary of the Pengxi River in Kaixian County, Chongqing, see Figs. 3 and 4) with special focus on ecological engineering for the restoration of functional littoral wetland ecosystems (Yuan et al. 2011, 2012; Li et al. 2012a, b; Wang et al. 2012a). Lands associated with this field station are reserved for experimental purposes and include extensive parts of the Three

Fig. 3 The experimental dike ponds at Laotudi Bay on Baijia Stream on 1 May 2009. In the photograph, the water level is about 150 m above sea level, which is close to the normal summer low-water level. The bay had been flooded to about 172 m during the previous winter. The farm houses are permanently above water, while the dike ponds are inundated annually during winter

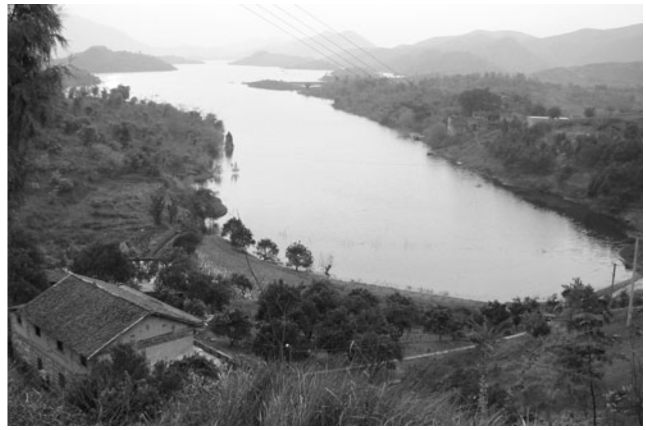

Fig. 4 The experimental dike–pond area at Laotudi Bay on 18 December 2010. The photograph was taken at roughly the same position as Fig. 3. The water level was at its highest in the annual cycle, about 175 m above sea level, which is the planned height of the reservoir for about 3 months each year

Gorges Reservoir drawdown zone as well as lands that lie both above and below it. The work began in 2008 with several projects involving dike–ponds in which water is retained during the low-water period (Fig. 3), submergence-tolerant trees, and creation of waterfowl habitat. For creating waterfowl habitat, the following themes are being investigated: patch and network design, topography, substrates, and hydrophyte communities.

Understanding the dynamics of both natural and anthropogenic ecosystems is essential for making sustainable land-use policies, and permanent sampling plots are valuable tools for this purpose. When the water level falls in the reservoir, the drawdown zone quickly becomes green with terrestrial vegetation, but the plants that are present have followed a pattern of succession that is still evolving (Yuan et al. 2011; Wang et al. 2012a).

A large 60-m wide permanent sample plot has been established at the Pengxi River experimental reserve between the high and low water marks of the drawdown zone. The diversity and above-ground biomass of vegetation in the plot were measured in the summers of 2008, 2009, and 2010 and revealed clear variations related to depth of submersion and time (Wang et al. 2012a). There was a steady decline in the overall plant biodiversity during this period, with the total number of species falling from 52 to 35, presumably due to the progressive exhaustion of the seed bank and the death of persistent parts of perennial plants such as stolons and rhizomes. The area covered by deeper water in winter was dominated most strongly by *Paspalum paspaloides* (knotgrass) and *Xanthium sibiricum* (cocklebur) in 2008, but these species were replaced as dominants by *Cynodon dactylon* (couch grass) in 2009 and 2010. *C. dactylon* is deep-rooted and spreads quickly by means of stolons and rhizomes. By contrast *P. paspaloides* disappeared completely within the sampled plots, and *X. sibiricum*, which relies on annual production of seeds, was present only in the upper 165–175 m zone in 2010, apparently due to failure of seeds to mature in 2009. Above-ground biomass was negatively correlated with flooding depth and varied considerably from year to year. A biomass submergence gradient was evident in each year and may have become stronger over the period studied, but continued monitoring of this permanent sample plot will be required before trends can be shown to be statistically significant.

In July and August 2011, Li et al. (2012a, b) examined plant species richness in 113 plots, each 1 m square and set at 5 m height intervals in transects running between 145 and 180 m elevations (i.e., between the low water mark of the drawdown zone and 5 m above its maximum height). The transects were set at various points along the Baijia Stream starting at its confluence with the Pengxi River. Plant diversity in four of these five transects had been studied in 2008 after the water level in the reservoir had been raised to 156 m and lowered again (Sun et al. 2010). The new study was therefore conducted to compare the same sites 3 years later and after reservoir impoundment to 175 m. Thirteen characteristic plant community associations were identified. Species diversity had declined significantly below 156 m, with only 19 species in 2011 compared with 96 species in 2008. The invasive annual weed *Echinochloa crus-galli* (barnyard grass) had become a new dominant in various parts of the drawdown zone. It is clear that plant community structure in the reservoir drawdown zone is evolving rapidly and that further ecological succession can be expected.

Ecodesign and ecological engineering in the drawdown zone

Creating a "new socialist countryside" is a major plank in Chinese public policy (Fock and Wong 2008) and it includes the idea that development must also be "harmonious with nature". Shi 2002 argued that to obtain sustainable agricultural development in China will require that it be "tailored to specific ecological, economic, political and socio-cultural settings". Consistent with these ideas are the concepts of ecodesign (see Shu-yang et al. 2004) and ecofriendly utilization of resources (Yuan et al. 2011), both of which were emergent themes throughout the Kaixian conference and its published proceedings.

While plants will naturally colonize any available space, intervention by planting desirable species is also common practice. Flooding-tolerant woody species that have been planted at the experimental Baijia Stream site include: Chinese swamp cypress (*Glyptostrobus pensilis*), American bald cypress (*Taxodium distichum*), American pond cypress (*Taxodium ascendens*), a hybrid cypress known as *Ascendens mucronatum*, Chinese dawn redwood (*Metasequoia glyptostroboides*), Chinese tallow (*Sapium sebiferum*), white mulberry (*Morus alba*), a Chinese urticaceous species named *Debregeasia orientalis*, Chinese wolfberry (*Lycium chinense*), and Chinese tamarisk (*Tamarix chinensis*; Yuan et al. 2012). These species have the potential to provide a wide range of benefits including stabilizing reservoir banks against erosion, sequestering carbon, beautifying the landscape, and providing valuable economic resources such as wood, fruits and medicinal oils.

Cypress species are well known for their ability to tolerate deep submersion and therefore have been introduced to fit a special niche in the ecological engineering of woodlands for the drawdown zone. White mulberry, on the other hand, was already present, having been grown by farmers for many years in the area that was subsequently inundated. It has a surprising capacity to tolerate flooding, as observed by the survival of mulberry trees repeatedly flooded to depths of several meters of water for several months in the winter. Unlike Chinese swamp cypress, mulberry does not survive complete immersion, but it does appear suitable for growing in the upper part of the drawdown zone and therefore offers a special place in the planting strategy because it provides a wider range of economic resources than other species of interest: flavonoid-rich fruit, protein-rich leaves for silkmoths and farm animals, medicinal roots, and others.

Mulberry species tolerate a wide range of stresses and are grown in both wet and arid climates. Chongqing is very hot in summer and there is often a period of summer drought when extremely high temperatures cause rapid loss of soil water. For this reason, growth of mulberry in the upper part of the drawdown zone will require that the trees are both flood tolerant and drought tolerant. Huang et al. (2012) therefore examined the drought tolerance of *M. alba* by growing seedlings in pots in a greenhouse during summer under different soil water regimes: irrigated, moderate drought stress, and severe drought stress. They measured plant heights, base diameters, root surface area, and root–shoot ratio, and found that the drought-stressed seedlings appeared to reallocate biomass to root growth such that capacity to absorb water was retained despite inhibition of plant growth (Huang et al. 2012). These observations help to explain the survival of mulberry trees through some of the severe summer droughts that have been experienced in Chongqing.

It is valuable to have information derived from ecophysiological experiments when growing trees in plantations. Wang et al. (2012b) examined the responses of two tree species selected for use in drawdown zone plantations in response to three watering treatments: normal watering, light drought, and shallow flooding. The species of interest were one exotic tree (American pond cypress, *T. ascendens*) and one native tree (Chinese wingnut, *Pterocarya stenoptera*) and they were grown in containers together with simulated ecosystems containing willow shrubs and couch grass. In addition to the variation in watering, two standardized planting designs were assessed: either six wingnut and three cypress, or six cypress and three wingnut in each container. Eight physiological and biochemical indicators of stress were assessed, such as chlorophyll content, peroxidase activity, and free proline content. The results showed that the different configuration modes resulted in little or no significant differences in the indicators, but that water stresses elicited clear adaptive responses in both species. For example, both drought and flooding significantly increased the activity of a protective enzyme that removes excess reactive oxygen (superoxide dismutase) in both species. Experimental results indicated that there were some differences between the two species with respect to the details of their physiological responses but that both displayed the capacity to adapt to the hydrological stresses that arise in the Three Gorges Reservoir drawdown zone.

After taking account of the ecology of the drawdown zone and the biology of desirable species, it is wise to create a comprehensive revegetation strategy and Lu and Jiang (2012) have initiated a proposal to this effect. They emphasize that the first step is to make careful and extensive observations about which species survive in the drawdown zone. For example, eight naturally occurring hardwood species have recently been discovered growing in the drawdown zone after tolerating several cycles of flooding (Wang et al. 2012c). In addition, monitoring must be conducted of plant communities in fixed plots to observe spontaneous changes in community structure over time, including monitoring of the soil seed bank so that the ecological dynamics can be properly understood. There are many seeds in the soil bank that are apparently unable to germinate under the hydrological conditions of the reservoir (Lu and Jiang 2012). While some annual plants with suitable physiology and life history strategies will colonize readily, these may not all be desirable (e.g., *E. crus-galli*), while other plants that are more desirable may need to be introduced or propagated (e.g., *Salix* spp., *Carex* spp., and *G. pensilis*). Existing paddy fields that are seasonally inundated can be planted with wetland vegetation such as lotus (*Nelumbo nucifera*). Lu and Jiang (2012) proposed a set of species suited to the vertical gradient of the drawdown zone, with annual herbs at the lowest elevations and trees at the highest elevations.

Control of erosion

In recent years, the government of China has placed emphasis on programmes that enhance natural ecosystem services throughout China, particularly the restoration of forest cover (Liu et al. 2008). In Xingshan County of Hubei province, which drains into the Yangtze River, the total value of ecosystem services on sloping lands clearly exceeds the value of products derived by farming those slopes (Guo et al. 2001). The most successful of the forest restoration programmes has been “Grain to Green” (conversion of cropland to forest) in which farmers who were using steep slopes have been paid to replace crops with forest trees and other perennial vegetation designed to hold soils in place (Liu et al. 2008; Zhang and Lou 2011). In this way, farmers who were previously eking out a living on marginal sloping lands have guaranteed incomes and are able to improve their livelihoods by joining the industrial workforce. Vegetating the slopes of the Three Gorges Reservoir, both above and below the high water mark, is consistent with the multiple objectives of these conservation programmes.

An example of recent research on soil conservation by Chinese agricultural scientists is provided by the work of Wu et al. (2011) who looked at various indices of soil nutrient retention in citrus groves, which are abundant on slopes in the Three Gorges Reservoir Area. They found two soil management regimes that provided improvements on “conventional management”, namely wheat straw and white clover as ground covers. These management regimes provided benefits of higher retention of nutrients and less soil erosion. Other treatments were also found to provide benefits, including intercropping and hedgerows. Research of this kind is critical for the development of sustainable agriculture and environmental protection.

In the symposium volume, He et al. (2012) reported on their experiments with nutrient loss and soil erosion from moderately sloping farmlands with “purple soil” in the Three Gorges Reservoir Area. Purple soil is a weathered clay soil that is common in the region. Fifteen comparable plots each with an area of 32 m^2 were selected and divided into five groups of three replicates each. The variables were: no treatment control, manure and inorganic fertilizer treatment, inorganic fertilizer treatment, enhanced inorganic fertilizer treatment, and horizontal furrows. Plots were separated by concrete walls equipped with runoff pools and were managed conventionally for winter wheat and summer maize production. Both sediment and water that ran off the plots were collected and analyzed for N, P, and K nutrients. Results were mostly as expected: fertilizers increased the available nutrients in the soil, horizontal furrows reduced nutrient loss, use of combined manure and inorganic fertilizer increased the nutrients available to plants, manure appeared to improve the retention of nutrients in the soil, more N was lost from inorganic fertilizers, and P was largely lost through sediment rather than solution. Results such as these are important for the Three Gorges Reservoir because sediment deposition and nutrient enrichment that wash away from farmlands are two of the greatest problems for the reservoir and any knowledge that will reduce these inputs is therefore of great environmental value.

Plant production and carbon sequestration

The Three Gorges Dam has the largest installed electricity generating capacity of any hydroelectric project in the world and is therefore important in terms of its capacity to lower carbon outputs in a country in which most electricity is generated by coal burning. Full carbon accounting needs to be conducted, however, in order to properly assess the relative costs and benefits of hydropower generation. Both carbon sequestration as woody material and carbon emission from decomposing vegetation need to be assessed. Plant production in the drawdown zone both prior to and after impoundment need to be explored, and opportunities for additional carbon sequestration, such as by growing woody perennials, should be considered. Lu et al. (2010) found that the soil seed bank of the Three Gorges Reservoir is rich in seeds of annual plants but has few viable seeds of the woody plants that were typical of the drawdown zone prior to flooding. This is valuable knowledge for the rehabilitation strategy and tends to justify selective planting of suitable woody vegetation.

Three studies of carbon uptake, sequestration, and emissions were reported in the Kaixian conference proceedings (Li et al. 2012a, b; Sun and Yuan 2012; Wu et al. 2012).

Li et al. (2012a, b) estimated spatial and temporal variations in net primary productivity (NPP) during the period 1998–2007 using a variety of remote-sensing data for most of the administrative region surrounding the Three Gorges Reservoir. The region studied has an area of about 46,000 km^2 and a population of about 19 million people. The reservoir was not completely filled until 2008, and so this study provides valuable baseline information about primary productivity prior to flooding of the reservoir. NPP was highest in summer (676 gC/m^2 on average) and lowest in winter (40.5 gC/m^2 on average). There appeared to be a slight downward trend in productivity over the period studied despite significant interannual variation which makes this conclusion tentative. Summer productivity varied from a high of 1 022 gC/m^2 in 2000 to a low of 318 gC/m^2 in 2006. High productivity was found in forested regions in northeast Chongqing (Wuxi, Wushan, and Fengjie) and in southeast Chongqing (Shizhu, Wulong, and elsewhere). Relatively low productivity was found in Zhongxian, Fuling, and major urban districts. The order of productivity by vegetation and land class was: broad-leaved evergreen forest (11 % of the area studied), bushy fallow and irrigated grass, coniferous forest (21 % of the area studied), cultivated land (58 % of the area studied), forest plantation, grassy marshland, aquatic vegetation, and open water (Li et al. 2012a, b). It is notable that broad-leaved evergreen forest is the natural climax vegetation of most of the region and had significantly higher primary productivity that any other vegetation class in every year studied, being about 1.6 times as productive as cultivated land, the most extensive class by area. Broad-leaved evergreen forest is therefore the most valuable land class for the purpose of carbon uptake and sequestration.

Sun and Yuan (2012) calculated the amount of carbon stored in vegetation in the Three Gorges Reservoir drawdown zone according to elevation and slope. The relative land areas of elevation and slope classes were estimated by using a geographic information system and the vegetative biomass of these different land classes was derived from published studies. It was estimated that the total biomass (both above and below ground) is about 515,000 t of carbon, with at least 80 % assumed to be below ground. Roughly 60 % of the biomass is in the drawdown zones of the secondary tributaries and the remainder lies in the main stem of the Yangtze River. Higher elevations and lesser slopes tended to be more productive. Nevertheless, variations in soil type, climate, and land uses also strongly affect the accumulated biomass. The fate of this biomass through the continuing cycles of flooding and exposure will be important to understand through future research in order to discover whether the drawdown zone acts as a net carbon source or carbon sink. Similarly, it will be important to learn about the ecological succession of plant communities in the drawdown zone as the reservoir evolves over time.

In order to create a meaningful carbon budget for the Three Gorges dam and reservoir system, emissions of greenhouse gasses should be assessed, particularly those from ecosystems that have been altered as a result of the operation of the dam. One potential change is the emission of carbon dioxide from newly created wetlands in the reservoir drawdown zone (Wu et al. 2012). From early July to late September 2008, Wu et al. (2012) measured carbon dioxide emissions due to respiration from grassy marshes that had arisen in the Pengxi River wetland reserve at Baijia Stream, using static opaque chambers to collect emitted gasses and gas chromatography to measure the quantity of carbon dioxide. Measurements were made of emissions from four different stands: *Juncus amuricus*, *Typha angustifolia*, *Scirpus triqueter*, and *Paspalum distichum*. Emissions varied considerably from one stand to another but were within the range normally found for terrestrial vegetation. Dominant species, water depth, and aboveground biomass appeared to be significant factors accounting for the variability. *S. triqueter* and *P. distichum* were growing in deeper water, had more biomass, and tended to emit more carbon dioxide. Seasonal variations in carbon dioxide emissions correlated closely with changes in temperature. These results provide a valuable baseline for monitoring changes in the carbon budgets of these newly created marshes as they age.

Phytoremediation of pollution

Pollution with industrial and urban wastes in both water and sediments are serious concerns in the Three Gorges Reservoir Area (Zhang and Lou 2011) and remediation of polluted sites is therefore important. Plants provide many potential benefits in remediating sites that have been damaged by pollution or other forms of anthropogenic disturbance (Schaeffer et al.

2012). Plants are capable of binding and sequestering toxic elements such as heavy metals; and in some cases, are able to degrade toxic compounds and render them harmless. The breakdown of cyanide and the reconstitution of its carbon and nitrogen atoms into proteins have been demonstrated in laboratory experiment with water hyacinth, an aquatic plant (Schaeffer et al. 2012). In a field experiment using a small artificial pond, all of the applied cyanide was removed by water hyacinths within 20 h, while none was removed in a control without plants (Schaeffer et al. 2012). This shows the potential for water hyacinth to eliminate cyanide from tailings ponds, such as those associated with gold-mining.

Land plants can also be used to remediate damaged and polluted sites. A site at Rhenania in Germany had been used for dumping wastes from phosphate mining. Heavy metals and sulfides had been leaching from the site for many years, causing serious contamination of local groundwater, but improvements in leachate water quality are planned by putting an impermeable cover over the waste site and planting deep-rooted trees on its surrounding slopes (Schaeffer et al. 2012). Deciduous birch trees had naturally established on the contaminated site and helped to reduce leaching of contaminated water by means of evapotranspiration, but this was only effective in summer when the trees are in leaf. Fifteen thousand evergreen Douglas-fir trees (*Pseudotsuga menziesii*) were planted recently among the birches with the intent that they will reduce the leaching of water from the contaminated site in all seasons, as well as help to stabilize the banks against erosion. This field experiment will need to be monitored for many years to determine whether it is effective in stabilizing and remediating this contaminated site.

Strong interest in floating bed technology has developed recently in China to deal with the widespread problem of eutrophication of lakes and reservoirs. Zhang et al. (2012) reported on experiments with "ecological floating beds" stocked with water spinach (*Ipomoea aquatica*) as an experimental plant for the removal of N and P nutrient contamination from a lake. The beds were made of four bamboo poles, each 3 m long, arranged as a square and draped with nylon netting on which the water spinach was placed. The relative benefits of three floating bed designs were examined: simple beds, beds with hanging hemp rope attached, and beds with hanging synthetic polymer rope attached. After the beds had been in place in the lake for 40 days, samples of the plants and ropes were taken and tested further for their capacity to absorb N and P under laboratory conditions. It was found that the plant–hemp–rope combination removed N and P most efficiently and could absorb the majority of the N and P in the water under experimental conditions. The plants absorbed P more effectively, and microbes associated with the ropes appeared to absorb N more effectively, presumably by means of nitrification and denitrification. The results indicate the need for further field-scale experimentation with floating bed technology for decontaminating eutrophic reservoirs (Zhang et al. 2012).

River and reservoir management strategies

Dams on rivers in China have caused significant changes to fish populations (Zhong and Power 1996) and the effects are ongoing. Connections to habitat that is necessary for fish spawning, rearing, and refuge from predators is lost when dams are constructed. Allowing for the passage of fish around artificial barriers such as dams is therefore an important aspect of restoring the ecological health of river systems. The Yangtze River is especially rich in fish diversity, having 177 endemic species among its 361 reported fish species (Zhang and Lou 2011). For these reasons, Johnson and Rainey (2012) described the ecodesign of fishways that allow upstream movement of fish past dams, based on experience in the Columbia River system and with special attention to fish passage needs in the Three Gorges region. Fishways are best constructed as part of the original plan for a dam or other obstruction, but can be designed and implemented afterwards when the need becomes evident.

Several fishways designs are used in the Columbia River region, ranging from near-natural ramps that allow passage beyond a weir to sets of concrete elevated steps that circumvent a high dam. Johnson and Rainey (2012) described a fishway ecodesign process that they have used, and then demonstrated how it might be used in the Three Gorges Reservoir Area with reference to a specific dam. The process involves: identifying the focal fish species, understanding their ecology and behavior, identifying the environmental conditions at the blockage, establishing the required design criteria, selecting the preferred fishway from among suitable options, conducting research to resolve any critical uncertainties that may exist, working with stakeholders to apply the design criteria and develop the final design, and building the fishway and monitoring its effectiveness. The process is intended to be used adaptively so that lessons that are learned as the process unfolds are quickly applied.

In addition to designs for fishways, process models from other countries will also be very useful for the development of environmentally sustainable and ecologically informed processes for management decision-making affecting the drawdown zone of the Three Gorges Reservoir. The Columbia Estuary Ecosystem Restoration Program (CEERP) in the US northwest provides one such example (Johnson et al. 2012). The CEERP applies to the 235 km long estuarine region of the Columbia River below the power supply dams on the river and is aimed at mitigating the environmental effects of both the dams and land uses adjacent to the estuary "by working to understand, conserve, and restore ecosystems" (Johnson et al. 2012). Factors that affect the health of fish populations, such as food webs, detritus fluxes, and nursery areas have all been strongly affected by alterations of the river. The restoration program aims to understand ecosystem stressors and by this means restore vital ecosystem structures and processes. Salmon (*Onchoryhnchus* spp.) are the focal fish species and the program aims to improve their diversity, foraging success, growth, and survival by actions that improve habitats and ecosystem processes such as wetland connectivity. To accomplish its objectives, the program is adaptive and cooperative, taking a government-led approach with broad stakeholder engagement. An adaptive and cooperative management approach is specially recommended for the Three Gorges Reservoir Area, including the five-phase annual cycle of the CEERP: strategize, decide, act, monitor/research, and evaluate (Johnson et al. 2012). This cycle can be applied to the ecofriendly sustainable-use objectives for the drawdown zone of the Three Gorges Reservoir.

Hanfeng Lake is a special part of the Three Gorges Reservoir that is surrounded by the urban area of Kaixian, a county in northern Chongqing (Fig. 5). The 15 km^2 "lake" is partially separated from the rest of the reservoir by a dam designed solely to moderate the water level so that the amenity values provided by the lake will be retained throughout the year (Willison et al. 2012). The lake lies on the Pengxi River, which is the tributary river having the largest flooded area of all the tributaries that empty directly into the reservoir, due to the relatively shallow slopes of its river banks. Substantial funds have been made available to the local Kaixian government for investing in ecoenvironmental lake development, and the lake has been declared part of the sustainable-use component of a nature reserve, with special emphasis on providing habitat for aquatic birds and attracting nature

Fig. 5 The photograph taken 16 April 2012 shows some of the engineering of the banks of Hanfeng Lake which is a distinct part of the Three Gorges Reservoir lying within Kai City in Kaixian, a county-level administrative unit in Chongqing Municipality, China. The lake level had been lowered following its winter peak to reveal artificially created dike ponds which were designed to maintain desirable aquatic plants at the water's edge throughout the fluctuation cycle of the lake level. Hardened sloping surfaces and lakeside recreational amenities are also visible

tourists (Chongqing Municipal Government 2010). To this end, a bird watching station has been erected in a plantation of trees at the edge of the lake.

Once the water regulatory dam is fully operational, the height of the water surface in Hanfeng Lake is planned to be drawn down from its winter peak of 175 m above sea level to 172 m in summer. This will result in an exposed drawdown zone during summer and several experimental engineering approaches are being taken within this zone. These include traditional hardened surfaces, hardened surfaces that can support plant growth, systems of engineered dikes and ponds that can support permanent shallow-water vegetation (Fig. 5), and plantations of flood-tolerant trees such as Chinese swamp cypress (*G. pensilis*). In addition, vegetated floating islands will be used to assist with removing nutrients and reducing the eutrophic status of the lake (Willison et al. 2012).

Willison et al. (2012) proposed that ecodesign principles be adopted for management of this special drawdown zone at Hanfeng Lake and recommended that the urban community be involved in its use, including using it for local food production and environmental education.

A useful comparison with Hanfeng Lake is provided by Shuanglong Lake, which lies in the Yubei district of Chongqing city. This 17 ha reservoir is not part of the Three Gorges Reservoir system, but is nevertheless an example of intensive intervention to alter the condition of a lake in a densely populated urban setting in China (Guo et al. 2012). At the outset in 2008, the lake was highly eutrophic having been polluted with sewage and industrial runoff. Multiple interventions were then performed including dredging, aeration, bottom drainage, landscaping, and tree planting on surrounding banks; stocking the lake with algae-eating fish and molluscs; creation of large floating islands stocked with aquatic plants; addition of nearshore floating beds of aquatic plants; and engineered wetlands stocked with sedges (*Cyperus alternifolius*) along input streams. About 1 ha of floating beds and 1 ha of sedge wetlands were created in total. Aquatic plants are routinely harvested and composted so as to remove nutrients. In addition, measures were put in place to reduce the input of pollutants and to educate the local public about their role in combating eutrophication. The result is that the quality of the water in the lake has improved considerably, with nitrogen and phosphorus levels having dropped in 2011 to less than a third of their previous values (Guo et al. 2012). This example shows that it is possible to remediate a severely polluted urban lake if enough effort is invested, but even for a relatively small lake it is a complex task.

Conclusions

The reports reviewed here show that there is growing recognition in China of the importance of wetlands in ecosystem management at the regional level. It is also clear that wetlands ecological engineering is a rapidly emerging scientific discipline in China which has some distinctive characteristics because it is founded partly on traditional approaches such as dike–pond engineering. The reports reveal that wetland engineering and management in the Three Gorges Reservoir Area need to be specifically adapted to the distinctive environmental, ecological, economic and social conditions that exist there. In recent years, international scientific exchanges and cooperation in research have assisted with environmental management progress in the Three Gorges Reservoir Area. We recommend that such cooperation continue and expand in the future. Studies that focus on the concept of "ecofriendly utilization", tap into local knowledge, and make use of the field research stations that have been created in the Three Gorges Reservoir Area will be especially valuable. The unprecedented environmental and social challenges that are being faced as a result of creation of the Three Gorges Reservoir provide exciting opportunities for scientific invention, experiment, and novel outcomes that have the potential to provide valuable lessons not only for the affected region of China but for the whole world.

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