Biodivers Conserv (2008) 17:3149–3163
DOI 10.1007/s10531-008-9416-2

REVIEW PAPER

Impacts of large dams on riparian vegetation: applying global experience to the case of China's Three Gorges Dam

Thomas New · Zongqiang Xie

Received: 14 February 2008 / Accepted: 26 June 2008 / Published online: 16 July 2008

Abstract Dams are widely recognised as having significant negative consequences for the surrounding natural ecosystems and environment. China's Three Gorges Dam, being one of the largest in the world, stands to inflict more damage than most for numerous reasons. This paper reviews the current knowledge on the impacts of dams and impoundments with regard to reservoir riparian vegetation in order to apply this knowledge to the Three Gorges Project. It also summarises research performed to date on the effects of the Three Gorges Dam on the local riparian zone and vegetation. The known and potential outcomes for local plant communities are examined in terms of their responses to the increased water levels, altered hydrological characteristics and other adverse effects associated with the construction of the dam. Vegetation responses will be diverse and change over time, but will ultimately result in a markedly different landscape and riparian zone within the Three Gorges Reservoir. These changes will take place through a loss of previous vegetation, potential invasion by exotics and result from the significant alteration in hydrological regimes and also erosion and sedimentation processes influencing and creating novel plant communities. Management of the environmental consequences of the Three Gorges Project should take into account factors associated with these processes, in order to facilitate vegetation recovery in the reservoir and to conserve biodiversity of the surrounding ecosystems.

Keywords China · Dam · Management · Reservoir · Riparian zone · Riparian vegetation · Three Gorges Dam · Water level fluctuation

T. New (✉) · Z. Xie
State Key Laboratory of Vegetation and Environmental Change, Centre of Ecology Institute of Botany, The Chinese Academy of Sciences, 20, Nanxincun Xiangshan, Beijing 100093, China
e-mail: thomas.j.new@gmail.com

Z. Xie
e-mail: xie@ibcas.ac.cn

Introduction

It is currently estimated that two-thirds of the world's flowing fresh water is obstructed from reaching the oceans by more than 45,000 large dams and approximately 800,000 small dams (Fuggle et al. 2000). These dams provide services such flood mitigation, increased navigation capabilities, irrigation, reliable water supplies and hydroelectricity. The utilisation and subsequent alteration of hydrological regimes has had a significant impact on river processes and their associated ecosystems and environments. The hydrology of large rivers have undergone more marked alterations as their higher flows present the greatest potential for hydroelectricity generation (Stanford and Ward 1992). Adverse environmental and social effects of large dams are well documented, and include effects such as changes in local climate patterns, habitat fragmentation, generation of methane gas, loss of biodiversity and inundation of cities and highly productive agricultural land. The environmental impacts have formed the focus of a large amount of research in recent decades, which has assessed the changes in aquatic fauna and flora, effects on downstream river hydrology, large-scale habitat fragmentation and responses of shoreline vegetation in regulated rivers around the world (e.g. Obat 1986; Nilsson and Jansson 1995; Hill et al. 1998; Riis and Hawes 2002; Ali 2006). It is widely recognised that large dams can result in a significantly altered shoreline and riparian vegetation both in the impoundment area (Springuel et al. 1991) and in downstream reaches (Merritt and Cooper 2000). The main mechanism through which dams affect shoreline vegetation is by altering the natural water flow regime (Nilsson and Berggren 2000), but other factors associated with dams also have the potential to change surrounding plant communities.

China has an extensive history of water resource development and is home to almost half (22,000 out of an estimated 45,000) of the world's large dams (Fuggle et al. 2000). Interestingly, only 22 of China's large dams existed prior to the founding of the People's Republic of China in 1949 (Wu et al. 2004), illustrating the rapid progress and development China is currently undergoing. However, many negative aspects surround China's dams, including large-scale population relocation, loss of cultural heritage sites, spread of infectious diseases, pollution and degradation of the watershed and negligent science leading to serious misjudgements being made regarding dam locations and function. China's largest project to date is the damming of the Three Gorges, which was initiated in 1992 despite much internal and external concern, and is due to become fully functional in 2009. The dam serves multiple purposes; primarily as a flood mitigation measure but also to generate hydroelectricity, provide water resources and increase transport capabilities along the Yangtze River. The dam was constructed on the Yangtze River at Yichang City and runs approximately 660 km upstream to Chongqing (see Fig. 1), forming a total inundation area or reservoir of 1,080 km^2 with an average width of 1.1 km, approximately double the pre-dam river width (Wu et al. 2004). The Three Gorges Reservoir Area (TGRA) is formed by a rise in the water level by 175 m at maximum capacity (due at the end of 2009).

The Three Gorges Dam (TGD) lies in a region which is considered to be one of the three richest flora centres in China (Ying 2001) and is also recognised as one of 25 biodiversity hotspots in the world (Myers et al. 2000). This is due to its unique geography and complex topography and also the fact that a group of species found here are survivors from the late Tertiary and Quaternary periods, resulting in a high level of endemic, rare and ancient species. Although the climate of the region is considered to be monsoonal subtropical, the flora is characterised by a mix of tropical, subtropical and temperate species. Much concern has arisen from the scientific community over the environmental and social consequences of the TGD (e.g. Fearnside 1988; Edmonds 1992; Wu et al. 2003; Shen and Xie 2004). The

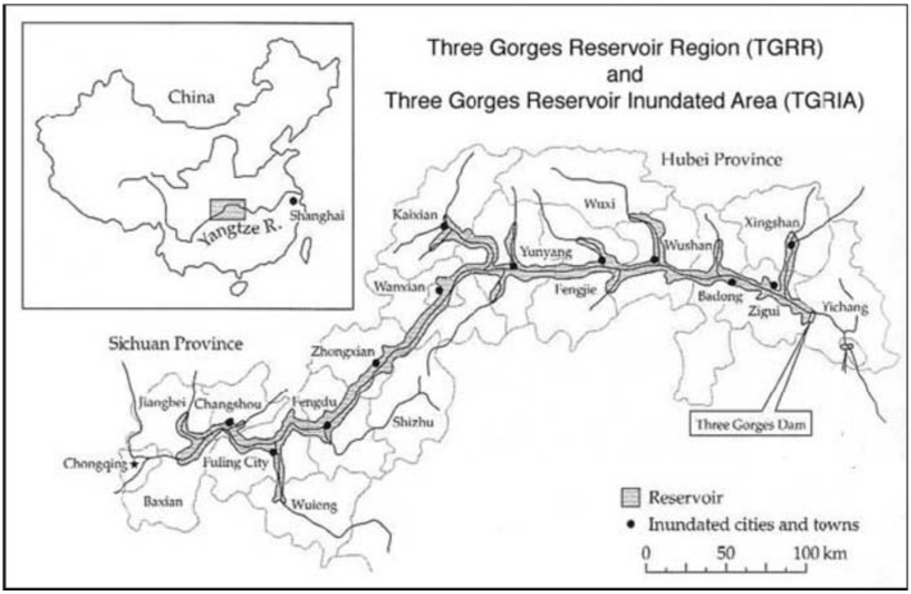

Fig. 1 Location of the Three Gorges Dam in Hubei Province (extracted from Wu et al. 2004)

necessary relocation of over 2 million people, threats to endangered aquatic fauna, doubts over the life expectancy and function of the dam, China's poor environmental record, unbalanced economic costs, potential for increased seismic activity, significant loss of cultural heritage sites and adverse downstream effects have cast a large cloud of controversy over the TGD. Of particular concern to the Chinese scientific community is what impact the TGD will have on the shoreline and riparian vegetation through the inundation of existing habitats and the creation of a substantial water level fluctuation zone (WLFZ) (up to 30 m) in the impoundment area. Chinese scientists have compiled a significant body of work in order to form baseline knowledge and attempt to assess and manage future changes in the local environment. The aim of this paper is to collate this knowledge and combine it with other experiences and studies of the impact of dams and river regulation around the world in an attempt to predict possible effects from the TGD on the riparian zone vegetation in the reservoir area. From this, insight into the aspects of management issues and potential future problems can be formulated in order to minimise the environmental impact of the TGD on surrounding vegetation communities.

Natural river hydrology and riparian zones

Riparian ecosystems form a transitional zone between terrestrial and aquatic ecosystems, encompassing the area between the low and high-water marks, and also the landscape above the high-water mark which may be influenced by floods or elevated water tables (Naiman and Decamps 1997). They are generally highly diverse, dynamic and complex habitats due to the range of environmental factors that affect them. Plant community types which form riparian zones vary from deciduous trees and shrubs on heterogenous substrates, broad wetland floodplains with eucalypts, grasses and sedges, complex forest systems with high animal diversity and deltas with distinct plant zonation (Nilsson and

Svedmark 2002). The riparian zone is critical in maintaining the health of riverways and watersheds, as vegetation stabilizes riverbanks, maintains habitat connectivity, enhances water quality and filters surrounding run-off water. Natural riparian areas also form important pathways for migrating species and plant dispersal, particularly species that utilise water as a dispersal mechanism (Jansson et al. 2000). Riparian zones act as important biological corridors for both plants and animals as they exist as extended networks between different habitats. They are also particularly sensitive to changes in hydrological regimes and have been recognised as good indicators of environmental change (Nilsson and Berggren 2000).

Hydrological regimes greatly influence the characteristics of riparian zones (Toner and Keddy 1997), particularly seasonal variations in flow and alternating wet and dry cycles. Five key water flow characteristics have been identified as important factors in shaping riparian plant communities; timing (season), duration, frequency, rate of change and magnitude (Nilsson and Svedmark 2002). Flooding and water level fluctuations create landscape disturbances resulting in a wide variety of habitats for plants that possess different adaptations. Duration, timing, magnitude and frequency affect the length of the growing season by determining the amount of exposed land present in summer or during periods when plants are able to grow and reproduce. There can be considerable year-to-year, as well as within-year variation of these factors, further increasing the level of disturbance in riparian ecosystems. Seasonal variations will have different impacts compared to fluctuation events occurring over longer time-spans. The magnitude of floods can hold different consequences for riparian ecosystems, as high-magnitude floods may create new geomorphic features and affect the entire landscape while smaller magnitude floods will influence ecosystems characteristics such as plant community structure or may only have impacts at the plant species level (Hughes 1997). Magnitude and rate of change can influence scouring processes and cause mechanical damage to plants, to which woody plants are generally more resistant compared with herbaceous species. These flow characteristics interact with other environmental factors to form a wide range of variables which can influence the riparian zone.

Erosion and sedimentation processes are strongly linked to the hydrology of a river and also holds consequences for the surrounding plant communities. These processes can result in the creation of new landforms such as in-stream sandbanks and temporary islands and determine shoreline characteristics as well. In watersheds with high levels of erosion, sedimentation and deposition (i.e. rivers with high flow rates or seasonal fluctuations), a natural mosaic of patches is created along the shoreline, providing a range of niches and habitats available for colonization (Naiman and Decamps 1997). These processes can also influence substrate characteristics such as coarseness of gravel and organic content in the riparian zone. Plant communities can be structured and to an extent, determined, by substrate availability, as plants often display a preference or tolerance for a specific range of soil and substrate types.

Vegetation patterns found within riparian communities are generally a result of a combination of the factors outlined above. Plant communities commonly display a distribution according to local elevation gradients (according to water levels), with herbaceous species dominating the lower wet zones and larger shrubs and trees occurring in the higher zones and border terrestrial areas less prone to lengthy periods of inundation (Wilson and Keddy 1985; Nilsson and Svedmark 2002; Ali 2003; Bai et al. 2005). This zonation only occurs when the water level gradient (elevation gradient) corresponds with the soil moisture conditions (Stromberg 1997), and has been linked to the identification of different functional plants types. Ali (2003) proposed groupings of plant types where the wettest zone is dominated by shallow rooted plants with reduced lateral branching and the ability to produce high amounts of water dispersed propagules; the moist zone (next along the gradient) is dominated by plants that survived the harsh conditions through below-ground rhizomes or stolons and vertical shoots less prone to flood induced damage; while in the higher zones with dryer conditions taller trees with well developed root systems able to access ground water dominate. These plant groups also correspond with Naiman and Decamps' (1997) grouping of riparian plants according to mechanisms of coping with water conditions and flooding disturbance. The four groups being: (1) invaders—produce large numbers of wind- and water-disseminated propagules that colonize alluvial substrates; (2) endurers—resprout after breakage or burial of either the stem or roots from floods or after being partially eaten; (3) resisters—withstand flooding for weeks during the growing season, moderate fires, or epidemics; and (4) avoiders—lack adaptations to specific disturbance types; individuals germinating in an unfavourable habitat do not survive. The overall general pattern is one of decreasing flood and disturbance tolerance with increasing altitude or distance from the shoreline. Associated with this are different plant life cycle strategies. Annual plant species are able to persist despite seasonal water level variations as they have reduced life cycles and can colonise patches exposed for limited periods of time. Perennials must be able to endure the entire spectrum of water conditions during a season in order to persist in a riparian environment (Keddy and Reznicek 1986).

The means by which hydrological characteristics interact with and affect the riparian zone are complex and often unique to individual rivers. Despite the strong influence of hydrology on riparian systems, other factors such as geology, local climate, herbivory, nutrient cycles, competition and substrate can be of significance in determining plant community structure (Wilson and Keddy 1985). The combination of these other environmental variables with the hydrology regime leads to a complex network of mechanisms that influence vegetation characteristics in the riparian zone. The result is an ecosystem that is naturally adapted to high levels of natural disturbance and prone to changes over time.

Effects of dams and impoundments on riparian zones

Due to their complex nature, species-rich characteristics and position within the landscape, riparian zones are subject to a high level of anthropogenic alteration. The impact of river regulation on riparian vegetation has become a point of major focus in studies over the previous two decades. While the effect of regulation has been studied at all levels of the watershed scale, the predominant area of focus is on the downstream impacts of damming. Aside from the obvious loss of habitat through inundation, damming holds a wide range of consequences for the surrounding habitats. Impoundment transforms free-flowing rivers into reservoirs or lakes, which are by nature subject to vastly different processes. This can alter local climate through the "lake effect", result in new sedimentation processes leading to changing landforms, affect the nutrient composition of both aquatic and terrestrial environments and create island habitats and habitat fragmentation. Damming results in significant changes in shoreline vegetation through affecting diversity and composition of plant communities as well as altering structural patterns (Obat 1986; Nilsson and Jansson 1995; Jansson et al. 2000; Deiller et al. 2001; Ali 2006; Wintle and Kirkpatrick 2007). However, it remains difficult to predict the precise impacts of damming since rivers all exhibit individual flow patterns and have different surrounding environments. Impoundments create fundamentally different hydrology regimes compared to free-flowing rivers by changing the timing and intensity of water level fluctuations as well as increasing their frequency

(Jansson et al. 2000). This factor is generally regarded as one of the driving forces that will determine riparian vegetation responses to damming.

Previous outcomes of river regulation

One of the more frequently observed impacts of damming is a reduction in species richness. In Sweden, numerous studies on boreal rivers have illustrated that reductions in species richness and plant cover are greatest on the impoundment shoreline compared to the run of the river reaches (Nilsson 1991, Nilsson and Jansson 1995; Nilsson et al. 1997; Jansson et al. 2000; Johansson and Nilsson 2002). Increased flood duration, frequency, increased magnitude and changed timing have all been identified as key influential factors in maintaining impoverished riparian vegetation across numerous impounded and dammed rivers (Jansson et al. 2000; Johansson and Nilsson 2002). The limited growth season resulting from increased flood duration prevents annual species from completing their life cycle, while a change in seasonal timing of floods to summer (the growth season) strongly reduces plant growth and performance as many plants have reduced flooding tolerance during growth periods. However, the reduction in species richness has been found to affect all species groups found along the boreal rivers of Sweden (Nilsson and Jansson 1995; Jansson et al. 2000) suggesting that the altered flow regimes are so different from any natural rhythm that no plants currently possess adaptations to cope with them. The altered timing and increased intensity of water fluctuations have been shown to be important in disrupting pre-regulation plant zonation patterns, the result being that many species are able to grow at elevations lower than their natural range of occurrence (Nilsson 1983; Jansson et al. 2000; Johansson and Nilsson 2002). The importance of indirect effects has also been frequently noted. Wave action, ice scour and erosion were found to be more pronounced in impounded areas compared to free flowing rivers (Johansson and Nilsson 2002). This type of erosion activity has been associated with the development of coarser substrates less suitable for plant colonization (Nilsson and Jansson 1995). Plant community composition also changed according to dispersal traits (Jansson et al. 2000), as the number of vegetative dispersers and species with long-floating seeds increased in impoundment riparian vegetation. This implies that dams and impoundments act as a barrier to dispersal, although this theory does not have a consensus (Jansson et al. 2005).

The construction of the Aswan High Dam on the river Nile has also lead to considerable changes in the surrounding riparian vegetation. Springuel et al. (1996) identified the presence of a new plant group on the Lake Nasser (Nile River) shoreline that is able to persist due to the increased water levels. Previously, all plants in the region relied on either groundwater flows or precipitation. The constant water supplies brought about by the dam has allowed a substantial extension of vegetation into new areas and an increase in biodiversity. In another area of the dam, Lake Nubia, vegetation has thought to be reduced (when compared to previous studies) (Ali 2006). This is a result of the new predictable flooding regime creating a relatively stable and less disturbed habitat compared to the natural highly variable flows and flood events of an arid system. Period of inundation, MSL and texture of soil deposition have all been indicated as driving factors for vegetation characteristics in Lake Nubia. Increased deposition of finer grained sediments can be a result of amplified water fluctuations, wave action or the dam functioning as a large sediment trap. In the Aswan High Dam resulting variations in soil texture combined with increased water levels have led to new plant zonation patterns with the riparian belt (Ali 2006).

In the US, dams have displayed a range of impacts on shoreline vegetation. Johnson (2002) noted from aerial photographs of Lake McConaughy, formed by Kingsley Dam in

1941, that the novel riparian vegetation within the reservoir was dominated by a native *Populus* and *Salix* species. The formation of the new riparian zone occurred relatively rapidly after the reservoir was filled and was structurally similar to vegetation assemblages found upstream. Plant zonation also demonstrated a distribution according to water level fluctuations and soil moisture gradients, with water tolerant species occurring in and along the lower water line progressing up to shrubs and small woody species in the higher areas. Upstream vegetation communities have been attributed to the formation of the novel riparian vegetation, acting as a relict habitat providing a source of progules and parent matter for colonisation downstream. However, many other dam operations in the US have not enabled the maintenance of vegetation resembling the native pre-dam communities. In arid areas such as Arizona, Colorado and eastern Oregon, the creation of permanent water availability has resulted in the invasion of exotic species such as *Tamarix* that thrive in such conditions (Friedman et al. 1998; Stromberg et al. 2007; Nagler et al. 2008). In areas where both new and old vegetation persist together, a more complex and diverse riparian zone is formed. However, in some areas the introduced T*amarix* spp. has been able to out-compete native vegetation and resulted in stretches of *Tamarix* dominated communities. Shorelines of reservoirs along the multi-dammed Missouri River have experienced limited establishment of new riparian zones (Johnson 2002). A combination of large reservoir size resulting in loss of all pre-existing vegetation, steep unstable banks, high flow magnitudes and severe wave action has limited recolonisation to patches of ephemeral species in sheltered, flatter reaches of the reservoir shoreline.

The variety of habitat responses to damming illustrated above highlights the complexity of interactions involved with river regulation. Although hydrological regime is often cited as a driving factor, local geography, rainfall patterns, dispersal processes, nutrient cycling, pre-dam species composition and species traits will all influence the responses of riparian flora to damming. Also important is the individual functioning and operation of the dams, as this will determine the water level fluctuation patterns and reservoir characteristics. The absence of a general pattern of response makes it extremely difficult to predict the future effects of a dam on the local environment. Time scale is also a critical factor, as the succession of new riparian communities may take several decades to be fully realised. Short-term responses have frequently differed from long-term responses (Nilsson et al. 1997). Local, regional and historic context are also critical considerations when evaluating and predicting dam effects (Katz et al. 2005), which makes it difficult to predict the environmental outcomes of a dam based on knowledge and experiences from different locations.

Consequences of the Three Gorges Dam for the riparian zone

Once the dam becomes fully operational in 2009, it will have created a total reservoir region of approximately 58,000 km^2, including an inundation area of 1,080 km^2 (Wu et al. 2004). One of the initial, most obvious and certain environmental impacts of the dam is the loss of vegetation through inundation. Field studies have estimated that between 400 and 770 vascular plant species will be flooded when the water level reaches its maximum (175 m) (Wang et al. 2004, 2005b). Two species, *Myricaria laxiflora* and *Adiantum reniforme* var. *sinese*, will have their entire distribution inundated and become extinct in the wild (Xie et al. 2006), although conflicting reports exist regarding this issue. Numerous other studies have predicted that only *M. laxiflora* will be completely inundated but a further two species, *Securinega wuxiensis* and *Neyraudia wushanica*, may lose critical habitat (Huang 2001). The pre-dam riparian flora in the TGRA was considerably degraded due to centuries of agricultural activity and any remaining forests in the area were secondary growth and highly disturbed (Chen et al. 2007). Despite this fact, seasonal flooding and hydrological regimes have been identified as playing an important role in determining species richness in the riparian zone (Jiang et al. 2005). Aside from the four species (two in doubt) that will be inundated and loose critical habitat, there will be limited loss of plant communities of major conservation value as a result of the increased water level. Fortunately or sadly, all remaining communities of conservation significance largely lay at altitudes of 800 m ASL or more.

Further impacts resulting from the TGD are more uncertain and difficult to predict, although it is highly likely that they will be of significant consequence. Landslides and large-scale erosion events are common in the TGRA due to the steep valleys, high seasonal rainfall, heavy deforestation and high mountains in the area (Dai et al. 2004). While these hazards have been recognised and attempts have been made to mitigate them, such as reforestation and restriction of human activities on land with a slope greater than 25%, sheet erosion and minor landslides are still occurring along the TGRA (Yang and Peng 2007). It has been predicted that this will continue at potentially increased levels during the first 5–10 years of the dam life. This is due to the naturally unstable geology of the region, further amplified and exacerbated by the elevated water levels and increased severity of fluctuations. Erosion in the TGRA currently accounts for approximately 55% of the total erosion activity along the Yangtze River (Wang et al. 2005a). Sediment deposition processes may also significantly change in the reservoir due to increased water residency times and potential heavier sediment loads. Soil characteristics and substrate are largely affected by these processes, which in turn influence plant communities.

These events create another form of disturbance within the riparian zone, removing existing vegetation and opening up new patches for colonization. Invasive species are able to take advantage of disturbances of this nature, particularly along riverbanks as the river acts as efficient dispersal mechanism. The likelihood of invasive or exotic species appearing in the TGRA is high given the amount of human disturbances and the number of exotic plant species already present in the Three Gorges region (personnel observation). Species diversity may also be enhanced by this additional source of disturbance, as the maintenance of rare species has been previously linked to lakeshores exposed to high levels of disturbance (Morris et al. 2002). High disturbance regimes such as will be present in the TGRA maintain a high level of spatial heterogeneity and patchiness, leading to an increased availability of niches and gaps with reduced competition, creating increased opportunities for all forms of plants including poor competitors. However, if erosion events and landslides occur at the high frequency as is predicted in the TGRA, it may significantly hamper revegetation processes, both natural and human assisted, in the reservoir. It can also have many adverse effects on the function of the dam and water quality in the reservoir.

Pre-dam riparian vegetation in the Three Gorges had developed specific mechanisms to cope with the natural summer flooding patterns in the area. *M. laxiflora* has been found to undergo a period of summer dormancy and reduce its biomass in order to tolerate extended periods of complete summer flooding (Chen and Xie 2007). *Buxus ichangensis* has also demonstrated a strong tolerance to summer flooding, with morphological adaptations such as lenticels and adventitious roots enabling it to endure extended periods of water logging (Xue et al. 2007). *Arundinella anomala* is another local species which been experimentally shown to have a high tolerance to flooding (Luo et al. 2006). Other local species possess different adaptations to deal with summer flooding patterns. Plant zonation exhibited a typical pattern according to water level gradients and soil moisture conditions as described by Naiman and Decamps (1997), Ali (2003). Annual herbs (only present during the inter-flood

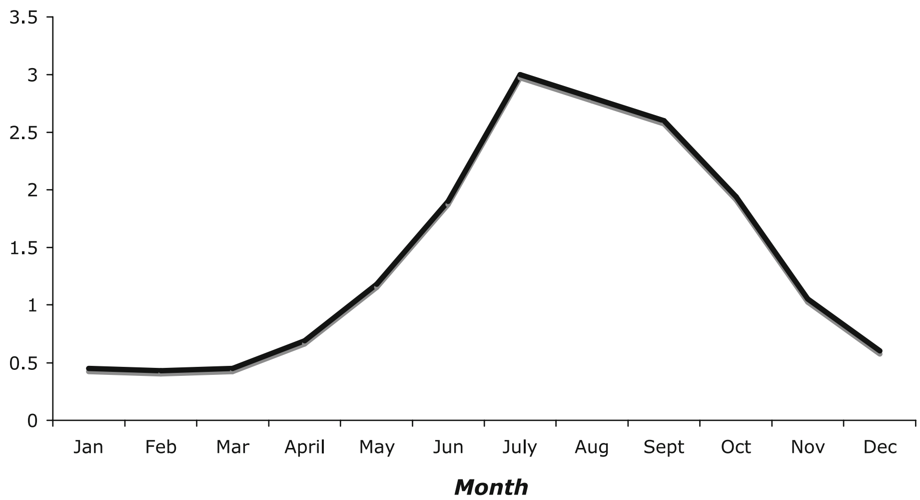

Fig. 2 Annual streamflow of the Yangtze River, taken at Yichang Hydological Station (extracted from Xu et al. 2007)

period) dominated the lowest level, the low to middle zone was mainly composed of perennial herbs capable of enduring periods of submergence, arid grassland and shrubs (deciduous and evergreen) distributed in the mid and high areas while evergreen shrubs and trees with a limited tolerance of flooding were located in higher zones (Wang et al. 2004; Bai et al. 2005).

The new hydrological regime brought about by the dam is the absolute opposite of the natural flood rhythms of the Yangtze River (Wang et al. 2004; Bai et al. 2005). Natural peak flows occurred during July, August and September (summer) with low flows in January, February and March (winter). This flow pattern is illustrated in Fig. 2. The Yangtze also experiences naturally large differences in yearly flows due to variations in the monsoonal weather patterns in the region. The reversal of flooding times to winter, increased duration, as well as a regulated water level fluctuation zone (WLFZ) with a 35 m magnitude, is going to dramatically alter the conditions in the riparian zone. Bai et al. (2005) have determined duration of flooding in the future WLFZ for the lower, middle and upper areas and the new hydrological regime is illustrated in Fig. 3. The lower zone (<145 m ASL) will experience inundation for >8 months, the middle area (146–155 m ASL) will be submerged for approximately 6–7 months while flooding in the upper zone (156–175 m ASL) may last 3–4 months. Terrestrial zones above the 175 m mark will also experience changing conditions in soil moisture caused by the water level fluctuations and wave action within the reservoir. This is almost a doubling of magnitude and inundation period (Wang et al. 2005a).

It is likely that the new hydrological regime in the TGRA will differ to such an extent that a significant portion of the pre-dam vegetation will be unable to adapt to it, at least not in the immediate future. Habitat availability will be decreased due to extended flooding periods, while disturbances will become more frequent through erosion, deposition and altered frequency and intensity of WLF. Certainly *M. laxiflora* will be unable to persist in the new riparian zone (Chen and Xie 2007). In the short term, it is probable that significantly reduced amounts of vegetation will be able to persist under the new conditions, resulting in a bald or naked zone, particularly in the lower parts of the WLFZ which can already be seen to be forming (personal observation). This phenomenon has been reported

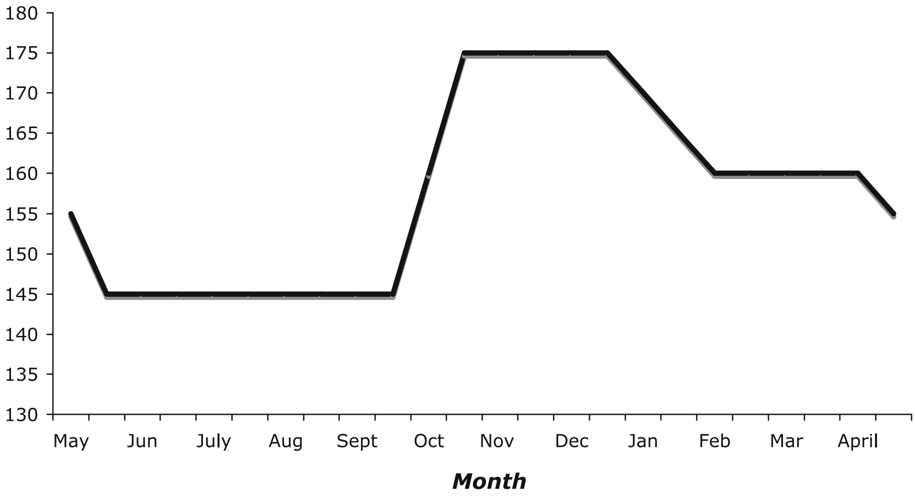

Fig. 3 Annual water fluctuation management schedule for the Three Gorges Dam (source: Three Gorges Project Preliminary Design Report. Changjiang Water Resources Commission, The Ministry of Water Resources, P.R. China 1992)

in numerous other cases of newly formed reservoirs and lakes (Baxter 1977). Concern exists over this bald zone, as it detracts from the Three Gorges natural scenery and may negatively affect tourism in the area. Given time, it is possible that natural successional paths will occur and a new riparian community will establish itself.

Plant species that previously endured inundation could persist in the future, although it remains to be seen what impact the alteration of flood timing will have on their growth. Logic would suggest that the occurrence of drawdown in the growth season (summer) would facilitate more rapid colonisation and growth, particularly of ephemerals and annual species, compared to the previous hydrological regime. This may result in the prevalence of entirely new plant communities such as grasslands as experienced in the Kariba Reservoir on the Zambezi River (Baxter 1977). It may also create a temporary arid environment in the higher areas during summer that would favour xeric species. The absence of summer flooding may also lead to the contraction of species formerly found at high zones to lower elevations in order to avoid water stress (drought) during the growing season.

However, it is possible that a similar plant zonation will persist, albeit with altered species and a contracted zonation. Bai et al. (2005) have predicted that the former arid species found at the lower level and waterline will be replaced by water-tolerant species such as *Cynodon* spp. and *Hemarthria* spp. or other aquatic species that can persist due to wave action or revive after desiccation during periods of drawdown. Aquatic and semi-aquatic plant species have been found to occur in circumstances such as this in numerous man-made reservoirs and lakes (Murphy et al. 1990; Riis and Hawes 2002). Wang et al. (2004) have proposed a list of plants that may potentially occur in the new riparian community, including perennial species *Cynodon dactylon*, *Arundinella fluviatilis*, *Paspalum paspaloides*, *Beckmannia syziganchne*, *Saccharum arundinaceum*, *Carex thompsonii*, *Polygonum cpaitatum* and *Equisetum palustre*. Suggested shrubs include *Salix variegata*, *Cynanchum verticillatum*, *Distylium chinense*, *Buxus ichangensis* and *Rosa multiflora* var. *cathayensis*. *Pterocarya stenoptera* (Chinese wingnut) has also been experimentally shown to have a high tolerance to flooding compared to other local tree species (*Quercus variabilis* and

Quercus glandulifera var. *brevipetiolata*) and is proposed as another candidate for the novel riparian community (Fan et al. unpublished).

While these species have all demonstrated flooding tolerance to a degree, it was under the natural hydrological rhythms or experimental conditions mimicking these rather than the post-dam flow patterns. It is still largely unknown how many of these species will respond to the dryer conditions in summer, increased periods of winter flooding and other effects associated with the reservoir. To date, numerous studies have been conducted on the local vegetation's ability to tolerate summer flooding, however few have focused on the effects of winter flooding. One study is being performed to assess how riparian vegetation from the TGA will respond to winter flooding. The results of this experiment will provide valuable insight into the future effects of the dam.

Implications for management

It has already been recognised that the Three Gorges Dam provides an excellent opportunity to conduct large-scale experiments on habitat responses to disturbance and fragmentation, albeit at an extremely high cost. Plans for another large dam in the south of China and further Chinese-developed dams in Myanmar, Laos and Pakistan, will soon provide numerous more opportunities to conduct such research. Since China is set on pursuing its aggressive dam development program, it is vital to gain a complete understanding of their environmental impacts in order to generate functional management practises. In the short term, research being carried out in the TGRA will provide some insight in this area, but given the long-term nature of the responses of habitats, it will not be until 30 or more years down the track that the full impacts of the dam become evident. Another major problem surrounding assessing the impacts of the dam is the limited amount of baseline pre-dam knowledge and data. The concept of riparian zones and aquatic-terrestrial ecotones has only gained recognition in China within the past two decades (Wang et al. 2005a). By this time construction of the TGD had already begun, rendering the formation of solid local baseline data almost impossible. This is reflected in the inconsistencies in estimates of inundated species and species that are expected to become extinct in the wild reported in numerous studies (see Wang et al. 2004, 2005a).

Restoration and protection of the riparian flora along the TGRA is vital to ensure the life and function of the dam, connectivity of the surrounding ecosystems, preservation of local biodiversity, and health of the watershed, and to conserve the remaining relatively intact ecosystems at higher altitudes. The riparian zone functions as a buffer of change for upland ecosystems, and provides vital habitat for the local fauna, which is also under significant threat. It is also necessary to ensure the natural scenery of the area remains as unblemished as possible as it forms the backbone of a major, and growing, tourist industry in the region. On a larger ecosystem scale, restoration of the riparian zone is important to protect surrounding and previously connected habitats for both flora and fauna. Conversely, these surrounding habitats will facilitate the natural rehabilitation of the riparian zone by dispersing propagules for colonisation, provided they are not so fragmented that transfer of vegetal matter is prevented.

Clearly, reversing the timing of floods to mimic the natural system is not an option since this would defeat the main function of the dam. Of particular concern is the extremely rapid rate of increase planned for the water level in October (approximately 30 m in one month or less, see Fig. 3). These polar differences in flow regime should be minimised where possible, as they result in major divergences from the previous or natural conditions to which the local ecosystems were adapted. The natural vegetation is the central key to successfully re-establishing a riparian zone in the reservoir. Numerous species are already known to possess a high tolerance to summer inundation, and screening of these plants for tolerance to winter flooding will reveal the plants most suitable for revegetation. It is probable that more species will adapt to the new conditions in the reservoir after an initial lag period. After this lag period, natural regeneration and succession will occur over a longer time period, and it is likely that several shifts or changes in vegetation communities will be associated with this. However, until this occurs, it is necessary to facilitate as much recovery of the riparian zone as possible through revegetation works. Protection of any remnant vegetation communities is also critical as these will serve as source communities for re-establishment in the riparian zone.

The current and continuing work on local vegetation responses to flooding will serve as the most valuable tool in selecting plants that may be suitable for revegetation activities in this zone. These species are pre-existing riparian species which have the most suitable local adaptations, even though it is still largely uncertain how the new hydrological conditions will affect them. It should be noted that local species selection also infers maintaining the local gene pool; therefore any seedlings used should be sourced from remnant vegetation patches in the TGRA rather than plants of the same species but distributed outside the TGRA. The importance of maintaining local species persistence has been recognised in other post-dam rehabilitation activities, as it results in greater success in riparian rehabilitation activities (Webb and Erskine 2003). It also serves as a further step towards local biodiversity preservation.

Rehabilitation activities should take into account factors such as the original plant zonation, edge effects and invasive species, successional pathways and the importance of local gene pools and species. Plants selected for rehabilitation should be based on the outcomes of the current research on winter flood tolerance, but also incorporate knowledge on the original and remnant vegetation in the area. Any planting performed should replicate the pre-damming plant zonation as described by Wang et al. (2004), Bai et al. (2005) and Jiang et al. (2005). The role of disturbance is extremely important in riparian rehabilitation activities, as seedlings are most susceptible to mortality derived from flooding and scouring processes during the initial years of establishment (Johansson and Nilsson 2002). Therefore, it will be necessary to perform a higher level of monitoring and maintenance in these initial stages to ensure the vegetation successfully establishes. Additional works such as weed removal and replanting where losses have occurred will also be necessary during this period. Revegetation operations on this scale also offer excellent opportunities for research and trials on regeneration ecology.

The sheer size of the TGRA will hold unique implications for management of the surrounding ecosystems. Different locations along the reservoir will be subject to varying degrees of disturbance, water level fluctuation and external impacts. This requires that management and regeneration plans will have to be developed at micro-scales to account for the different ranges of topography and geology and the varying hydrological processes associated with individual sites. For example, banks with steep slopes will experience a higher rate of change in WLF, higher rates of erosion and scour and a sharper soil moisture gradient compared to banks of less inclination. It holds that specific plant species will be suitable or able to persist in areas such as this. Other areas may not be suitable for performing any revegetation initially due to an extremely high probability of uncontrollable landslides or erosion occurring. Rehabilitation and conservation measures adopted in the TGRA should take into account local and regional scales and the spatial heterogeneity of the reservoir and the ecological implications associated with this.

Several factors stand to significantly undermine conservation and management efforts in the TGD. If landslides and erosion occur at the high rate that has been predicted (or even worse), the potential for revegetation is greatly reduced. It could result in the ill use of resources and a waste of effort if they occur in areas where revegetation and management works have already been undertaken. Also of concern is the potential for continuing human degradation from local communities. Old habits may die hard in this case, considering the long history of land utilisation, population pressure and land shortage in the region. Further detrimental human activities such as agricultural practices and harvesting of forest products in these areas must be limited to a minimum to allow the natural vegetation to recover. Pollution in the region is severe, with a total absence of sewage treatment and waste management programs, meaning a large proportion of raw waste and rubbish ends up in the waterways. The increased water residency time in the reservoir will only amplify the pollution problem. The implementation of proper waste management and treatment services are essential in the entire region of the Three Gorges in order to prevent serious water quality issues, degradation of both terrestrial and aquatic habitats and further loss of plant and animal communities. To date, token action has been taken by authorities and the dam construction company to minimise negative effects such as these. However, for anyone who visits the TGRA it is obvious that pollution, landslides and population pressure are going to pose serious and ongoing problems in the region (personnel observation).

Concluding remarks

The alteration of the riparian plant community is just one aspect of the environmental consequences of the TGD. Larger scale impacts are and will continue to occur both downstream and upstream of the reservoir, as well as in other terrestrial and aquatic ecosystems surrounding the reservoir. The disturbance regime brought about by the dam will have major negative environmental implications along the entire length of the Yangtze River for the lifespan of the dam, and for years after the decommissioning of it. Further than this, the social and economic effects associated with the loss of highly productive land and relocation of approximately 2 million people has very serious implications. On considering all of these factors, the wisdom of the Three Gorges Project becomes highly suspect. However, China is planning more large-scale dam projects both at home and abroad, so it is vital to gain an understanding of the complete range of effects of these operations in order to manage them effectively in the future and to minimise environmental and social impacts to the fullest.

Acknowledgements I would like to thank my colleagues at the Institute of Botany who assisted me with this paper, in particular Fan Dayong, Zhang Xiangying and Fu Zengjuan for translating the Chinese papers that have formed the base of much of the research. I acknowledge the National Key Technology R & D Program: ecological restoration within the water level fluctuation zone of Three Gorges Area (2006 BAC10B01) and CAS project (KZCX2-XB2-07-03) whose funding enabled the research and production of this paper.

References

Ali MM (2003) Plant functional types in Lake Nubia in relation to physiogeographic factors. Limnologica 33:305–315. doi:10.1016/S0075-9511(03)80025-7

Ali MM (2006) Shoreline vegetation of Lake Nubia, Sudan. Hydrobiologia 570:101–105. doi:10.1007/s10750-006-0168-2

Bai BW, Wang HY, Li XY, Feng YL, Zhi L (2005) A comparative study of the future water-level-fluctuating zone and the natural water-level-fluctuating zone in the Three Gorges Reservoir. J Southwest Agric Univ (Nature Science) 27(5):684–691

Baxter RM (1977) Environmental effects of dams and impoundments. Annu Rev Ecol Syst 8:255–283. doi:10.1146/annurev.es.08.110177.001351

Chen FQ, Xie ZQ (2007) Reproductive allocation, seed dispersal and germination of *Myricaria laxiflora*, an endangered species in the Three Gorges Reservoir Area. Plant Ecol 191:67–75. doi:10.1007/s11258-006-9214-4

Chen WL, Jiang MX, Zhao CM, Tian ZQ (2007) Plants and vegetation in the valley of the Three Gorges Reservoir. China Water Power Press, Beijing (in Chinese)

Dai FC, Deng JH, Tham LG, Law KT, Lee CF (2004) A large landslide in Zigui County, Three Gorges area. Can Geotech J 41(6):1233–1341. doi:10.1139/t04-049

Deiller AF, Walter J-MN, Tremolieres M (2001) Effects of flood interruption on species richness, diversity and floristic composition of woody regeneration in the Upper Rhine alluvial hardwood forest. Regul Rivers Res Manage 17:393–405. doi:10.1002/rrr.649

Edmonds RL (1992) The Sanxia (Three Gorges) project: the environmental argument surrounding China's super dam. Glob Ecol Biogeogr Lett 2(4):105–125. doi:10.2307/2997637

Fan DY, Yi YH, Xie ZQ, Chen FQ (unpublished) Ecophysiological responses of Oriental Oak (*Quercus variabilis*), Short Stipes Oak (*Quercus glandulifera* var. *brevipetolata*) and Chinese wingnut (*Pterocarya stenoptera*) seedlings to flooding

Fearnside PM (1988) China's Three Gorges Dam: "fatal" project or step toward modernization? World Dev 16(5):615–630. doi:10.1016/0305-750X(88)90190-8

Friedman JM, Osterkamp WR, Scott ML, Auble GT (1998) Downstream effects of dams on channel geomorphology and bottomland vegetation: regional patterns in the Great Plains. Wetlands 18:619–633

Fuggle R, Smith WT, Hydrosult Canada Inc, Agrodev Canada Inc (2000) Large dams in water and energy resource development in The Peoples Republic of China (PRC). A country review paper prepared as an input to the World Commission on Dams, Cape Town, www.dams.org. Cited 23 October 2007

Hill NM, Keddy PA, Wisheu IC (1998) A hydrological model for predicting the effects of dams on the shoreline vegetation of lakes and reservoirs. Environ Manage 22(5):723–736. doi:10.1007/s002679900142

Hughes FMR (1997) Floodplain biogeomorphology. Prog Phys Geogr 21:501–529. doi:10.1177/030913339702100402

Jansson R, Nilsson C, Dynesius M, Andersson E (2000) Effects of river regulation on river-margin vegetation: a comparison of eight boreal rivers. Ecol Appl 10(1):205–224. doi:10.1890/1051-0761(2000)010[0203:EORROR]2.0.CO;2

Jansson R, Zinko U, Merritt DM, Nilsson C (2005) Hydrochory increases riparian plant species richness: comparison between a free-flowing and a regulated river. J Ecol 93:1094–1103. doi:10.1111/j.1365-2745.2005.01057.x

Jiang MX, Deng HB, Cai QH, Wu G (2005) Species richness in a riparian plant community long the banks of the Xiangxi River, the Three Gorges region. Int J Sustain Dev World Ecol 12:60–67

Johansson ME, Nilsson C (2002) Responses of riparian plants to flooding in free-flowing and regulated boreal rivers: an experimental study. J Appl Ecol 39:971–986. doi:10.1046/j.1365-2664.2002.00770.x

Johnson WC (2002) Riparian vegetation diversity along regulated rivers: contribution of novel and relict habitats. Freshw Biol 47:749–759. doi:10.1046/j.1365-2427.2002.00910.x

Katz GL, Friedman JM, Beatty SW (2005) Delayed effects of flood control on a flood-dependent riparian forest. Ecol Appl 15(3):1019–1035. doi:10.1890/04-0076

Keddy PA, Reznicek AA (1986) Great Lakes vegetation dynamics: the role of fluctuating water levels and buried seeds. Great Lakes Res 12:26–36

Luo FL, Wang L, Zeng B, Ye XQ, Chen T, Liu D et al (2006) Photosynthetic responses of the riparian plant *Arundinella anomala* Steud. In Three Gorges Reservoir region as affected by simulated flooding. Acta Ecol Sin 26(11):3602–3609 (in Chinese)

Merritt DM, Cooper DJ (2000) Riparian vegetation and channel change in response to river regulation: a comparative study of regulated and unregulated streams in the Green River Basin, USA. Regul Rivers Res Manage 16:543–564. doi:10.1002/1099-1646(200011/12)16:6<543::AID-RRR590>3.0.CO;2-N

Morris PA, Hill NM, Reekie EG, Hewlin HL (2002) Lakeshore diversity and rarity relationships along interacting disturbance gradients: catchment area, wave action and depth. Biol Conserv 106:79–90

Murphy KJ, Roslett B, Springuel I (1990) Strategic analysis of submerged lake macrophyte communities: an international example. Aquat Bot 36:303–323. doi:10.1016/0304-3770(90)90048-P

Myers N, Mittermeier RA, Mittermeier CG, da Fonseca GAB, Kent J (2000) Biodiversity hotspots for conservation priorities. Nature 403:853–858. doi:10.1038/35002501

Nagler PL, Glenn EP, Hinojosa-Huerta O, Zamora F, Howard K (2008) Riparian vegetation dynamics and evapotranspiration in the riparian corridor in the delta of the Colorado River, Mexico. J Environ Manage 41(3):322–335

Naiman RJ, Decamps H (1997) The ecology of interfaces: riparian zones. Annu Rev Ecol Syst 28:621–658. doi:10.1146/annurev.ecolsys.28.1.621

Nilsson C (1983) Frequency distributions of vascular plants in the geolittoral vegetation along two rivers in northern Sweden. J Biogeogr 10:351–369
Nilsson C, Berggren K (2000) Alterations of riparian ecosystems caused by river regulation. Bioscience 50:783–792. doi:10.1641/0006-3568(2000)050[0783:AORECB]2.0.CO;2
Nilsson C, Jansson J (1995) Floristic differences between riparian corridors of regulated and free-flowing boreal rivers. Regul Rivers Res Manage 11:55–66. doi:10.1002/rrr.3450110106
Nilsson C, Svedmark M (2002) Basic principles and ecological consequences of changing water regimes: riparian plant communities. Environ Manage 30(4):468–480. doi:10.1007/s00267-002-2735-2
Nilsson C, Jansson R, Zinko U (1997) Long-term responses of river-margin vegetation to water level regulation. Science 276:798–800. doi:10.1126/science.276.5313.798
Obat EA (1986) Ecological comparison of the pre- and post-impoundment macrophyte flora of the river Niger and Lake Kainji, Nigeria. Vegetatio 68:67–70
Riis T, Hawes I (2002) Relationship between water level fluctuations and vegetation diversity in shallow water of New Zealand lakes. Aquat Bot 74:133–148. doi:10.1016/S0304-3770(02)00074-8
Shen G, Xie ZG (2004) Three Gorges project: chance and challenge. Science 304:681. doi:10.1126/science.304.5671.681b
Springuel I, El-Hadidi NM, Ali MM (1991) Vegetation gradient on the shores of Lake Nasser in Egypt. Vegetatio 94:15–23
Springuel I, Sheded M, Murphy KJ (1996) The plant biodiversity of the Wadi Allaqi Biosphere Reserve (Egypt): impact of Lake Nasser on a desert wadi ecosystem. Biodivers Conserv 6:1259–1275. doi:10.1023/B:BIOC.0000034012.93599.c0
Stanford JA, Ward JV (1992) Management of aquatic resources in large catchments: recognizing interactions between ecosystem connectivity and environmental disturbance, pp 91–124. In: Naiman RJ (ed) Catchment management: balancing sustainability and environmental change. Springer-Verlag, New York, 542 pp
Stromberg JC (1997) Growth and survivorship of Fremont cottonwood, Goodding wilow and salt cedar seedlings after large floods in Central Arizona. Great Basin Nat 57(3):198–208
Stromberg JC, Beauchamp VD, Dixon MD, Lite SJ, Paradzick C (2007) Importance of low-flow and high-flow characteristics to restoration of riparian vegetation along rivers in arid south-western United States. Freshw Biol 52:651–679. doi:10.1111/j.1365-2427.2006.01713.x
Toner M, Keddy P (1997) River hydrology and riparian wetlands: a predictive model for ecological assembly. Ecol Appl 7:236–241
Wang Y, Wu JQ, Huang HW, Lui SB (2004) Quantative analysis of plant communities in water level fluctuation zone within the Three Gorges Reservoir Area of Changjiang River. J Wuhan Bot Res 22(4):307–314 (in Chinese)
Wang Y, Liao M, Sun G (2005a) Analysis of the water volume, length, total area and inundated area of the Three Gorges Reservoir, China using the SRTM DEM data. Int J Remote Sens 26:4001–4012. doi:10.1080/01431160500176788
Wang Y, Liu YF, Liu SB, Huang HW (2005b) Vegetation reconstruction in the Water-level-fluctuation Zone of the Three Gorges Reservoir. Chin Bull Bot 22(5):513–522 (in Chinese)
Webb AA, Erskine WD (2003) A practical scientific approach to riparian vegetation rehabilitation in Australia. J Environ Manage 68(4):329–341. doi:10.1016/S0301-4797(03)00071-9
Wilson SD, Keddy PA (1985) Plant zonation on a shoreline gradient: physical response curves of a component species. J Ecol 73:851–860. doi:10.2307/2260152
Wintle BC, Kirkpatrick JB (2007) The response of riparian vegetation to flood-maintained habitat heterogeneity. Austral Ecol 32:592–599. doi:10.1111/j.1442-9993.2007.01753.x
Wu J, Huang J, Han X, Xie Z, Gao X (2003) Three Gorges Dam-experiment in habitat fragmentation? Science 300:1239–1240
Wu JG, Huang JH, Han XG, Gao XM, He FL, Jiang MX et al (2004) The Three Gorges Dam: and ecological perspective. Front Ecol Environ 2(5):241–248
Xie ZQ, Wu JQ, Xiong GM (2006) Conservation ecology of rare and endangered plants in the Three Gorges Reservoir Area. China Water Power Press, Beijing (in Chinese)
Xu KQ, Brown C, Kwon HH, Lall U, Zhang JQ, Hayashi SJ et al (2007) Teleconnections to Yangtze River seasonal streamflow at the Three Gorges Dam, China. Int J Climatol 27(6):771–780. doi:10.1002/joc.1437
Xue YH, Chen FQ, Fan DY, Xie ZQ (2007) Ecophysiological responses of *Buxus ichangensis* to summer waterlogging. Biodivers Sci 15(5):542–547. doi:10.1360/biodiv.060236 (in Chinese)
Yang GX, Peng YH (2007) The Three Gorges Project conservation and reservoir landslides. China Three Gorges Constr 3:27–29
Ying T (2001) Species diversity and distribution pattern of seed plants in China. Biodivers Sci 9:393–398 (in Chinese)