Hydrol. Earth Syst. Sci. Discuss., 12, 8247–8287, 2015
www.hydrol-earth-syst-sci-discuss.net/12/8247/2015/
doi:10.5194/hessd-12-8247-2015

Hydrology and Earth System Sciences
Open Access
Discussions

A century scale human-induced hydrological and ecological changes of wetlands of two large river basins in Australia (Murray) and China (Yangtze): development of an adaptive water resource management framework

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Received: 24 June 2015 – Accepted: 14 August 2015 – Published: 24 August 2015

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Recently, the provision of food and water resources of two of the world's large river basins, the Murray and the Yangtze, has been significantly altered through widespread landscape modification. Long-term sedimentary archives, dating back to past centuries, from wetlands of these river basins reveal that rapid, basin-wide development has reduced resilience of biological communities, resulting in considerable decline in ecosystem services, including water quality. In particular, large-scale human disturbance to river systems, due to river regulation during the mid-20th century, has transformed the hydrology of rivers and wetlands, causing widespread disturbance to aquatic biological communities. Historical changes of cladoceran zooplankton (water fleas) were used to assess the hydrology and ecology of three Murray and Yangtze River wetlands over the past century. Subfossil assemblages of cladocerans retrieved from sediment cores (94, 45 and 65 cm) of three wetlands: Kings Billabong (Murray), Zhangdu and Liangzi Lakes (Yangtze) strongly responded to hydrological changes of the river after the mid-20th century. River regulation caused by construction of dams and weirs, and river channel modifications has led to hydrological alterations. The hydrological disturbances were either: (1) a prolonged inundation of wetlands, or (2) reduced river flow, which caused variability in wetland depth. These phenomena subsequently transformed the natural wetland habitats, leading to a switch in cladoceran assemblages preferring poor water quality and eutrophication. An adaptive water resource management framework for both of these river basins has been proposed to restore or optimize the conditions of wetland ecosystems impacted by 20th century human disturbance and climate change.

1 Introduction

There has been a worldwide growing awareness for the value of flow regime (hydrology), as a key ‘driver’ of the ecology of large rivers and their associated floodplain wetlands (Bedford, 1996; Puckridge et al., 1998; Richter et al., 2003). Natural flows maintain ecological processes, including biodiversity in the ecosystems of the river system and its associated floodplain wetlands. The river channels connecting to floodplain wetlands discharge water, mixed with rich sources of carbon, energy, and nutrients, from the river and its catchments to the wetlands (Bunn and Arthington, 2002; Maddock et al., 2004). The allochthonous sources of organic matter deposited during flood pulses support reproduction and growth of biota (Junk et al., 1989; McGowan et al., 2011). Integration of local autochthonous production, including algae and inputs from the riparian zone, during pulse events further support available energy for higher trophic levels (Thorp and Delong, 1994). As a result, large rivers and their associated floodplain wetlands are a potential source of ecosystem goods and services to humans; for example, flood attenuation, water purification, fisheries and other foods, and marketable goods (Poff et al., 2003).

However, the flow regime of large rivers has been consistently modified to meet demands of water for agriculture and hydroelectricity (Nilsson and Berggren, 2000; Davis et al., 2015). Many floodplain wetlands have been transformed into a new regime as a result of over-allocation of water to off-stream uses, or other alterations to the natural flow regimes of large river systems (Walker, 1985). The construction of dams and dikes obstruct migration pathways for fish between the river channels and wetlands, and the newly built reservoirs trap water-borne sediment. The diversion of water may lead to channels becoming permanently or intermittently dry. Subsequent inundation of upstream riparian zones increases soil anoxia, often extinguishing entire plant and animal populations and altering the riparian environment. Furthermore, downstream hydrological and geomorphological alterations can reduce groundwater recharge, and modify the pattern of sediment exchange between rivers and wetlands (Nilsson and

Berggren, 2000). The threats posed by widespread hydrological alterations to large rivers are often ignored or sidelined, with projected growth of human population and its associated demand for energy, irrigated food production, and industrial use given a higher priority (Power et al., 1996). As water allocation plans are being formulated to provide greater water security, among other social benefits, it will be critically important to ensure that the considerable socioeconomic benefits provided by healthy floodplain wetland ecosystems associated with these large rivers are not lost, and that degraded ecosystems are restored for the benefit of future generations (Poff et al., 2003).

Recent evidence suggests that a significant proportion of the national economy of Australia and China has been generated by the two of the world's large river systems: Murray and Yangtze Rivers. These rivers have contributed to a range of ecosystem services, including food, mineral, and water resources, to the people living in the river basins (Palmer et al., 2008; Zhang et al., 2015). For instance, water has been abstracted heavily for irrigation, hydroelectricity, and industrial development in both river basins. This has caused widespread disruption in hydrology, such as frequency, timing, and volume of flow in the main river and associated river channels linking to adjacent floodplain wetlands (Walker et al., 1995; Zhang et al., 1999). The varying natural flow regimes have interrupted natural flood pulses leading to changes in hydraulic residence time, wetland depth, nutrient inputs, and sediment cycling, in addition to changing the structure, function, and species diversity of downstream floodplain ecosystems (Power et al., 1996; Kingsford, 2000; Chen et al., 2011; Kattel et al., 2014).

Following the arrival of Europeans in Australia in the early 1900s, the Murray River system began to be regulated for irrigation, hydroelectricity and navigation. The wetlands connected to the river were either inundated as water storage basins, or dehydrated due to upstream water extraction or diversion of connecting channels. Deforestation of the catchment became widespread during the expansion of agriculture. As a result, majority of wetlands have been subjected to significant bank erosion and sedimentation (Gell et al., 2009). In China these large scale modifications of rivers and wetlands occurred more recently, during the 1950s–1970s. Riparian floodplain and wetland habitats across the Yangtze River Basin were extensively reclaimed for agriculture and rural development by the construction of dikes. This resulted in a significant loss of vegetation in the upper reaches of the Yangtze, followed by soil erosion and siltation of downstream wetlands (Yin and Li, 2001). The river sediment load of the Yangtze River between the 1960s and 1970s alone was more than 450 Mt yr^{-1} (Yang et al., 2011). Consequently, many lakes experienced reduced flood retention capacity due to disconnection from the main channel of the Yangtze River by construction of embankments and sluice gates in the river channels, which was subsequently followed by widespread eutrophication (Yu et al., 2009). Because of alterations in natural flood pulses, ephemeral and temporary lakes tended to have fewer taxa than semi-permanent channels or terminal lake habitats (Sheldon et al., 2002). Excessive water abstraction or river-flow regulation in Yangtze River disrupted natural variability in connectivity, and hydrological regimes, consequently threatening ecological integrity, including the biodiversity of the floodplain system (Sheldon et al., 2002; Yang et al., 2006).

Studies show that Murray and Yangtze River wetlands have lost significant density of submerged littoral macrophytes over the past century (Reid et al., 2007; Yang et al., 2008). For example, the subfossil assemblages of diatoms and cladocerans in the floodplain wetlands of mid-reaches of the Murray River indicate a collapse of submerged vegetation coincident with the first appearance of introduced conifer, *Pinus radiata* (Reid et al., 2007). Similarly, the multi-proxy responses, including diatoms and physical and physico-chemistry of sediment of the Taibai Lake (lower Yangtze), show that after the 1990s the lake shifted to hyper-eutrophic condition, due to increased dominance of algal biomass and a reduced density of submerged macrophytes (Liu et al., 2012). There has been characteristic state shift in wetlands of both river systems due to the changes in the dynamics of submerged vegetation (Reid et al., 2007; Yang et al., 2008). The submerged vegetation in wetlands reduces phytoplankton by shading the substrate and competing for underwater light sources for photosynthesis, consequently improving the water quality by stabilising sediment resuspension (Jeppesen and Sammalkorpi, 2002; Folke et al., 2004). However, the characteristic alternative stable states of ecosystems, which are thought to be buffered by naturally occurring hydrology, nutrient enrichments, and submerged vegetation dynamics in large river floodplain wetlands (e.g. Scheffer et al., 1993) have been substantially disrupted in recent decades. Today, the prior, undisturbed ecological state of the Murray and Yangtze River wetlands has been difficult to understand, due to the effects of multiple stressors, including human disturbances and climate change. For instance, following river regulation (1950s), the wetlands of Yangtze have become eutrophic, even in the presence of submerged vegetation (Qin et al., 2009).

Understanding the effects of disruption in natural hydrological regimes of the Murray and Yangtze rivers on diversity and community structure of consumers, such as cladcoeran zooplankton (water fleas), in adjacent floodplain wetlands is crucial to assess wetland ecosystem health. Both Australia and China have faced increasing challenges in addressing shortages of water and food supplies, resulting from reduced water flows in these catchments. A long term monitoring of wetlands exposed to hydrological disturbance is important to ensure maintenance of ecosystem services, by identifying the causes of degradation and using effective and adaptive restoration measures. The subfossil cladoceran have responded to past climate change, eutrophication, and water pollution in many shallow lakes (Jeppesen et al., 2001). Some cladocerans are also significant indicators of locally associated hydrological factors, including the river flow, lake water depth, sediment properties, macrophyte cover, and biotic interactions (Nevalainen, 2011). However, the response of subfossil cladocerans to river hydrology and water level change of the wetlands of the Murray and Yangtze rivers has not yet been investigated. In this paper, we aim to examine three Murray and Yangtze River floodplain wetlands, Kings Billabong (Murray), Zhangdu and Liangzi Lakes (Yangtze), each of which have been exposed to a large scale human-induced hydrological disturbances during the 20th century, as inferred by subfossil assemblage and diversity of cladocerans. We also assess the state of the wetland ecosystems following river regulation and provide an appropriate framework for adaptive water resource management program in these two river basins.

2 Study areas

2.1 Kings Billabong (Murray River)

Kings Billabong (34°14′ S and 142°13′ E) is located along the River Murray near Mildura (northwest Victoria), Australia. Parks Victoria is the agency that manages Kings Billabong (Fig. 1). Historically the *Nyeri Nyeri* Aboriginal community were closely associated with Kings Billabong, utilizing it for food and water resources. From 1891 to until 1923, European settlement intensified in the Victorian Mallee region (http://www.murrayriver.com.au), substantially altering the landscapes around Kings Billabong. The construction of dams, including the series of locks and weirs for upstream water storages, modified natural flow of the River Murray (Gippel and Blackham, 2002). As a result, the hydrology, and in particular, the variability of flows including duration and water retention time in the river has been substantially affected (Gippel and Blackham, 2002). Kings Billabong was used as a pumping station site from 1896, after it was converted to a water storage basin. However, regulation of the section of the River Murray adjoining Kings Billabong commenced in 1927, when Lock 11 was constructed at Mildura in 1927, and was further modified with the construction of Lock 15 at Euston in 1937 (http://www.savethemurray.com). The construction of these weirs altered downstream river flows, in addition to naturally occurring flood pulses through Kings Billabong (Gippel and Blackham, 2002). The artificial flooding, which links Kings Billabong to the weir pool of Lock 11, has changed Kings Billabong into a permanently inundated wetland. This subsequently led to significant dieback of River Red Gum (RRG) forests and establishment of fringing Cumbungi (*Typha* sp.) vegetation. Additionally, logging of RRG forests was intensive in this region until the 1950s, with the timber used to fuel steam-operated pumps and paddleboats along the River (Parks Victoria, 2008).

2.2 Zhangdu Lake (Yangtze River)

Zhangdu Lake (30°39′ N and 114°42′ E) is a floodplain wetland of the Yangtze River system, which is located in Hubei Province, central China (Fig. 2). At high flows, Zhangdu Lake previously received flood pulses from the Yangtze River. However, the lake was disconnected from the Yangtze River in the 1950s, due to the construction of dams and widespread land reclamation across the catchment. By the 1980s, the shoreline of Zhangdu Lake had been significantly modified as a result of the increased reclamation activity and construction of water conservancy infrastructure, which commenced in the 1970s. In 2005, after the reclamation of 50 square meters of shoreline, funding from the World Wildlife Fund (WWF) enabled Zhangdu Lake to be seasonally reconnected with Yangtze River for the purpose of habitat restoration. This lake now has an area of 35.2 km^2, with an average depth of 1.2 m and a maximum depth of 2.3 m. The watershed lies within the northern subtropical monsoon zone, with a mean annual temperature of 16.3 °C, mean annual rainfall of 1150 mm and evaporation of 1525.4 mm. The terrain slopes gently with an elevation of 16 to 21 m. The main inflows of Zhangdu Lake are from the Daoshui River in the west and the Jushui River in the east. Water drains from the lake into the Yangtze River via an artificial channel in the south-eastern corner. Historically, Zhangdu Lake has interacted not only with the Yangtze River when the water level is high, but it has also connected with surrounding lakes, Qi Lake and Tao Lake, during flood events. However, due to the construction of dams and dikes, in addition to land reclamation, it became disconnected from the river in the 1950s. Water conservancy and reclamation construction reached a peak in the 1970s, attaining the current finished and formed shape during the 1980s. Following the mid-20th century reclamation phase, the rate of carbon accumulation in Zhangdu Lake has increased, possibly due to an increase in shallow marginal areas favouring the growth of carbon rich macrophytes (Dong et al., 2012). However, the ecological impacts of disconnection from the river in Zhangdu Lake have become severe. Wild fishery production has reduced, from 95 % in 1949 to less than 5 % in 2002, and fish diversity has decreased, from 80 species in 1950s to 52 species at present (Wang et al., 2005). To address this decline, funding from the WWF in 2005 reconnected Zhangdu Lake with the Yangtze River.

2.3 Liangzi Lake (Yangtze River)

Liangzi Lake (30°3′ N, 114°26′ E) is located in southeast region of Hubei province on the southern bank of the middle reaches of the Yangtze River. The lake is 304.3 km^2, with a drainage area of 3265 km^2. This has an elevation of 20 m with 31.7 km length and the mean width is 9.6 km (Fig. 2). The lake has an area of 22 067 ha, with the depth ranging from 3–5 m. The lake connects to Yangtze River via a 43.3 km river canal (Xie et al., 2001). Since 1992, the western part of the lake, approximately 6000 ha in area with mean depth of 4.2 m, has been separated from the main lake by a 2000 m nylon screen (mesh size 20 mm) for the purpose of aquaculture. Water exchange occurs easily between the two parts of the lake. Intensive stocking with commercial fish, including grass carp *Ctenopharyngodon idella* (Val.), bighead carp *Aristichthys nobilis* (Richardson) and silver carp *Hypopthalmichthys molitrix* (*Cuvier* and *Valenciennes*), is common in the western part of the Liangzi Lake (Xie et al., 2001). Because of grass carp stocking, macrophytes were completely eliminated from the western part of the lake. However, areas of less intensive aquaculture still maintain an abundant density of submersed macrophytes, with *Potamogeton maackianus* (A. Bennet) as the dominant species (Xie et al., 2001). Apart from fisheries, Liangzi Lake provides significant services for drinking water, irrigation, transportation and recreation to the people living around the four large cities, Wuhan, Huangshi, Ezhou and Xianning. Recently, one of the largest foreign investment projects projects, the Hubei Liangzi International Golf Club, in central and southern China, has opened a training center at the edge of the lake.

3 Frameworks for changes in hydrology of Murray and Yangtze River wetlands

The focus of this study was to identify how ecosystem structure and functions were driven by changes in flow regime (hydrology) of the two large rivers in Australia and China. Specifically, how the deviation in baseline flows resulted in the variability in water levels of the associated wetlands and, consequently, how the wetland ecosystem responded to these changes. There was a significant regulation of flow, including the construction of dams and weirs, in both the Murray and Yangtze Rivers during the 20th century. The construction of weirs in the lower Murray in 1920–1930s (Lloyd, 2012) and the construction of dams in the lower Yangtze during the 1950s–1970s (Yang et al., 2011) has had considerable implications for peak flows and downstream hydrology of both rivers, as well as their associated river channels and wetlands.

Based on the 20th century river regulation, hydrological frameworks for the Murray and Yangtze rivers and their associated wetlands, including Kings Billabong and Zhangdu Lake, have been developed (Fig. 3). Prior to the construction of a weir at Lock 11 in the River Murray in 1927, spring peak flows would occur and recede during late summer and autumn. However, the construction of downstream weirs has altered the patterns of retaining winter and spring inflows entering from the upstream storages (Hume and Dartmouth Dams) of the Murray River, and the amount of water released to meet peak irrigation demands during summer and autumn. Usually the combination of low summer flows of abstracted water for irrigation, and unregulated inflows are sufficient to restore the natural patterns of higher flows in the late winter to early spring period (Lloyd, 2012). However, regulation in the lower Murray River system has reduced the river flow and switched the water level to below the historical baseline flow (Fig. 3ai). Weirs in the lower Murray River have been managed to maintain water at a constant level for prolonged periods. This has further reduced natural hydrological variability including the river flows resulting in the maintenance of a constant water level in the adjoining Kings Billabong. During pre-regulated conditions, the water level of Kings Billabong periodically reduced to a chain of dry, and even saline, ponds; which is to say, it is historically naturally ephemeral. Under regulated conditions, by contrast, there has always been some flow to this wetland from the river. This has maintained the water level at higher than naturally occurring levels, resulting in long-term switching up of the water level beyond the historical baseline depth (Fig. 3aii).

Water levels in Zhangdu Lake are maintained through inflows from two rivers, the Daoshui River from the west and the Jushui River from the east, and outflow to the Yangtze River via by an artificial channel to the southeast corner of the lake. Prior to the 1950s, Zhangdu Lake was permanently connected to the Yangtze River and the water level of wetland was maintained by regular river flushes (Fig. 3bi). However, there has been a recent significant decline in annual discharge of the Yangtze River (−11 %) and in particular reduced monthly discharges from August to November (−47 % for November). There has also been a trend for discharge to increase during the dry season, in January (+30 %) and February (Yang et al., 2011). These trends are attributed to human impacts such as reservoir construction, which has subsequently increased water consumption. Following the 1950s, the baseline flow of the Yangtze River has reduced, leading to a reduced water level in the Zhangdu Lake (Fig. 3bi). The South-to-North Water Diversion Project, as well as increased water consumption and the construction of new dams within the river basin, will further influence the wetland hydrology including the water level of Zhangdu Lake (e.g. Yang et al., 2010). The hydrological disruptions in Zhangdu Lake, where reclamation and water conservancy construction was very high by the 1970s, have led to a significant decline in lake area by the 1980s (Qin et al., 2009). The 2005 World Wildlife Fund project, to seasonally reconnect Zhangdu Lake with Yangtze River, has resulted in a gradual change in lake hydrology (Fig. 3bii).

The baseline hydrological framework for the Liangzi Lake has not been shown in the figure. However, unlike Zhangdu Lake, the inflow from the Yangtze River channel has been constant. In 1992 the local government placed restrictions on aquaculture in Liangzi Lake. As a result, this activity is confined to the western part of the Liangzi Lake, reflecting concerns about the significance of human-induced disturbances in hydrology and ecosystem of the lake more widely (Xie et al., 2001).

4 Methods

4.1 Assessment of diversity and ecosystems of Murray and Yangtze River wetlands

The diversity and ecological conditions of the three floodplain wetlands, Kings Billabong, Zhangdu Lake and Liangzi Lake, associated with two large river systems were assessed using subfossil cladoceran zooplankton (water flea) remains retrieved from lake sediments deposited over the past century. A high resolution subsampling of 94 cm long core, collected from Kings Billabong, was carried out at 1 cm intervals.

In the case of Zhangdu Lake, a subsampling of 45 cm long core was carried out at 1 cm intervals for up to 27 cm, and at 2 cm intervals for up to 45 cm, respectively. For Liangzi Lake, the subsampling of 65 cm core was carried out at 2 cm intervals. Each subsample, weighing approximately 3–4 g as wet sediment, from all three lakes was treated with 100 mL of 10 % KOH solution, and heated at 60 °C on a hotplate for at least 45 min. Sieving of the sub-sample mixture was carried out through a 38 µm mesh. More than 200 identifiable cladoceran remains were enumerated at 400 × magnification from each subsample. Numbers were converted to individuals per g dry weight of sediment, followed by the calculation of relative proportion of the remains present in the sample (Kattel et al., 2008). Cladoceran taxa were identified following (Frey, 1986; Shiel and Dickson, 1995; Zhu et al., 2005; Szeroczyńska and Sarmaja-Korjonen, 2007).

4.2 Dating

The age chronology was based on the standard ^{210}Pb dating for all sites (Appleby, 2001). For Kings Billabong, the radionuclide activity was detected at 51 cm, while the radionuclide activities for Zhangdu and Liangzi Lakes were detected at 45 and 65 cm, respectively. The age modelling of Kings Billabong can be found in detail in Kattel et al. (2014).

The sediment samples from Zhangdu and Liangzi Lakes were dated using ^{210}Pb and ^{137}Cs by non-destructive gamma spectrometry laboratory at the State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology Chinese Academy of Sciences (NIGLAS). The activities of ^{210}Pb, ^{226}Ra and ^{137}Cs in samples were determined by counting with an Ortec HPGe GWL series well-type coaxial low background intrinsic germanium detector. The ^{137}Cs was used to identify the peak that indicated use of the 1963 nuclear bomb. This evidence was then used for developing a constant rate of supply (CRS) model to calculate ^{210}Pb chronology for the core. The important dates relevant to hydrological changes were indicated in the stratigraphy.

4.3 Numerical analyses

Dendrograms for subfossil cladoceran samples were produced in TILIA Graph following the constrained incremental sums of squares (CONISS) analysis. Zonation of samples in the diagram was based on the chord-distance dissimilarity coefficients obtained in CONISS (Grimm, 1987). Indirect ordination techniques, such as detrended correspondence analysis (DCA) were used for identifying species alignments with samples over time (Hill and Gauch, 1980). DCA was run for sub-fossil cladoceran samples meeting 200 counts in each sample followed by running CA or PCA as per the gradient length of the first DCA axis (ter Braak, 1995). The CA and PCA sample scores were incorporated in the stratigraphy diagrams.

5 Results

5.1 Diversity of subfossil cladocerans (water fleas) in Murray and Yangtze River wetlands

The species richness of subfossil cladocerans was higher in the Murray River wetland than in the Yangtze River wetlands. More than 40 species of subfossil cladoceran were recorded from Kings Billabong, while core samples from Zhangdu Lake and Liangzi Lake had 36 and 20 species, respectively. The most commonly recorded cladoceran taxa in Kings Billabong were *Bosmina meridionalis*, *Chydorus sphaericus*, *Biapertura setigera*, *Dunhevedia crassa*, *Biapertura affinis* and *Alona guttata*, while the most commonly recorded taxa in Zhangdu Lake were, *Bosmina*, *Chydorus sphaericus* and *Sida crystallina*, and the Liangzi Lake were, *Bosmina*, *Acroperus harpae*, *Alona guttata*, *Alona rectangula* and *Chydrorus sphaericus* (Figs. 5 and 6).

The N2 diversity index of cladocerans reflected a small change in both river systems. In Kings Billabong the N2 diversity was low during the 1900s. However, prior to human disturbance of the river (c. 1870s), as well as in c. 1960s, N2 Index was relatively high (Fig. 5). In Zhangdu Lake, the N2 diversity index prior to the construction of the dam (c. 1881–1954) was low, compared to the post-dam construction period (Fig. 6). Similarly, the N2 diversity index of Liangzi Lake during the earlier period (c. 1900–1930) was lower than post dam construction period in the Yangtze River (Fig. 6).

5.2 Cladoceran responses to ecological and hydrological changes of Murray and Yangtze River wetlands

5.2.1 Kings Billabong

The subfossil assemblage of cladocerans in Kings Billabong showed four distinct changes in ecosystem. Until the 1890s, (Zone I) Littoral cladocerans such as *Dunhevedia crassa*, *Alona guttata*, *Chydorus sphaericus* and *Graptoleberis testudinaria* were the dominant species until the 1980s (Zone I). This period experienced a relatively low abundance of planktonic, *Bosmina meridionalis* (Fig. 4). However, total littoral cladocerans gradually declined, while small littoral species such as *Alona guttata* became abundant in the 1890s–1950s (Zone II). During this time, the increased density of planktonic *B. meridionalis* contributed to total planktonic cladocerans. Some *Daphnia* records (1950s–1970s) were also retrieved, and coincided with the timing of the 1956 flood in the River Murray (Zone III) (Fig. 4). Although total littoral cladocerans declined, some littoral species such as *Alona guttata* and *A. quadrangularis* were still abundant during this time. However, in the 1970s-2000s, planktonic *B. meridionalis*, and littoral *A. guttata*, *Biapertura longispina*, *A. quadrangularis* and *Chydorus sphaericus* dominated, while the littoral *D. crassa* declined significantly. In the meantime, frequency and density of cladoceran resting eggs also increased in the sediment (Fig. 4).

In Kings Billabong, the littoral to planktonic (L : P) ratios of cladocerans began to decline rapidly from about 75 cm depth (c. 1930s) (Fig. 4). The subfossil assemblages of littoral and planktonc cladocerans responded to hydrological changes of the Murray River, together with subsequent changes of water level of Kings Billabong. The construction of Lock 11 in the Murray River near Mildura led to permanent inundation of Kings Billabong during the 1920s–1930s, the time of major hydrological shift (Fig. 4). Because of the expansion of the pelagic habitat in Kings Billabong, the assemblage of subfossil *Bosmina* increased (Fig. 4). Although the billabong was inundated, there was sustained increase in the abundance of some littoral cladocerans including *Alona guttata*, *Alona quadrangularis* and *Biapertura longispina*. Following the hydrological shift, Kings Billabong began to respond this change with declining water quality. For example, littoral cladocerans such as *A. guttata* and *A. quadrangularis* preferring poor water conditions sustained together with *B. meridionalis*. However, the assemblage of the dominant littoral cladoceran, *Dunhevedia crassa* preferring clean water conditions significantly declined following the hydrological shift, from pre-regulated, variable water levels to post-regulated, constant inundation, in Kings Billabong, due to the imposition of river regulation in 1927 (Fig. 4).

5.2.2 Zhangdu Lake

Three distinct ecosystem changes were observed in Zhangdu Lake, based on the subfossil assemblage of cladocerans from lake sediment. Planktonic cladocerans dominated the period c. 1880s–1960s (Zone I), when the planktonic *Bosmina* sp. was the most dominant species. During this time, the abundance of total littoral cladocerans declined, when only a few species, including those that characteristically occupy both littoral and planktonic habitats, such as *Chydorus sphaericus* were present (Fig. 5). However, the major hydrological shift occurred during the c. 1960s–1980s (Zone II). Following the construction of dams across the Yangtze River channels (c. 1950s), sediments deposited in the dam contained increasing numbers of remains of the littoral cladocerans, where by some of the common species of cladocerans such as *Acroperus harpae*, *Alona guttata*, *Alona rectangula*, *Chydorus sphaericus*, *Graptoleberis testudinaria* and *Sida crystallina* were gradually becoming dominant (Fig. 5). The abundance of littoral cladoceran species such as *A. harpae*, *Alona intermedia*, *Alona affinis*, *Kurzia lattissima*, *Leydigia leydigi*, *A. guttata*, *Camptocercus rectirostris* and *Disparalona rostrata* increased further during the c. 1990s–2000s (Zone III) indicating a significant change in the system. In addition, the concentration of the cladoceran resting eggs increased during this time (Fig. 5).

In Zhangdu Lake, increased diversion of the water from the Yangtze River, during the 1960s–1970s because of the construction of dams, led to significant decline in water level. This resulted in decrease of water depth around the lake margins, consequently providing suitable conditions for the increased growth of littoral vegetation and associated habitat for cladocerans. In response, the abundance of littoral cladocerans, including *Alona affinis*, *Alona guttata*, *Alona intermedia*, *Camptocercus rectirostris*, *Kurzia latissima* and *Leydigia leydigi*, increased with high L : P ratios (Fig. 5). Smaller *Alona* such as *A. guttata*, *A. rectangula* and *A. intermedia* showed a distinct presence during this time (Fig. 5).

5.2.3 Liangzi Lake

Four distinct ecosystem changes were observed in Liangzi Lake, based on subfossil assemblage of cladocerans retrieved from lake sediment. Prior to 1900 (Zone I), the total abundance of planktonic *Bosmina* was high. In the c. 1900s–1920s (Zone II), the relative abundance of *Bosmina* began to decline, while abundance of littoral species increased. The dominant species during this time were *Acroperus harpae*, *Alona rectangula*, *Camptocercus rectirostris* and *Dunhevedia crassa* (Fig. 6). During the c. 1930s–1950s (Zone III), the relative abundance of *Bosmina* was relatively constant, but the abundance of littoral species continued to increase. Four dominant species were found in this community; *Alona rectangula*, *Chydrorus sphaericus*, *Dunhevedia crassa* and *Graptoleberis testudinaria*. During the c. 1960s–2000s, the period of major dam construction in the Yangtze, the total abundance of *Bosmina* increased, particularly in the early 2000, and four species of littoral species, *Alona guttata*, *Alona intermedia*, *Chydorus sphaericus* and *Sida crystallina* also became dominant throughout this period (Fig. 6).

6 Discussion

6.1 Shifts in hydrology and its implications for ecosystem functioning of wetlands including the Murray and Yangtze River wetlands

Over the past century, impacts on the Murray and Yangtze Rivers include the construction of irrigation dams, hydroelectric power plants, regulation works for navigation, land reclamation projects, and large-scale flood control measures (Maheshwari et al., 1995; Sun et al., 2012). As a result, vast areas of floodplain wetlands of both river systems have been drained and disconnected from the river. In some areas, this reduced hydrological connectivity has resulted in a flushing of organic matter and nutrients from the floodplains only during extreme floods, when the river retention capacity is the lowest. Therefore, organic matter from the floodplain system is not accessible to wetland organisms. With the loss of dynamically connected floodplains, the biogeochemical budget of the Murray and Yangtze River wetlands has changed significantly. Previous evidence strongly suggests that the climatic cycles of drought and flood have become extreme, triggering unusual responses of floodplain wetlands to the disturbance regime of these rivers (Zhang et al., 2013).

Wetlands losing hydrological connections with the river resulted in divergence of aquatic micro- and macro-invertebrate assemblages (Qin et al., 2009). The disruptions in the natural variability and connectivity of hydrological regimes, due to river-flow regulation, have consequently reduced ecological integrity, resulting in reduced invertebrate diversity (Sheldon et al., 2002). The downstream impacts of low flows in the River Murray were visible mainly following the construction of Hume Dam in 1936. At present, average monthly and annual flows are considerably lower than those that of natural conditions in the past (Maheshwari et al., 1995). The study of natural flow regimes in the Murray River suggests that the strength of average annual floods (annual exceedance probability 50 %) has reduced by over 50 % at all stations. The effects on large floods, however, (average recurrence interval 20 years or more) are relatively low (Maheshwari et al., 1995). The low flows for a given annual non-exceedance probability are higher under regulated conditions than under natural conditions (Maheshwari et al., 1995). The implications of these changes are not only for communities of native plants and animals in both riverine and floodplain environments, but also for the long-term use of the riverine resources by humans (Maheshwari et al., 1995). Rivers and their associated wetlands exchange particulate and dissolved organic matter, including suspended sediments, nutrients, and algal biomasses (Tockner et al., 1999). These nutrients are fundamental for the support of ecosystem structure and function in riverine food webs (Bunn and Arthington, 2002). The current flow regimes also determine which physical habitats are available for all aquatic species that have evolved life history strategies primarily in direct response to natural flow regimes (Bedford, 1996).

Permanent inundation of wetlands occurred in many areas across the Lower Murray River in response to the 1914 Commonwealth Act. This legislation enforced a requirement to manage the Murray River's water by the construction of locks, weirs, and water storage areas. Construction of the Mildura Weir (Lock 11), which began in August 1923, resulted in an increased water level in Kings Billabong by the time construction was completed in 1927. The long periods of water storage in Kings Billabong are thought to have increased stagnation, nutrient levels, and primary productivity, subsequently impacting the higher trophic levels around the billabong (Kattel et al., 2014). Some have argued that the high nutrient input in the river system, combined with relatively long water residence times in water storages, supports phytoplankton growth and a tendency towards eutrophication (e.g. Tockner et al., 1999; Chaparro et al., 2015).

In the Yangtze River, construction of many dams and water impoundments has significantly altered downstream hydrological regimes and directly affected the relationship between the Yangtze River and its river channels and floodplain wetlands, including the Zhangdu Lake (e.g. Yang et al., 2011). The construction of dams throughout this catchment has caused changes in channel morphology and sedimentology, with a drastic decline in sediment transportation and severe channel erosion in connections to lakes. From the monitoring of stream cross-sections, changes to river channels are evident, including the reduction of water level within wetlands (Yang et al., 2011). These have inevitably induced alterations in inundation patterns of the wetlands, resulting in changes to ecosystem structure and function, which in turn have disturbed the habitats of biota (Maheshwari et al., 1995; Sun et al., 2012). As a consequence of a rapid expansion of human activity in the watershed during the 1960s, significant changes at the base of the food web in Zhangdu Lake have been observed in the subfossil composition of testate amoeba communities. For instance, the characteristic oligotrophic, lake-dwelling species (e.g. *Difflugia biwae*) have been replaced by eutrophic species (e.g. *Difflugia oblonga*) (Qin et al., 2009).

6.2 Cladoceran-inferred responses to hydrological shifts in Murray and Yangtze River wetlands

Cladoceran assemblages of three floodplain wetlands, Kings Billabong, Zhangdu Lake, and Linagzi Lake all have shown strong responses to human-mediated hydrological alterations in the Murray and Yangtze Rivers over the past century. Although the N2 diversity index did not show a strong response to disturbance, the impact of river regulation and permanent inundation of Kings Billabong in the 1920s nonetheless revealed a decline in the density of littoral species. The species such as *Dunhevedia crassa* and *Graptoleberis testudinaria*, are adapted to submerged vegetation and their decline in abundance indicates a reduction of suitable habitat including increased water quality. The increase in the abundance of lentic species such as *Bosmina meridionalis* demonstrates a switch from the prior ephemeral state to one of more or less constant inundation. Although drought had no or little impact on the water nutrient levels in Kings Billabong following regulation, large-scale flood events, by contrast (e.g., 1956 AD), may have significantly increased nutrient input in the water column. The apparent result was to increase the population of *Bosmina*, as well as littoral species (e.g. *A. guttata*) that prefers enriched nutrient environments (e.g. Hofmann, 1996). Turbidity from suspended sediment, during flood events, also limits growth of submerged vegetation, due to a reduction of light penetration. By the early 2000s, planktonic *B. meridionalis*, and littoral *A. guttata* and *Biapertura longispina* were the dominant species. The high density of cladocean ephippia retrieved from the wetland sediment also indicates “stress” among the cladoceran community during the prevailing conditions of post- regulation period in the Murray river system (e.g. Nevalainen et al., 2011). The low abundance of *D. crassa* following river regulation reflects the impact of river regulation on the aquatic ecosystem, with degraded water quality and reduced resilience in the wetland community. In shallow lakes, a consequence of human-induced actions is the tendency towards a regime shift, followed by poor ecological resilience (Folke et al., 2004). The loss of functional group species and consequent reduced species diversity may lead to a loss of whole trophic levels (top-down effects) (Folke et al., 2004).

The Zhangdu Lake aquatic community responded to downstream water shortages in the river channel connecting to the lake, as revealed by low lake level following the construction of dams and reservoirs for water conservancies in 1950s–1970s. Subsequent to river regulation during the 1950s, for example, hydrological alterations of the river channel and changes to the water level of Zhangdu Lake increased growth of littoral plants. This also resulted in increased abundance of littoral cladoceran species, such as *Acroperus harpae*, *Alona guttata*, *Alona rectangula*, *Chydorus sphaericus*, *Graptoleberis testudinaria* and *Sida crystallina* (Fig. 5) Although the abundance of littoral species in the lake indicated increased growth of submerged vegetation, the condition of the wetland ecosystem following regulation was poor. The clear water regime, present prior to regulation, gradually transformed to a eutrophic state following the construction of dams. Many small cladocerans recorded in Zhangdu Lake, following the 1950s, are typically associated with still (lotic) waters, eutrophic and poor water quality conditions, having similar habitat preferences elsewhere. For example, in Europe cladoceran species such as *A. harpae*, *C. sphaericus* and *S. crystallina* have a characteristic affiliation with lotic environments (Nevalainen, 2011). In Tibet, *Chydorus sphaericus* is adapted to wide range environmental gradients, *Alona affinis* and *Acroperus harpae* colonize dense aquatic macrophytes, *Graptolebris testudinaria* and *Eurycercus lamellatus* are adapted to shallow littoral environments, with a preference for debris-rich substrates (Liping et al., 2005). Eutrophication in Zhangdu Lake, due to hydrological changes of the wetland, was also indicated by the presence of testate amoeba (Qin et al., 2009). Our results strongly suggest that hydrological alterations of rivers and wetlands can result in eutrophication and lead to an increased abundance of littoral cladocerans. The low level of floods could reduce water level, increase telematic plant growth, and decrease the redox condition of the wetland resulting in the variation in growth, metabolism and reproduction of cladocerans (Pawlowski et al., 2015). The shallow littoral environment provides habitats for different fish species, and may increase the predator-prey interactions (Pawlowski et al., 2015). The large number of cladocearn ephippia recorded in the sediment in Zhangdu Lake (lower Yangtze), following regulation, also indicates the decline in lake levels and the loss of lentic habitats, which led to reduced feeding habitat and reproductive output or an increased ecological stress among the cladoceran community, particularly during the c. 1990s–2000s. In Europe, increases in sedimentary resting eggs of cladocerans are reported to be associated with major environmental transitions; for example, climate change (e.g. Pleistocene-early Holocene), timing of strong predator-prey interactions (e.g. fish predation pressure), and increased human impact in the catchment (e.g. unprecedented release of chemicals) (e.g. Sarmaja-Korjonen, 2003; Nevalainen et al., 2011).

The response of the subfossil assemblage of cladocerans in Liangzi Lake to hydrological change in the Yangtze River during the 1950s was difficult to establish. This could be due to the permanent inflow to this lake from the Yangtze River. The higher abundance of *Bosmina* prior to 1900s indicate that the lake was kept at a certain water level, or else much of the trophic materials contained in the surface water met the demands of planktonic cladocerans (e.g. Liping et al., 2005). However, the abundance of littoral species *Alona rectangula*, *Chydrorus sphaericus*, *Dunhevedia crassa* and *Graptoleberis testudinaria* during the 1950s are indicative of decreasing depth. During the 1990s to the 2000s, Liangzi Lake was impacted by intensive agriculture practices in the catchment and nutrient inputs into the wetland, as indicated by an increased abundance of planktonic *Bosmina* (Liping et al., 2005). In 1992, the local government restricted aquaculture to the western part of the Liangzi Lake, since this activity was affecting water quality throughout the entire lake (Xie et al., 2001). This problem had been detected from ecological stress responses of cladocerans, as revealed by an increased density of resting eggs in the sediment, as well as an increased abundance of *Bosmina* and the chydorid species such as *Alona guttata*, *Alona intermedia*, *Chydorus sphaericus*, since these are all found in nutrient rich environments (e.g. Sarmaja-Korjonen, 2003; Nevalainen et al., 2011).

All three of these wetlands appear to exhibit characteristic traits of hydrologically triggered ecosystem changes, as revealed by subfossil cladoceran assemblages, since each has tended to undergo regime shifts during recent decades. Furthermore, species richness in each is indicative of reduced water quality. Hydrology strongly drives the community composition of phyto- and zooplankton, relevant nutritional resources, and habitat characteristics, mainly via input of N and P from the eutrophic main channels during flood events (Van den Brink et al., 1994; Nevalainen, 2011). The phenomena observed in the dynamics of physical and biological assemblages, and the diversity of cladoceran zooplankton, in Kings Billabong and Zhangdu Lake, for example, have shown possible alternative stable states resulting from switching of ecosystems, irrespective of inundation (Kings Billabong) or dehydration (Zhangdu Lake). In Kings Billabong, the condition of increased aquatic vegetation density, prior to AD 1900, may have led to an increased species richness and water quality. By contrast, the open water habitat, characteristic of longer flood durations in recent decades, has led to increased turbidity followed by increased richness of filter-feeding zooplankton taxa (e.g. *Bosmina*). Van den Brink et al. (1994) reported that characteristic floodplain wetlands, of short annual flood duration, were dominated by well-developed aquatic vegetation, and the organisms including scraping zooplankton taxa associated with those bacillariophyceae plants were typical aquatic macrophyte preferring species.

In Zhangdu Lake, following upstream river regulation by reservoir construction, the lake may have become eutrophic and polluted. This was indicated by an increased abundance of smaller, mud-dwelling cladoceran species such as small *Alona* and *Leydigia leydigi*, which are indicative of water pollution and eutrophication (e.g. Hofmann, 1996). Our results are also agreement with other proxies (e.g. Testate amoeba) which have also responded to changing conditions of Zhangdu Lake in recent decades (Qin et al., 2009). Such indicators of declining ecosystem health in Liangzi Lake, increase in turbidity, eutrophic condition, and poor water quality during recent decades are supported by the finding of an increased abundance of *Bosmina* and *Chydorus* sp., which are indicative of increased trophic state and eutrophication (e.g. Hofmann, 1996).

6.3 Development of an adaptive water resource management framework for Murray and Yangtze River wetlands

Our results in ecosystem changes in these three wetlands suggests that the water resource management in the Murray and Yangtze River basins is facing major challenges from eutrophication, due to increasing uncertainties caused by climate change and socio-economic conditions in both river basins. Such phenomena in the lower Yangtze River ecosystem, for example, has already been identified as “lost resilience”, due to an increased tendency of regime shifts to occur in local ecological services, for example in water quality, following the 1970s (Zhang et al., 2015). From this time, China’s environmental pressures have gradually exceeded the carrying capacity of the ecosystem, resulting in greater challenges for water resource management (Varis and Vakkilainen, 2001). Similarly, following the 1950s in the Murray River basin, more than 80 % of wetlands have undergone significant ecosystem switches, due to rapid rates of sedimentation, turbidity and macrophytes loss (e.g. Gell and Reid, 2014). Recently, there has been intensification in the use of natural resources in the catchments across both river basins, because of increasing demand for water, food, fibre, minerals, and energy (e.g. Davis et al., 2015). As a result, the current management framework is unlikely to tackle the growing problems of insufficient water quantity, and quality, in both river basins.

We have proposed an adaptive water resource management framework for these two large hydrologically transformed river wetlands (Fig. 7), taking into account the historical environmental, technological, economic, institutional, cultural, and social values, to tackle these environmental and ecological problems. This framework is integrated and multidisciplinary in nature, is intended to improve management, and to accommodate change, by learning from the outcomes of management (restoration) policies and practices, as described by Holling (1978). Such framework is also simple and manageable by learning through experience to increase gradually the adaptive capacity of the ecological state of the wetlands in river basins (e.g. Pahl-Wostl, 2007).

In the framework, we consider that the ecological state of the Murray and Yangtze River wetlands is determined by both quality and quantity of water. Prior to regulation the quality and quantity of water was at the baseline (benchmark) level (Fig. 7). The hydrological (flow regime) and palaeoecological assessments can identify the benchmark of wetland ecosystem health, and assist with recognition of wetlands of high conservation values (e.g. Bennion et al., 2011). Based on our study, we argue that the quantity and quality of water of the Murray and Yangtze River wetlands have declined significantly since the 1950s. By the 2000s, the ecological health of these wetlands was at a critically low level, due to highly degraded water quality conditions (Fig. 7). All available restoration measures are essential to alter these states.

In large river systems, it is difficult to define benchmark conditions, as these may not exist due to re-engineering work, for use in formulating restoration approaches (Brown, 2002). It is apparent that the scale of human impact on ecosystems and the biodiversity of Murray and Yangtze river wetlands was significantly higher during the time of engineering works, including the construction of Hume Dam in 1930s in the Murray River (Maheshwari et al., 1995), and the several large dams, including the Three Gorges Dam (TGD), since the 1950s in the Yangtze River (Wu et al., 2003). However, the adaptive management framework we have proposed here can address these issues. Palaeoecological study can unravel the benchmark conditions of wetland hydrology and changes to ecosystems functioning, caused by large-scale disturbances in Murray and Yangtze rivers, and suggest suitable restoration measures for degraded wetlands (Fig. 7). In the framework, the restoration is based on three pillars: a scientific understanding of the ecosystem functioning, an efficient water allocation, and stakeholders' partnership (e.g. Liu et al., 2014). The framework identifies the basic need for adaptation to concurrently improve livelihoods, by building the institutional capacities, and the value of efficient infrastructure for adaptation (e.g. Yu et al., 2009). Hence we argue that adaptive management of wetlands should be cost-effective (efficient infrastructure), integrated (combined palaeo-eco-and-hydrological vs contemporary survey), and predictable (known through modelling). An adaptive management framework can enhance wetland resilience by improving both water quality and quantity, simultaneously assisting the basin-wide management of food and water security issues. For example, the WWF-supported partnership program, together with government agencies and local communities, was highly successful for improving water resources, both quantitatively and qualitatively, in the Yangtze Basin. Under this type of management program and in partnership with local people, the three Yangtze lakes (Zhangdu, Hong and Tian-e-zhou), which were disconnected from the main channel during the 1950s–1970s, have now been recharged by opening of sluice gates (Yu et al., 2009). The recharging of Zhangdu Lake has not only enhanced resilience of the lake environment to climate change and but also livelihoods of the local people (Yu et al., 2009). However, future ecological states of wetlands based on modelling suggest that not all wetlands would be restored to a benchmark level (Fig. 7). We recommend the wetlands of poorest ecological states, as shown by modelling, would not be worthy of investment for restoration.

7 Conclusions

Evidence from subfossil assemblages of cladocerans over the past few decades from all three wetlands, Kings Billabong, Zhangdu Lake and Liangzi Lake, suggest that river regulation by humans in the Murray (Australia) and Yangtze (China) rivers have altered natural flows, including the hydrology and ecology of these wetlands. The response of subfossil cladoceran assemblages was evident via both prolonged flooding (inundation) and dehydration (abstraction) of water in the Murray and Yangtze Rivers, respectively. Other factors, such as land use, socio-economic developments, and rapid climate change, particularly over the past 30–40 years, may have exacerbated the hydrological and ecological processes further. The conditions of wetlands following the large-scale disturbances, such as widespread river regulation, construction of dams and reservoirs, have shown a tendency to trigger wetland ecosystem switch, and highlight the urgent need for restoration programs to improve the ecosystem services, through better management of quantity and quality of water. The proposed adaptive management framework, based on science, engineering, and community participation, is expected to enhance resilience of the Murray and Yangtze River wetlands and help manage the basin-wide water and food security issues.

Acknowledgements. This project was supported by a number of grants awarded to GK including the Australian Institute of Nuclear Science and Engineering (AINSE) #AINSEGRA11087, Australia-China Science and Research Fund (ACSRF), Chinese Academy of Sciences (CAS) and National Science Foundation of China (Grant No. 41472314, 41102105). Australian Nuclear Science and Technology Organisation (ANSTO); Collaborative Research Network (CRN), and the Faculty of Science and Technology of Federation University Australia (FedUni); State Key Laboratory of the Nanjing Institute of Geography and Limnology Chinese Academy of Sciences (NIGLAS) assisted for collection of samples from the field and analyses at the respective laboratories. This paper was presented in Australia-China Wetland Network Research Partnership Symposium (24 March 2014), Nanjing, China. I would like to thank the HESS Editor, Giuliano Di Baldassarre for making a critical review of the manuscript, and Sandra Weller for editorial support.

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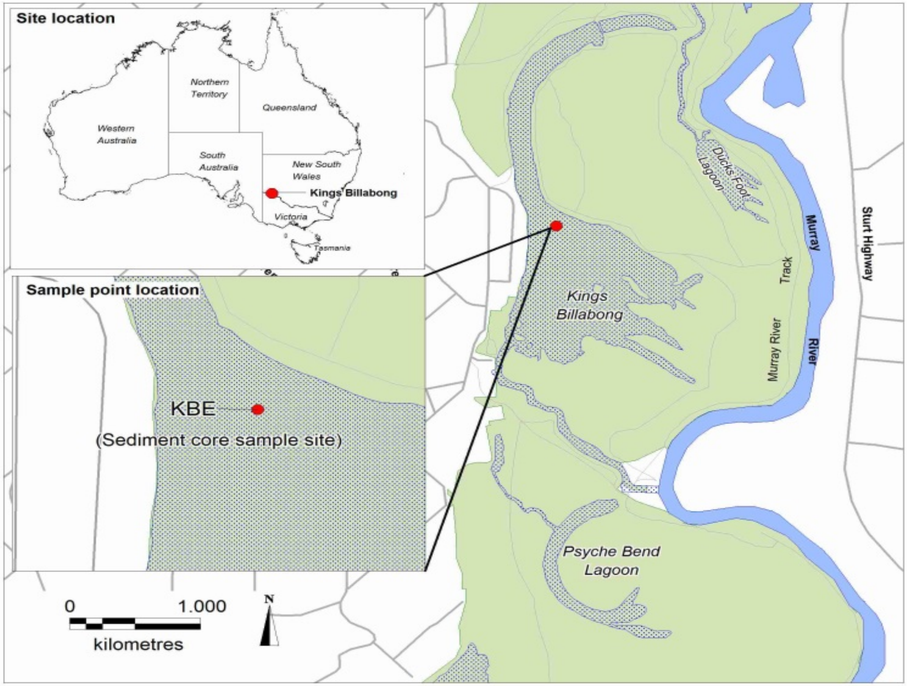

Figure 1. Kings Billabong, one of wetland complexes of the River Murray system in Southeast Australia. KBE was the deepest point of the lake, where a sediment core for this study was taken.

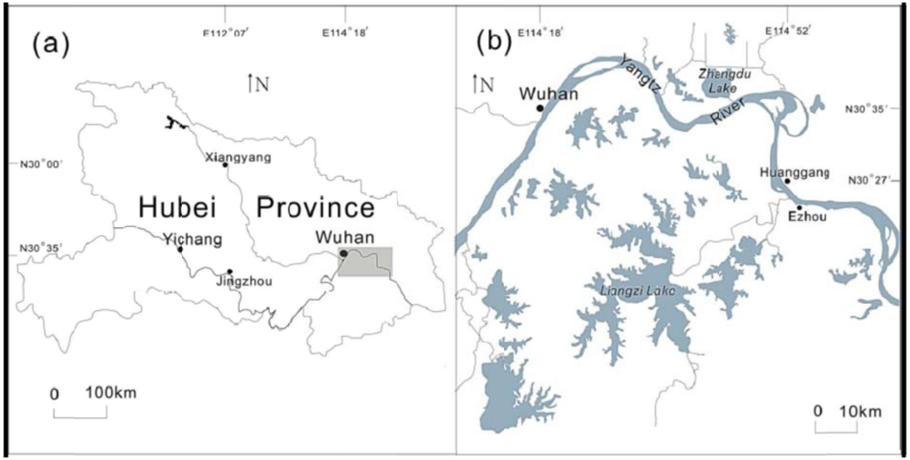

Figure 2. Zhangdu Lake and Liangzi Lake around the middle reaches of the Yangtze River in Hubei Province of China.

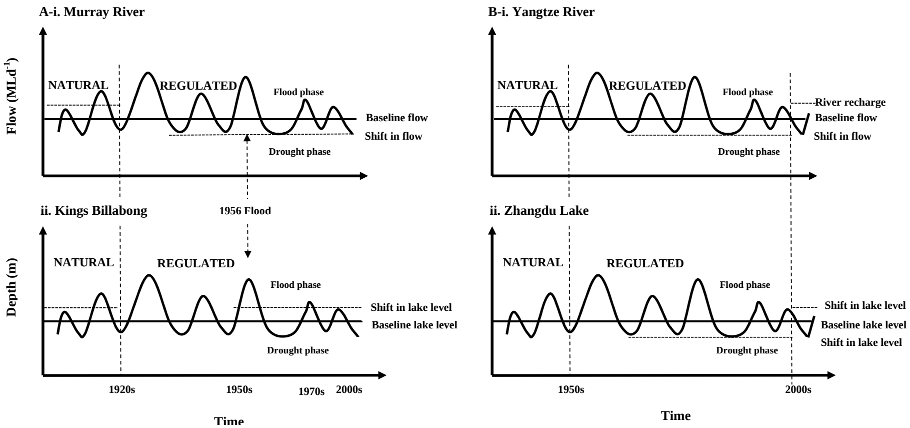

Figure 3. Hydrological frameworks of Murray and Yangtze rivers. **(ai, aii)**: River Murray: regulation was imposed by humans in the 1920s, which resulted in low water volume in the downstream river channels, but Kings Billabong was converted to a water storage tank permanently led to higher lake level, subsequently ceased natural dry-wet cycles; **(bi, bii)**: Yangtze River: the first large scale human impact on the river was imposed during the c. 1950s, which ceased naturally occurring flood pulses in adjacent wetlands leading to a drying up of the river channel connecting to wetlands including low water volume in Zhangdu Lake.

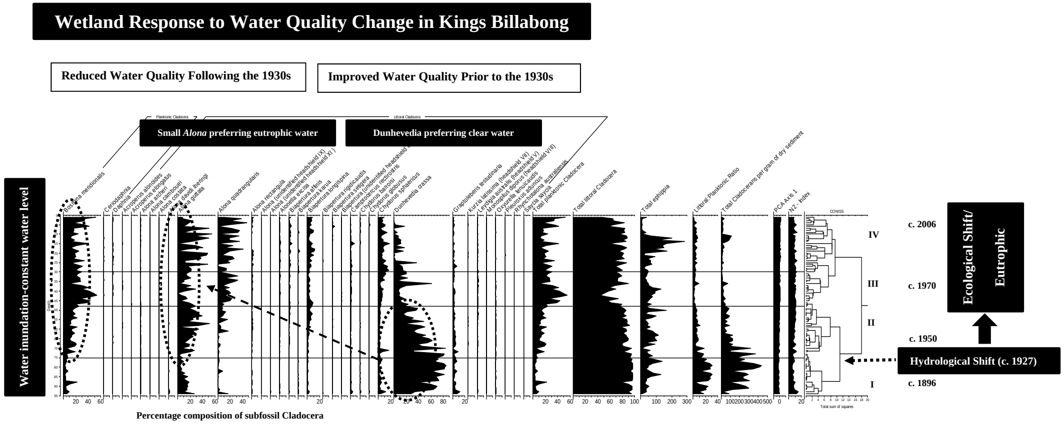

Figure 4. Percentage composition and N2 diversity index of subfossil cladocedans in Kings Billabong, their response to past hydrological and water quality change.

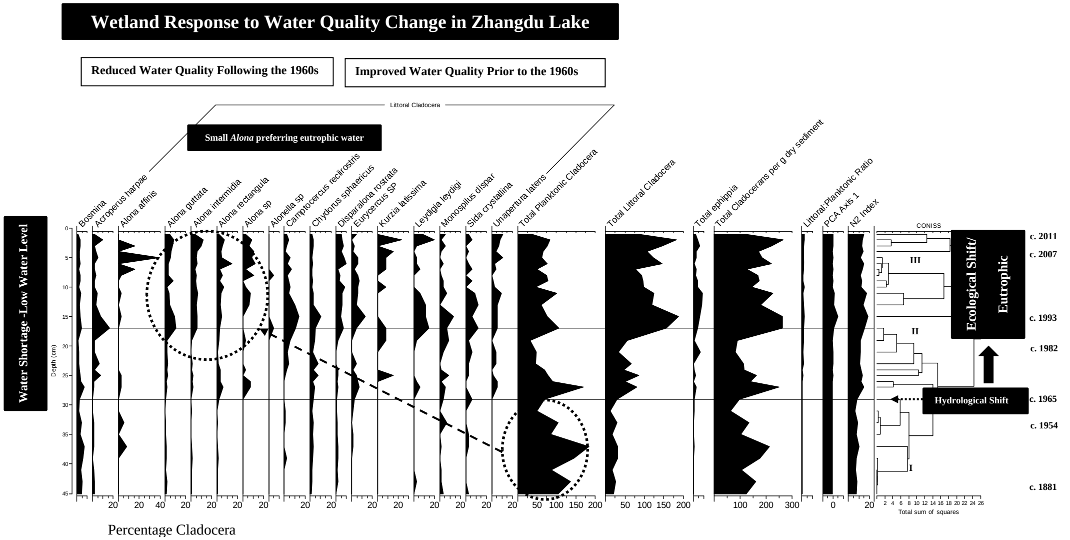

Figure 5. Composition (%) and N2 diversity index of subfossil cladocedans in Zhangdu Lake, and their response to past hydrological and water quality change.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀I
▶I
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

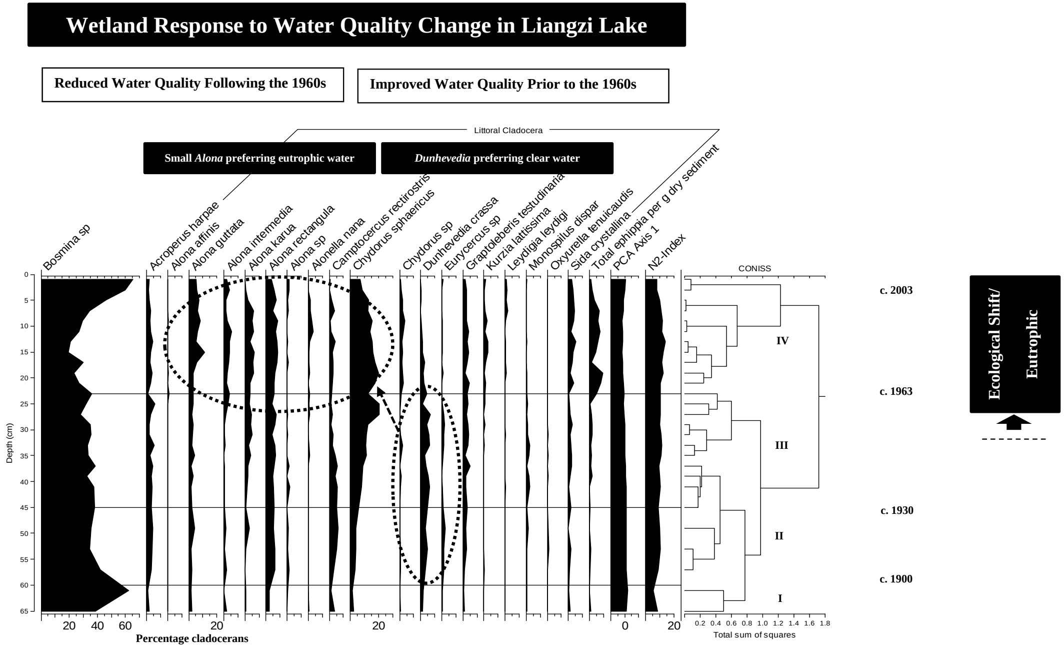

Figure 6. Composition (%) and N2 diversity index of subfossil cladocedans in Liangzi Lake, and their response to past water quality change.

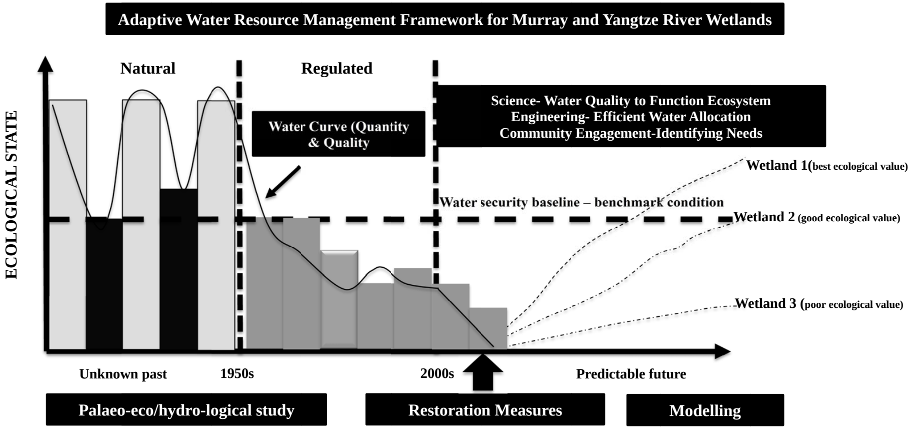

Figure 7. An adaptive water resource management framework based on palaeoecological study in Murray and Yangtze River wetlands: Prior to river regulation (c. 1930–1950s), the quantity of water and wetland ecosystems was determined by natural flood pulses, when the water security curve was above the baseline and the state of ecosystem was natural. However, following the 1950s, ecosystem responded to human impacts on both river systems showing a rapid downward movement of the water curve. By the early 2000s, the natural flood pulses reduced followed by deterioration of the condition of wetlands. Ecosystem structure and function were expected poor due to poor water quality and quantity and limited submerged vegetation. The restoration measures are proposed to bring the water quality and quantity back to the baseline condition by a joint effort from science, engineering and community participation. Scientific knowledge is enhanced by palaeoecological and hydrological monitoring and development of future prediction models in wetland ecosystem. However, not all wetlands can be restored to a baseline condition given their individual variability (detail is described in the text).