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A novel methodology for the assessment of water level requirements in shallow lakes

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ABSTRACT

Managing water level from an ecological perspective has become an urgent issue in recent years in efforts to conserve and restore lake ecosystems. Here we provide a novel methodology to assess water level requirements (WLRs) of shallow lakes, combining geomorphological, hydrological and biological characters. The approach involves five calculation steps, and was applied in a shallow lake of the Yangtze River basin. Whole-lake aquatic vegetation coverage was regarded as a surrogate of ecosystem health. Water level and light availability, two major factors limiting the distribution of aquatic plants, were considered and quantitative relationships were established between water level during germination and vegetation coverage. The germination water level was then treated as a benchmark in determining WLRs of life history stages of aquatic plants. In the model, water levels during the early life history stages were held low and constant to enable germination, and the overall regime was matched with historical natural conditions. The case study showed that vegetation coverage decreased with increasing water level during germination, and a higher Secchi depth (greater water clarity) was associated with a larger coverage. The observed vs. estimated regression line was not significantly different from unity, indicating a high predictive power of the model. The methodology established a quantitative linkage between hydrological variables and ecosystem health. It could be widely used in WLRs assessments in Yangtze shallow lakes as well as other similar waterbodies, providing a useful tool to manage lake ecosystems for conservation and restoration.

1. Introduction

Water level fluctuations (WLFs) are regarded as key hydrological elements of lakes and wetlands (Coops et al., 2003; Cott et al., 2008; Piñeiro et al., 2008; Wantzen et al., 2008). They play important roles in structuring physical habitats (e.g. erosion and sedimentation), biological communities (e.g. macrophytes and macroinvertebrates) and ecosystem functioning (e.g. production, decomposition and water quality) (e.g. Coops and Hosper, 2002; Dehedin et al., 2013; Leira and Cantonati, 2008; Pabst et al., 2008). Aquatic biota have adapted to natural water regimes over a long time period, and their life-histories depend on such regimes to different degrees (Leira and Cantonati, 2008). Most species are strongly influenced by specific water level components, such as magnitude, duration and timing, in different life history stages. As such, they are sensitive and vulnerable to changes in WLFs. Even a slight change of water level could significantly affect establishment and distribution of some aquatic species (e.g. Keddy and Reznicek, 1986). Consequently, water level management has been considered as a useful tool in conservation and restoration of lake ecosystems in recent years (e.g. Coops and Hosper, 2002; Coops et al., 2004; Zhang et al., 2014).

WLFs of lakes depend on catchment characteristics (e.g. area) and regional climate conditions (e.g. precipitation), but they are also largely disturbed by human activities (e.g. water abstraction) (Coops and Hosper, 2002; Riis and Hawes, 2002). Most riverine lakes have been regulated for multiple purposes such as flooding control, irrigation, power generation, fishery production and shipping (Cott et al., 2008; Wang and Wang, 2009). Water levels of these regulated lakes have become more stable and in some lakes water regimes, especially seasonal timing, have been inverted from their natural state (e.g. Coops and Hosper, 2002; Zhang et al., 2014). Such regulations are largely attributed to the over emphasis on economic development, and overlook water requirements of lake ecosystems. In addition, WLFs alteration was considered as the major cause of ecological degradation (e.g. vegetation degradation)

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and environmental problems (e.g. algae blooms) in many regions (Hosper, 1998; Nõges et al., 2010; Wang and Wang, 2009; Zhang et al., 2014; Zhao et al., 2012). Moreover, due to climate change and human activities, the extreme low and high water level events have occurred more frequently in the past decades, putting great pressures on lake environments (Xia et al., 2011). Therefore, managing water level from an ecological perspective becomes an urgent issue facing policy makers, lake managers and scientists.

One key question is how to assess the water level requirements (WLRs) in maintaining a healthy lake ecosystem. In the past decades, water level assessments were affiliated with environmental flows in rivers and streams. Although over 200 assessment methodologies were developed in environmental flows (Tharme, 2003), few of them were actually adapted to lakes or wetlands (Cui et al., 2005; Middleton, 2002; Tockner et al., 2000; Xu et al., 2004). Among the existing methodologies, most were dependent on hydrological or hydraulic calculations, while few directly linked water level with biological communities or ecosystem functioning (e.g. Cui et al., 2005; Xu et al., 2004). In addition, most methodologies focused on estimation of minimum water level requirement of lake ecosystems, and neglected the dynamic WLFs common to many riverine lakes and wetlands. Although the minimum value was important, it could not meet the requirements of water level in different life history stages of aquatic species. Therefore, it is necessary to develop a series of assessment methodologies based on WLRs of biological communities in lake ecosystems.

Aquatic vascular plants (hereafter aquatic plants), generally including hygrophytes and hydrophytes, play an important role in the maintenance of ecosystem health in lentic waters. They not only supply food, habitat and refuge for other aquatic biota such as macroinvertebrates, fish and water birds, but also improve self-purification capacity of waters and contribute directly to human society (Bornette and Puijalon, 2011). Aquatic vegetation is usually treated as an important target of conservation and restoration in wetlands, since aquatic plants are more sensitive to WLFs compared with other biological groups such as macroinvertebrates and fish (Merritt et al., 2010; Wilson and Keddy, 1985). Since most aquatic plants show clear elevational patterns and are distributed in a limited range of water depths (Keddy, 1983), it is possible to establish quantitative relationships between water level and their distribution area or coverage. Also, the distribution area or coverage of aquatic vegetation is easy to measure by remote sensing or rapid field surveys. Therefore, aquatic vegetation can be treated as a good surrogate of ecosystem health in WLRs assessment of lakes.

In recent years, there has been an increasing number of studies dealing with the effects of WLFs on lake ecosystems (e.g. Midwood and Chow-Fraser, 2012; Paillisson and Marion, 2011; Wantzen et al., 2008; Zhang, 2013; Zhang et al., 2014). Requirements of WLFs were primarily estimated in several riparian and aquatic plants with simulation experiments and field observations (e.g. Mahoney and Rood, 1998; Merritt et al., 2010; Yu and Yu, 2011; Zhang, 2013). These studies provided a scientific basis for water level management in lakes. In the present study, we developed a novel methodology, combining geomorphological, hydrological and biological characters, to assess WLRs of ecosystem health, as expressed by aquatic vegetation coverage in shallow lakes of the Yangtze River basin. We provide a series of calculation steps, verify the approach using a case study, and explore its strengths, weaknesses and potential applications to lake management.

2. Materials and methods

2.1. Yangtze shallow lakes and aquatic vegetation

Located in the middle to lower reaches of the Yangtze River (Fig. 1), the Yangtze shallow lakes cover an area of 15,770 km^2 at present. These lakes are in the monsoon zone where the climate is warm and wet. Annual mean temperature is 13–20 °C, and annual precipitation is 800–1600 mm of which 40% is distributed in June–August (Wang et al., 2016; and the references therein). The mean water depth of most lakes is ~2–3 m, and lake surface area is closely correlated with the water level (Wang and Dou, 1998). These lakes were once connected with the Yangtze mainstem and their WLFs were highly similar to that of the Yangtze River. However, most lakes were disconnected from the mainstem by sluices during the 1950s–1970s, resulting in WLFs changes to varying degrees across lakes. Aquatic plants in these lakes are abundant. A total of ca. 400 species of hygrophytes and hydrophytes have been recorded,

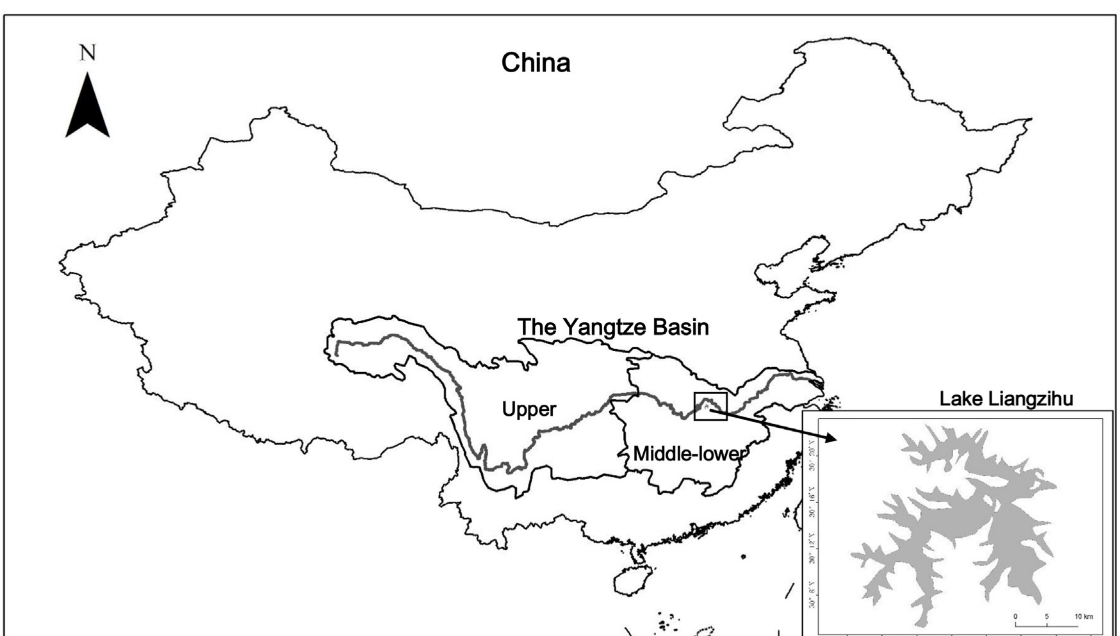

Fig. 1. Locations of the Yangtze Basin and Lake Liangzihu.

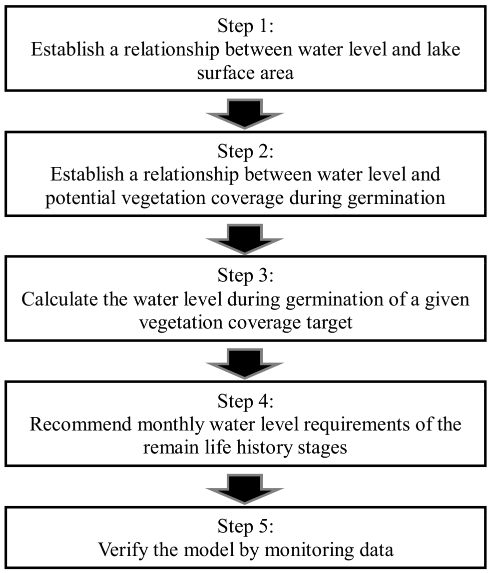

Fig. 2. General framework of the approach assessing water level requirements of aquatic vegetation in shallow lakes.

and the whole-lake vegetation coverage can reach as high as 100% and the wet biomass >9000 g/m^2 (Wang et al., 2016; Zhang, 2013).

2.2. General framework of the approach

The study provided a novel approach to assess WLRs for lake ecosystem health using whole-lake vegetation coverage as a surrogate. Fig. 2 shows the general framework to determine the WLRs. The relationship between water level and lake area was first established, followed by the relationship between water level and potential whole-lake vegetation coverage during germination. After that, water level during germination could be fitted for a given coverage target. Regarding germination as a benchmark, water levels in the following months were recommended to ensure that all aquatic plants could complete their life history. The final suitable water level regime for a given coverage target was estimated according to natural water regime and water level limits for growth of each month. The model was then verified using monitoring data.

2.3. Basic considerations

There are some basic considerations of the approach that must be discussed before the details of calculation steps are described. First, life history of aquatic plants in the Yangtze shallow lakes was generally divided into six stages, i.e. germination (February–March), seedling (April–May), growth and extending (June–July), mature (August–September), seed dispersal (October–November) and wintering (December–January), based on their phenological characters available from Flora of China (www.efloras.org) and other literature (Zhang, 2013; Zhao and Liu, 2009). Second, potential distribution of aquatic vegetation was largely determined by germination area because germination was the first step for development of a plant. Based on this consideration, the relationship between vegetation coverage and water level during germination could be established. Water level during germination was treated as the benchmark to determine WLRs of life history stages that followed. Third, besides water level, light availability was also considered in the present approach. Light availability, an important factor affecting aquatic vegetation development, was closely correlated with water level, bathymetry and Secchi depth in shallow lakes (Wang et al., 2005). Other factors such as substrate type, nutrients and the available seed pool were excluded, and were assumed as non-limiting for aquatic plant development in this study.

2.4. Calculation steps

Step 1 was to establish a relationship between water level (W) and lake surface area (A), expressed as $F_{A\sim W}$. To fit the function $F_{A\sim W}$ for a given lake, the bathymetry or digital elevational model (DEM) of the lake is needed. Bathymetry was assumed to be relatively constant. The planimetric area of any elevation could be calculated by $F_{A\sim W}$. This step provided a basic formula for calculations of the following steps.

Step 2 was to establish the relationship between water level (W) and potential vegetation coverage (C) during germination, expressed as $F_{C\sim W}$. The "potential" vegetation coverage was used here because even rarely wetted surfaces could be potentially covered by aquatic vegetation.

To calculate the vegetation coverage, a benchmark of lake surface area must be defined first. In this approach, the benchmark area (A_C) was defined as the surface area of the mean annual water level (W_C) located, where W_C was calculated from long term (over 25 year) monitoring water level data. Aquatic plants were generally classified into two groups according to their elevational distribu-

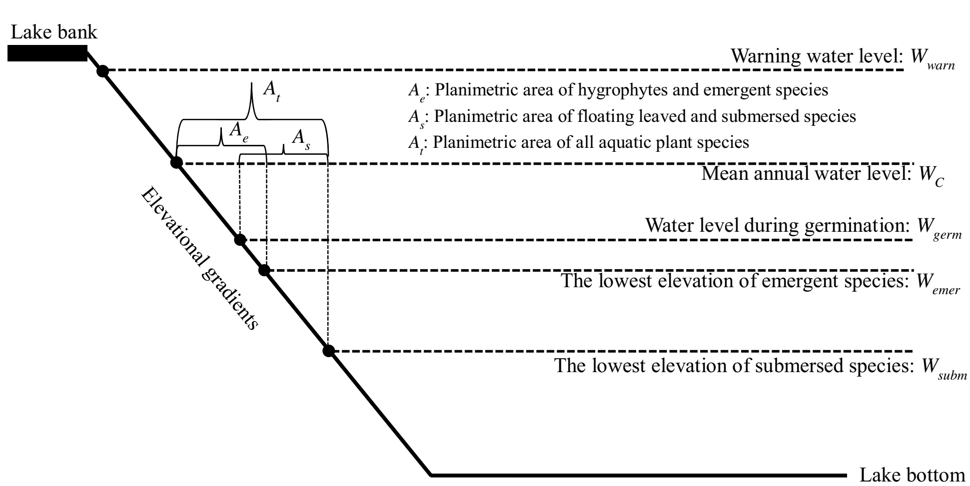

Fig. 3. Elevational gradients of aquatic plants in shallow lakes.

Table 1
Water level requirements (WLRs) of each life history stage of aquatic plants and the calculation basis.

Life history stage	Month	WLRs calculation		Calculation basis and meanings
		Lower limit (LL)	Upper limit (UL)	
Germination	February	$W_{t\text{-}germ}$		Calculated by $F_{C\sim W}$ described in Step 3 (see Materials and methods)
	March	$W_{t\text{-}germ}$		
Seedling	April	$W_{t\text{-}germ}$	$W_{t\text{-}germ}$ + MPH	UL: growth limit, by minimum plant height (MPH) among species or groups LL: determined by germination water level
	May	$W_{t\text{-}germ}$	$W_{t\text{-}germ}$ + MPH	UL: growth limit LL: determined by germination water level
Growth and Extending	June	$W_{t\text{-}germ}$	$W_{t\text{-}germ}$ + MPH	UL: growth limit LL: determined by germination water level
	July	$W_{t\text{-}germ}+(W_C-W_{t\text{-}germ})/2$	$W_{t\text{-}germ}$ + EMH	UL: growth limit, by emergent macrophyte height (EMH). If $W_{t\text{-}germ}$ + EMH > W_{warn}, UL = W_{warn}. LL: avoid rising too fast in August. If $(W_C-W_{t\text{-}germ})/2$ > EMH, LL = $W_{t\text{-}germ}$ + EMH
Mature	August	W_C	W_{warn}	UL: flood control LL: prohibit terrestrial plants invasion
	September	W_C	W_{warn}	UL: flood control LL: prohibit terrestrial plants invasion
Seed dispersal	October	$W_{t\text{-}germ}+(W_C-W_{t\text{-}germ})/2$	$W_{t\text{-}germ}$ + EMH	Same with July, avoid decreasing too fast
	November	$W_{t\text{-}germ}$	$W_{t\text{-}germ}$ + MPH	Same with June, according to natural water regime*
Wintering	December	$W_{t\text{-}germ}$	$W_{t\text{-}germ}$ + MPH	Same with April, according to natural water regime*
	January	$W_{t\text{-}germ}$	$W_{t\text{-}germ}$ + MPH	Same with April, according to natural water regime*

$W_{t\text{-}germ}$: water level during germination of a given coverage target; W_C: mean annual water level; W_{warn}: warning water level; $F_{C\sim W}$: relationship between whole-lake vegetation coverage and water level during germination.

* The natural water regime of the Yangtze lakes is generally as follows. Water level is the lowest during December–March; it rises and reaches the maximum in August-September, and decreases to November.

tion, i.e. hygrophytes and emergent plants (emergent group), and floating leaved and submersed plants (submersed group). Floating macrophytes were not included because they contributed little to whole-lake coverage in Yangtze shallow lakes (Wang et al., 2016; Wang and Wang, 2009).

Elevational distributions and corresponding planimetric areas differ between the different types of aquatic plants (Fig. 3). In the emergent group, hygrophytes and emergent macrophytes have overlapping elevation distributions, and they could both develop in shallow areas of a lake. They differ in that emergent macrophytes can germinate underwater while hygrophytes cannot. Therefore, the elevation distribution of hygrophytes and emergent species was from W_{emer} to W_C, where W_{emer} was the lowest elevation of emergent plants and could be determined by field observation or simulation experiments for any given species or assemblages. Their planimetric area (A_e) was then calculated according to the function $F_{A\sim W}$ (Fig. 3).

Regarding the submersed group, floating leaved and submersed macrophytes are found in overlapped elevations under water and the latter are able to colonize deeper areas, i.e. at lower elevation. Therefore, the elevation distribution of the group was from W_{subm} to W_{germ}, where W_{subm} was the lowest elevation of submersed macrophytes and W_{germ} was water level during germination. W_{subm} can be determined by light availability according to water depth and Secchi depth (Wang et al., 2005). Earlier research in Yangtze lakes showed that submersed macrophytes could develop only when the ratio of Secchi depth (SD) to water depth was beyond 0.5 during March-June (Wang et al., 2005). Therefore, W_{subm} was estimated to be W_{germ} minus 2SD. Secchi depth was chosen as the lowest or mean monthly value during March-June in the last or most recent year depending on available data. In this step, W_{germ} was fixed between the lowest water level observed in the historical record (W_L) and the mean annual water level (W_C). The planimetric area of floating leaved and submersed species (A_s) (Fig. 3) was calculated by the function $F_{A\sim W}$.

The elevation distribution of all aquatic plants was from W_{subm} to W_C, and again the corresponding planimetric area (A_t) could be calculated by $F_{A\sim W}$. Since the emergent group overlaps in elevation (W_{emer}-W_{germ}) with the submersed group (Fig. 3), the sum of A_e and A_s is necessarily larger than A_t.

The whole-lake coverages of the emergent group, submersed group and total aquatic plants were calculated as

$$C_e = \frac{A_e}{A_C} \times 100\%,$$

$$C_s = \frac{A_s}{A_C} \times 100\%,$$

$$C_t = \frac{A_t}{A_C} \times 100\%,$$

of a given germination water level (W_{germ}). Repeating the above calculating processes, whole-lake coverage at any germination water level could be calculated with a given Secchi depth value. W_{germ} was assigned a value from W_L to W_C, in increments of 0.1 m. The relationship between vegetation coverage and water level ($F_{C\sim W}$) was fitted based on the calculated data. The $F_{C\sim W}$ can be established for total aquatic vegetation as well as each elevational group. Also, under different Secchi depth conditions, the corresponding function can be fitted through the above processes.

Step 3 was to calculate the water level during germination of a given vegetation coverage target ($W_{t\text{-}germ}$). The conservation or restoration target of the aquatic vegetation coverage depends on the management goal for a lake. Once the coverage target is determined, $W_{t\text{-}germ}$ can be calculated by the function $F_{C\sim W}$. Although setting a conservation target is important, it was beyond of the scope of this study.

Step 4 was to recommend monthly water level requirements (WLRs) of the remaining life history stages. Three principles were taken into account while the WLRs for each stage was determined.

The first was that the recommended WLFs of the lake must be generally consistent with the historically natural water regime before major hydrological alterations occurred. Therefore, the historical water regime was treated as a reference for aquatic plants because their life history strategies have adapted to such regimes over a long time period (Lytle and Poff, 2004). The second was that the recommended water level during early life history stages must be strictly controlled. Many studies have shown that aquatic or riparian plants are more susceptible to hydrological alterations during germination and seedling (Mahoney and Rood, 1998; Wang et al., 2005; Zhang, 2013). Therefore, WLRs of aquatic plants were strictly limited during germination, with less restrictions placed on the seedling period, and least restrictions placed on the wintering period. The third was that, after germination, WLRs were mainly determined by species growth rates. Hygrophytes and emergent species are intolerant of submergence, and macrophytes' growth was prohibited if water level increased too fast (Zhang, 2013; Zhang et al., 2013; Zhu et al., 2012).

Based on the above principles, WLRs of each life history stage were assessed in Yangtze shallow lakes (Table 1). The recommended WLFs were generally consistent with the natural water regime of these lakes. Water levels were strictly controlled during the early life history stages using growth height of plants as the limiting factor. Only emergent macrophytes were considered in determining the upper limit of water level in July for two reasons: (1) most hygrophytes matured before July and they were little affected by WLFs after that time, (2) the critical time that water level impacted submersed macrophytes was March-June if Secchi depth was constant, according to an empirical study in Yangtze shallow lakes (Wang et al., 2005). Therefore, after June, water level has little effect on submersed macrophytes if Secchi depth remains unchanged. Such calculations were flexible and applicable to different conservation targets. For example, if we want to conserve or restore a specific species, growth rate of that species will be matched to increasing water level. If the whole assemblage is considered, the mean value of dominant or common species can be applied.

Step 5 was to verify the model by monitoring data. This approach was verified using historical or monitoring data obtained from literature or field observations. As described in Step 2, establishing the relationship between vegetation coverage and water level ($F_{C\sim W}$) was the key step of this approach. Theoretically, the predicted coverage would be larger than the observed value because other factors such as nutrients, seed pools and substrate type could also limit the distribution of aquatic plants. Also, growth rates of aquatic plants are affected by nutrients and other biota (competition, grazing, etc.) (e.g. Cao et al., 2014; Hough et al., 1989; Phillips et al., 1978; Søndergaard et al., 1996), resulting in variations in determination of upper water level limits. Therefore, it was necessary to adaptively adjust the parameters of the models to provide more precise predictions for aquatic vegetation management in the study lakes.

2.5. Case study of Lake Liangzihu

Lake Liangzihu (E 114°16′35″ ~ 114°56′09″, N 29°44′38″ ~ 30°34′08″), the second largest lake of Hubei Province, is located in the middle reach of the Yangtze River (Fig. 1). Its area is 304.3 km^2 at mean annual water elevation (W_C) (19.0 m A.S.L. at Wusong station). The lowest water elevation observed in the period of record (1961–2015) for this lake was 16.0 m, and the warning water level (W_{warn}) is 20.5 m. It is a typical shallow lake with the mean water depth of 4.2 m and maximum depth of 6.2 m. The annual mean air temperature is 17 °C, and annual rainfall is 1345 mm. In 1972, the lake was disconnected from the Yangtze mainstem by Fankou sluice (Wang and Dou, 1998). Although it was disconnected, WLFs changed little during the 1970s. The mean water elevation during January-March was maintained around 17.0 m from the 1960s to 1990s, and increased by 1.2 m from the 2000s to the 2010s. This lake was once clear and dominated by macrophytes, with a mean Secchi depth of 2.0 m and aquatic vegetation coverage ~95% in the 1950s (Wang, 1959). At present, the mean Secchi depth is approximately 1.0 m and vegetation coverage is only ~10%.

Using the new approach, the first step was to establish the relationship between water level and lake surface area of the lake. Due to lack of DEM, data for water levels and corresponding areas provided by Hubei Water Resources Research Institute were analyzed by a polynomial fitting method. According to Step 2, the relationship between water level and aquatic vegetation coverage was established. Whole-lake coverage of the emergent group, the submersed group and the total aquatic plants were considered. Most emergent macrophytes were found to germinate in areas where water depth was lower than 0.2 m, based on evidence from simulation experiments and field observations in the Yangtze basin (e.g. Cao, 2007; Wang et al., 1999; Zhang, 2013). Therefore, W_{emer} was estimated to be W_{germ} minus 0.2 m. According to Step 2, W_{subm} were estimated to be W_{germ} minus 2SD. Two Secchi depth scenarios that were considered here, i.e. 100 cm (a common value in the 1990s) and 40 cm (a minimum value observed at present), and the corresponding values of W_{subm} were W_{germ} minus 2.0, and 0.8 m, respectively. The $F_{C\sim W}$ functions were established for the emergent group, the submersed group and the total plants.

Regarding Step 3, the conservation target was set to be 30% of total vegetation coverage, a condition similar to that observed in the 2000s. The emphasis here was to illustrate the calculation processes and model outputs without emphasizing a particular conservation target. The next step was to recommend the WLRs of each life history stage. In this case, the whole aquatic plant assemblage but not a specific species was considered. A mean value of plant growth rate was calculated from data extracted from the literature for dominant or common species of hygrophytes, emergent and submersed macrophytes. Regarding hygrophytes, only data for *Carex* were available and its growth rate was estimated at approximately 40 cm/month (Zhang, 2013). For emergent macrophytes, data for the common species in Yangtze lakes including *Phragmites communis*, *Zizania latifolia*, *Scirpus validus*, *Typha orientalis* Presl, and *Acorus calamus* were used (Cao, 2007; Zhang, 2013; and the references therein), and the mean growth rate was 50 cm/month. With regard to submersed macrophytes, the mean growth rate was 30 cm/month, calculated from the following species: *Potamogeton crispus*, *P. malaianus*, *Vallisneria natans*, *Ceratophyllum demersum*, *Hydrilla verticillata*, and *Myriophyllum verticillatum* (Chen et al., 2006; Ji et al., 2011; Zhang et al., 2013). Most hygrophytes and emergent plants germinate from February, and submersed macrophytes from March (Zhang, 2013). According to the above information, the minimum plant height (MPH) was estimated to be 0.3 m in April, 0.6 m in May, and 0.9 m in June, respectively. The emergent macrophyte height was estimated to be 2.5 m in July (five months growth, from February to June).

In the last step, the model was verified using long term monitoring data of the lake (Appendix A in the Supplementary material). In total, nine data points of vegetation coverage from 1990 to 2014 were used, of which seven were extracted from the literature and two (2013, 2014) were from field surveys in this study. The seven historical surveys were carried out during summer-autumn, and surveys of 2013–2014 were in May. Aquatic vegetation coverages were estimated by the ratio of distribution area to lake surface area. The values were recalculated using a lake surface area of 304.3 km^2 as the benchmark for the purpose of comparison. The aerial distribution of aquatic vegetation was determined using GPS data recorded in the field, except for 1987 and 2004 when remote

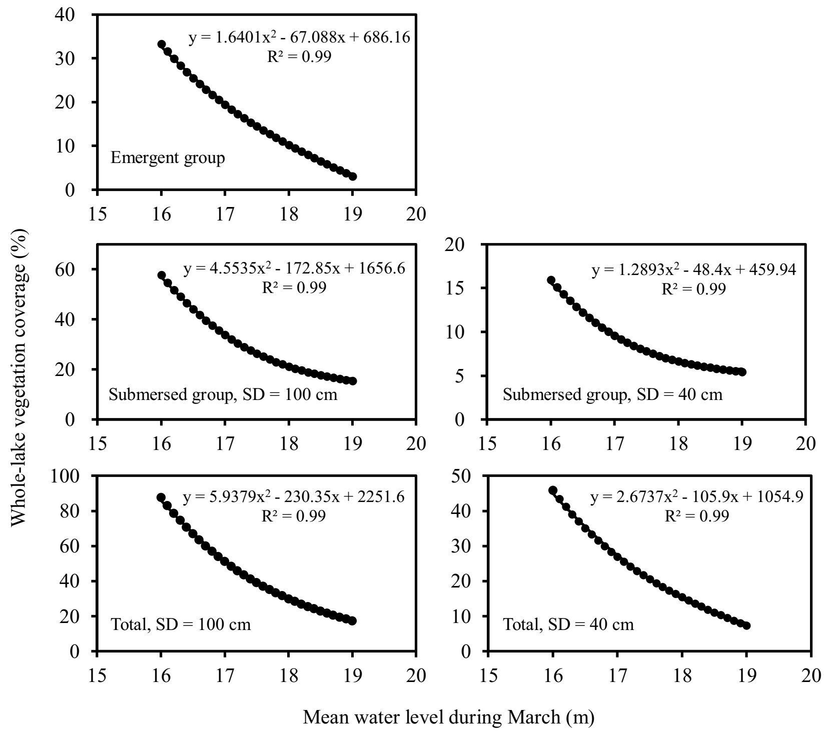

Fig. 4. Relationships between water level and aquatic vegetation coverage under two Secchi depth (SD) scenarios.

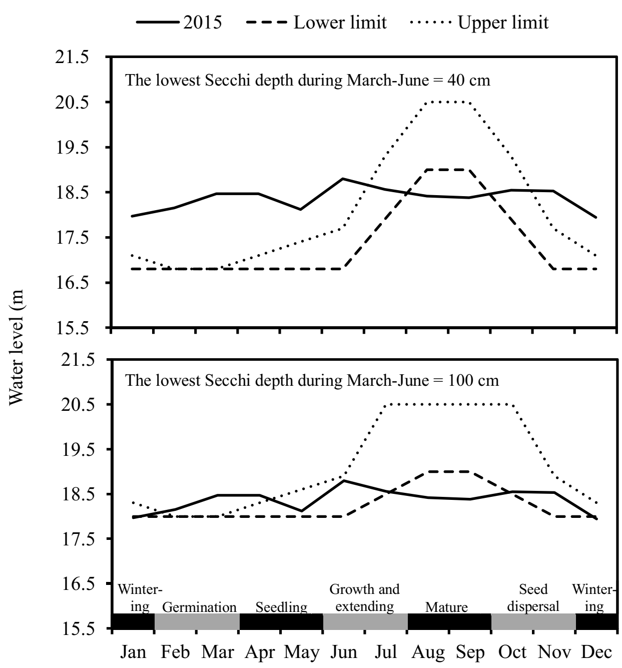

Fig. 5. The recommended WLFs (dashed lines) to achieve 30% vegetation coverage under two Secchi depth scenarios, compared with the current water regime (solid line) of Lake Liangizhu.

sensing data were available. Secchi depth data were extracted from the literature, and water level data were provided by Hubei Water Resources Research Institute (Appendix A in the Supplementary material). Vegetation coverage in each year was estimated according to the calculations described in Step 2. Model predictions were evaluated by regressing observed (y-axis) vs. estimated values (x-axis) according to the methods suggested by Piñeiro et al. (2008), and slope and intercept parameters were compared to the y = x line using an Analysis of Covariance (ANCOVA). Data analyses were carried out with Microsoft Excel 2010 and Statistica 10.

3. Results

The function $F_{A\sim W}$ of Lake Liangzihu was expressed as: $A = -0.2811W^4 + 20.862W^3 - 582.37W^2 + 7267.9W - 34015$ ($14.0 \le W \le 20.0$), where A is lake surface area (km^2) and W is water level (m). The relationships between water level and whole-lake vegetation coverage were established under two Secchi depth scenarios (40 cm and 100 cm), for the two elevational groups as well as the total species (Fig. 4). They showed that vegetation coverage decreased with germination water level in the lake, and a higher Secchi depth indicated a larger coverage. The recommended WLFs were shown in Fig. 5, under a scenario where the conservation target of aquatic vegetation coverage was set to be 30%. When the lowest Secchi depth during March-June was 40 cm, water level during germination (February–March) must be lowered down to 16.8 m, much lower than the current water regime. If the Secchi depth could be improved to 100 cm, a condition similar to the 1990s, the germination water level should be kept at 18.0 m. Water levels in the following months should rise steadily and peak at August–September, and then steadily lower down to a condition similar to germination.

The estimated values were significantly correlated with the observed ones for the nine years of available data (Fig. 6). The slope and intercept of the regression were not significantly different ($p > 0.05$) from those of the y = x line, indicating a high predictive power of the model. In most cases, the vegetation coverages were slightly overestimated as expected, with an average overestimation of 8.1% (absolute value).

4. Discussion

The present study provided a novel methodology to assess WLRs of shallow lakes, taking into consideration of geomorphological, hydrological and biological characters of these ecosystems. In contrast to the existed methodologies which rely heavily on hydro-

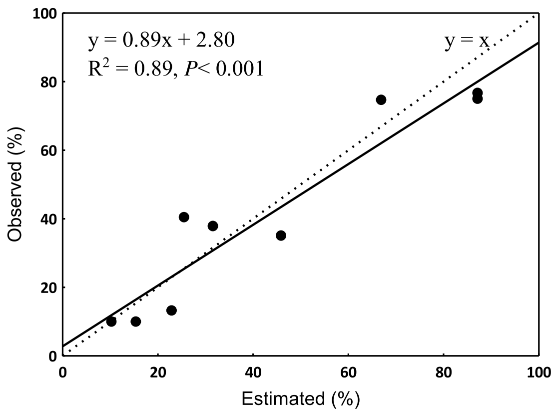

Fig. 6. Comparison of estimated and observed values of aquatic vegetation coverage of Lake Liangzihu.

logical and hydraulic calculations (e.g. Cui et al., 2005; Tharme, 2003; Yang et al., 2014), the approach established a quantitative linkage between water level and ecosystem health, providing a practical and useful tool for water level regulation and lake ecosystem management.

Although engineered flows can be an effective method in restoration of downstream ecosystems (Bond et al., 2014; Nilsson et al., 2005; Pittock et al., 2013), the relationship between hydrological variables and ecosystem health have rarely been quantified. In this study, the quantitative linkage (i.e. $F_{C\sim W}$) between water level during germination and aquatic vegetation coverage, a surrogate of ecosystem health, was established in shallow lakes. According to the model, aquatic vegetation coverage could be predicted under a given water level condition. The model proved to be powerful in estimating the vegetation coverage in the case study of Lake Liangzihu. Most values were overestimated because the approach calculated a theoretical maximum aerial distribution of aquatic vegetation (see Materials and methods). Also, this approach was based on the consideration that water depth and light availability were chief factors limiting the distribution of aquatic plants in shallow lakes. In conservation or restoration practices, other factors such as substrate type, seed pool and wave exposure should also be considered (Chen et al., 2006; Liu, 2005; Morris et al., 2002). According to $F_{C\sim W}$, a lower water level during germination would predict a higher coverage under a given Secchi depth condition, indicating that water level drawdown could promote vegetation recovery and extension. Similar to other studies (e.g. Coops and Hosper, 2002; Havens et al., 2004; Li et al., 2008; Zhang et al., 2016), this study indicated that both lowering water level and improving water transparency were effective measures for vegetation restoration (Fig. 5). Since extensive river regulation and sluicing, water levels in many Yangtze lakes has been maintained at a higher level during germination, and water transparency during March–June has decreased, as illustrated by Lake Liangzihu. Together, these changes have resulted in the degradation of aquatic vegetation in the whole lake (Appendix A in the Supplementary material). According to Fig. 5, the current water regime does not meet the requirements for aquatic vegetation development of the lake, indicating that re-regulating the water level from an ecological perspective (as suggested) is needed.

In the present approach, WLRs were determined according to the historical natural water regime and depth limitation during early life history stages of aquatic plants. Historical condition is often treated as a reference in ecosystem health assessment and restoration (Stoddard et al., 2006). The natural water regime of Yangtze shallow lakes was largely determined by seasonality of regional precipitation (Wang and Dou, 1998). Maintaining such seasonality of WLFs will likely play a strong role in aquatic vegetation restoration and conservation (Wang et al., 2016). Human induced water level alteration in this region, such as a reservoir-like regulation, resulted in degradation of aquatic vegetation to different degrees (Zhang et al., 2014). In this study, WLFs during early life history stages were strictly controlled according to the depth limitation of aquatic plants, while in other stages the limits were loosened. The reasons were as follows. First, aquatic plants are more prone to hydrological disturbance during early life history stages than other periods (e.g. Mauchamp et al., 2001; Wang et al., 2005; Zhang, 2013). Second, there is little knowledge about the effects of WLFs on aquatic plants during later periods such as seed dispersal and wintering in this region. The WLRs during July-September (from active growth and extending to maturity) were not estimated based on plant requirements, but rather by considerations of prohibiting terrestrial plant invasion and flood control which were more important than vegetation recovery during these periods. The Yangtze shallow lakes are located in the historical floodplain region, and thus aquatic plants in this region are adapted to flood events allowing quick recovery after they occur (Dou and Jiang, 2003). Considering the practical water level regulation using man-made structures, it is more difficult to control the water level during the flood season than the dry season.

The models established in the approach were simple and their parameters were easy to measure. The whole-lake vegetation coverage which was easy to measure by remote sensing or field surveys (e.g. Hu et al., 2015; Zhang et al., 2016), was used as the surrogate of ecosystem health. The $F_{A\sim W}$ was determined by bathymetric data. In the case study of Lake Liangzihu, the coarse data of water level and corresponding surface area were used because more complicated DEM data were unavailable. In the future, it may be possible to map aerial distribution in greater detail based on the DEM data and the $F_{C\sim W}$. The Secchi depth was used in determination of the $F_{C\sim W}$, and biological data were added to enable WLRs recommendation. Both data were accessible by field survey or from the literature. Another advantage of the approach is that it is flexible and can be adjusted depending on the target concerned, i.e. a specific plant species, a group or the total assemblage.

The present approach could be widely used for water level management in Yangtze shallow lakes, concerning conservation, restoration and population control of aquatic plants. Due to limited data availability, the models were only verified with the long term data of Lake Liangzihu at present. Further studies should include more data from other lakes to verify and adjust the models, and thus to make them more robust. Although it was established in the Yangtze Basin, the approach was potentially applicable in waterbodies where the $F_{A\sim W}$ could be determined and aquatic plants presented clear elevational gradients.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecoleng.2017.02.004.

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