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Developing water level regulation strategies for macrophytes restoration of a large river-disconnected lake, China

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ABSTRACT

Natural water regime is important for the germination, growth and distribution of aquatic plants. In order to restore the macrophytes of the Chaohu Lake, field investigations were conducted in 2010–2012, hydrological data were also collected for analysis. The results showed that macrophytes of the Chaohu Lake have changed greatly after disconnection from the Yangtze mainstem, and the alteration of natural water level fluctuation (WLF) was the primary factor. After disconnection, the water level of January–March was controlled and maintained at a higher level; while that of April–June was gradually decreased due to irrigation and flood control. Such a water level regime is completely opposed to the natural condition, and is unfavorable to the germination and growth of macrophytes. Combined the life history with hydrological data, we then analyzed the water level requirements of macrophytes in different life history stages. Based on the water demands of agriculture, industry, shipping and others, we developed specific measures for water level regulation, and tested using water budget equation. The results of this study should be useful for the recovery of aquatic vegetation in other similar regulated lakes.

1. Introduction

Water regime is the major factor determining the distribution and diversity of wetland vegetation (Casanova and Brock, 2000; Raulings et al., 2010). In long-term evolution, wetland plants have gradually adapted to periodic hydrological processes and formed a range of morphological, life history and phenological adaptations (Poff et al., 1997; Lytle and Poff, 2004). The spread, growth and reproduction of wetland plants require specific hydrological components, including magnitude, frequency, duration, timing and rate of change (Mahoney and Rood, 1998; Karrenberg et al., 2002; Middleton, 2002; Zhang et al., 2013). In shallow lakes, WLF as a decisive element of water regime may have an overriding effect on ecology, functioning and management of lakes (Coops et al., 2003; Leira and Cantonati, 2008). WLF not only can affect macrophytes directly, but also indirectly by acting on the substrate, nutrient, light, water and gas. Therefore, the spatial and temporal variations of water level are crucial in structuring macrophyte communities of lakes (Keddy, 1983; Wilcox and Meeker, 1991; Rills and Hawes, 2002; Leyer, 2005; Van Geest et al., 2005).

WLF mainly depend on regional climate conditions and human activities (Coops et al., 2003; White et al., 2008). The construction of dams and reservoirs has changed the natural patterns of WLF in many freshwater systems worldwide (Dynesius and Nilsson, 1994; Tharme, 2003; Aroviita and Hämäläinen, 2008), leading to a great change in diversity (Hill et al., 1998; New and Xie, 2008; Hammersmark et al., 2009; Raulings et al., 2010) and coverage (Jansson et al., 2000; Van Geest et al., 2007) of macrophytes. However, the degradation of aquatic vegetation has often been explained by increased nutrient loads (Scheffer and Carpenter, 2003; Tracy et al., 2003), and little attention was paid to hydrological alterations such as WLF in lakes (Van Geest et al., 2007). WLF can trigger regime shift between clear and turbid stable states in lakes, as low water level promotes the establishment of macrophytes by increasing light availability (Havens et al., 2005). Water level regulation is also regarded as an effective measure for aquatic vegetation restoration in lakes (Coops et al., 2004; Havens et al., 2004, 2005; Li et al., 2008). However, some studies still showed that extremely low or high water level is unfavorable to the growth of aquatic vegetation (Coops et al., 2003; O'Farrell et al., 2011), because macrophytes have different water level requirements in different life history stages. Therefore, it is

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important to understand such requirements for a successful water level regulation with regard to aquatic vegetation restoration.

Among the largest floodplains of the world, the Yangtze River floodplain owns a unique biota and a complex river-lake landscape where hundreds of shallow lakes were connected with the mainstem. WLF of these lakes are closely correlated with the hydrological regime of the Yangtze mainstem. However, such river-lake connections were blocked by sluices for most lakes during 1950s–1970s, and WLF of these disconnected lakes were flattened with increased annual mean water level and reduced fluctuation amplitude (Wang and Dou, 1998). For irrigation and flood control, a large area of lakes (more than 2340 km^2, 15% of the total) keep higher water level in winter to spring, and low water level in late spring to early summer, which is completely opposed to the natural condition (e.g. Chaohu Lake). Such water level regulation might have great effects on aquatic vegetation, but little study has been conducted on this topic, and the underlying mechanisms are unclear to date.

As hydrological process is the primary driving factor of river-floodplain ecosystem, we hypothesized that the adversely regulated water level would have great negative effects on macrophytes. In the present study, we selected a large river-disconnected lake, the Chaohu Lake, in the middle reach of the Yangtze River as the model system. We expected: (1) to determine the effects of WLF alteration on aquatic vegetation and underlying mechanisms; (2) to develop water level regulation strategies based on the understanding of WLF requirements of macrophytes. In a broader context, our results would be helpful in improving our understanding of floodplain ecology, and developing conservation strategies based on an eco-hydrological aspect.

2. Methods

2.1. Study site

The Chaohu Lake is a shallow eutrophic lake, located in central of the Anhui province. It belongs to the northern subtropical monsoon climatic zone. The annual average air temperature is 16.1 °C. The annual average rainfall and evaporation is 995.7 and 1124.4 mm, respectively (Wang and Dou, 1998). The elevation of the lake bottom is 4.0–5.5 m, and water level is often controlled at 8.0–8.5 m. The mean water level is 8.37 m, with a total area of 769.55 km^2, and a volume of 20.7×10^8 m^3 (Wang and Dou, 1998). The water has been polluted seriously, and the mean concentration of TN and TP was about 2.31 and 0.20 mg/L, respectively (Wang, 2007). The surrounding region of the Chaohu Lake is mainly dominated by farmland, and most shoreline was constructed with embankments.

The catchment area of the lake is 13,350 km^2, with 33 tributaries. The Yuxi River is the only one linking the lake and the Yangtze River. The Chaohu sluice and Yuxi sluice were successively built on the Yuxi River in 1962 and 1969 (Fig. 1), making the lake to be regulated. The maximum discharges of the two sluices are 1370 and 1400 m^3/s, respectively. Otherwise, for irrigation and flood control, the Zhaohe sluice and Fenghuangjing pump were built on other tributaries of the Chaohu Lake (Fig. 1). The Fenghuangjing pump can discharge water to Yangtze River at the rate of 240 m^3/s or discharge water to Chaohu Lake at the rate of 200 m^3/s. So, the water level of Chaohu Lake can be regulated by Chaohu sluice, Yuxi sluice and Fenghuangjing pump.

The alteration of water level was shown in Fig. 2. Before the building of Chaohu sluice, the water level was low in January–March, and rose gradually in April–June. After that, the water level is high all the year; in April–June, although the rainfall increases obviously, the water level shows a decreasing tendency because of irrigation and flood control.

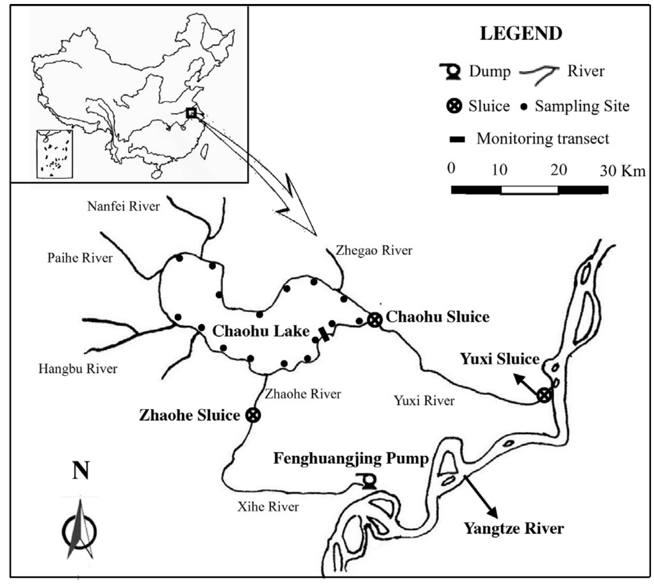

Fig. 1. Location of the sampling sites in the Chaohu Lake.

2.2. Field sampling

Field surveys were conducted during 2010–2012. To determine the total coverage of macrophytes (mainly submerged, floating and emergent species), a whole lake survey was carried out in autumn (September) of 2010. The survey was mainly concentrated in lakeshore regions due to the reason that no macrophytes were found in offshore waters in recent years (Lu, 1984; Ren and Chen, 2011). The area covered by macrophytes was estimated using a handheld GPS and a laser distance meter. The total coverage of macrophytes was then calculated as the ratio of plant-covered area to lake area.

To determine the community structures of aquatic vegetation, a further investigation was conducted in late spring (May), 2011. Sixteen sites were set in lakeshore regions (Fig. 1). In each site, three to ten (depending on vegetation complexity) plots (1 m × 1 m) were established perpendicular to the lakeshore. The upper limit of the survey was defined as the appearance of woody species or encounter of embankment, and the lower limit depended on the distribution of submerged macrophytes. A total of 131 plots were collected. All plants were identified and recorded within each plot,

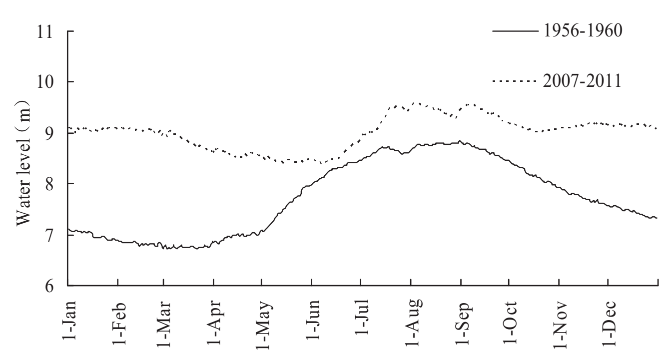

Fig. 2. Daily average water level before (1956–1960) and after (2007–2011) the building of Chaohu sluice.

and the coverage of each species was visually estimated. The distribution elevation of each species was measured by theodolite and meter stick.

To determine the effects of gradually decreased water level on macrophytes, a monitoring transect was set in May–July 2012 (Fig. 1). Four fixed plots (1 m × 1 m) with abundant floating and submerged macrophytes were artificially established in the monitoring transect. The density and length of each macrophyte in the plot were measured monthly during May–July.

2.3. Data analyses

The occurrence frequency, mean coverage, distribution range and mean elevation of each species were calculated according to field investigation in 2011. The hydrological data from 1956 to 2005, 2007 to 2011 was used to analyze the alteration of WLF. The former was provided by Anhui Survey and Design Institute of Water Conservancy and Hydropower (ASDI), and the latter was from Anhui Hydrological Telemetering Information System. Spearman correction was used to analyze the relationships between hydrological data and coverage area of macrophytes. The coverage area data in 1956–1959, 1963, 1978 and 1981 were from Compilation Commission of Chaohu Local Records (1988), the data in 2010 was from our filed investigation. To analyze the WLF requirements of macrophytes, we firstly divided the life history into different stages, and then analyzed the WLF requirements in each stage. Combined WLF requirements of macrophytes with other demands, we developed specific measures for water level regulation, and tested using water budget equation regarding 2004–2005 as an actuality year. The restrictive factors to regulate the Chaohu Lake were provided by ASDI (Appendix A). The water budget equation can be expressed by the following equation over a specified time interval (t) (Tu et al., 1990):

$$S(t) = P + Q_i1 + Q_i2 - E - Q_o \pm Q_r$$

where $S(t)$ = change in water quantity stored in the lake; P = precipitation falling on the lake; Q_i1 = river and district water flowing into the lake; Q_i2 = industrial and agricultural water return into the lake; E = evaporation volume; Q_o = industrial and agricultural water drawing out of the lake; and Q_r = the volume regulated by sluice or dump.

All data analyses were performed with SPSS 13.0.

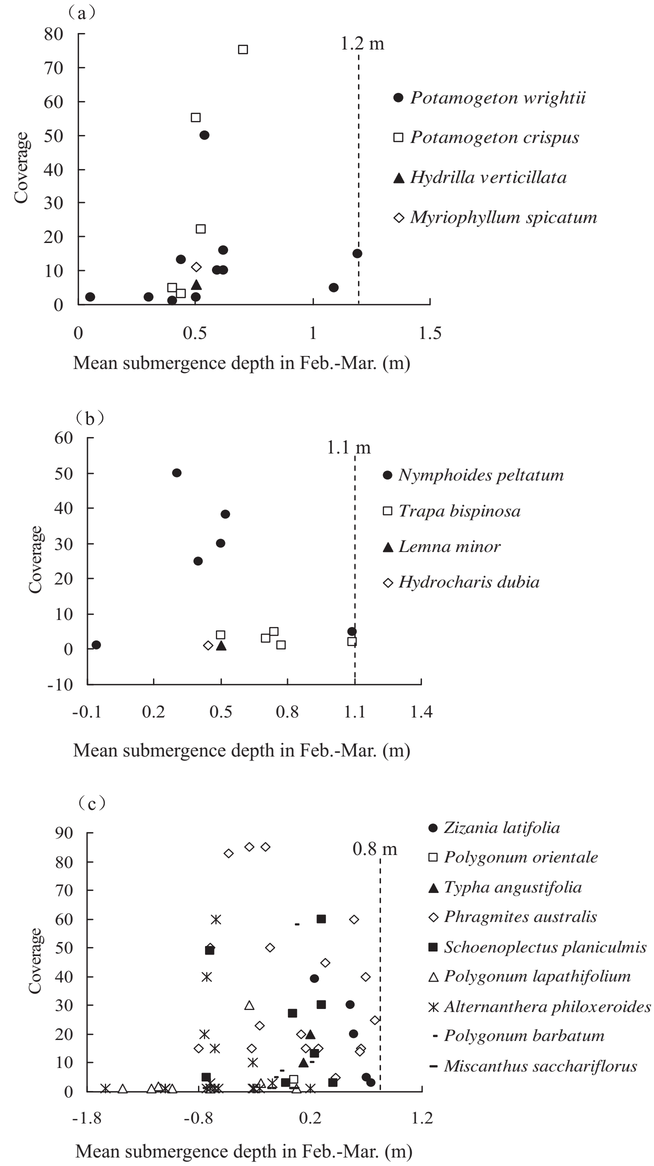

Fig. 4. Relationships between mean submergence depth in February–March and submerged (a), floating (b) and emergent (c) species coverage of each plot in May.

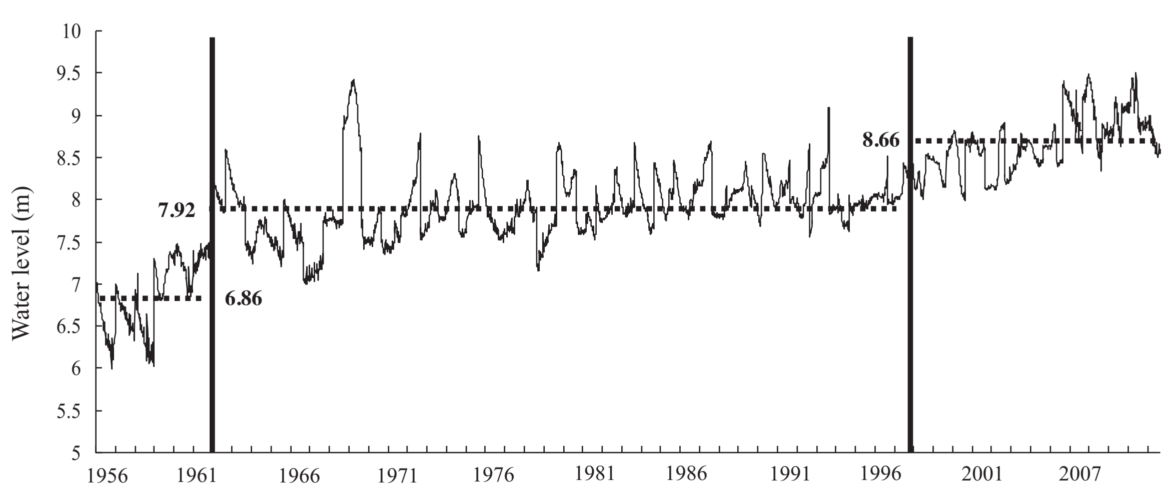

Fig. 3. The alteration of mean water level (January–March) in the Chaohu Lake from 1956 to 2011.

3. Results

3.1. Species composition, coverage and distribution

A total of 75 species were recorded in the Chaohu Lake (Appendix B). The number of hygrophytes, emergent, floating and submerged macrophytes was 56, 9, 4 and 4, respectively. The total coverage of macrophytes was about 0.4%, and most species were found to be scattered along the lakeshore with lower occurrence frequency and coverage (Appendix B). Hygrophytes dominated the lakeshore community and distributed at a wide range of elevations, while submerged species was the least and only occurred in limited areas. Within hygrophytes, *Cynodon dactylon* was dominant in terms of occurrence frequency and mean coverage. The dominant species of emergent macrophytes was *Phragmites australis*, with the mean elevation and coverage being 8.56 m and 5.04%, respectively. Floating and submerged macrophytes have little coverage in the lake; *Nymphoides peltatum* was relatively common in floating species, and *Potamogeton crispus* and *Potamogeton wrightii* in submerged species.

3.2. Effects of WLF alterations

The relationships between water level and coverage area of macrophytes were shown in Table 1. There were significantly negative correlations between coverage area and January–March mean water level ($P < 0.05$). January–March mean water level had been increased by 1.8 m, from 6.86 m before sluice gate construction to 8.66 m at present (Fig. 3). It indicated that the increase of January–March mean water level hindered the development of macrophytes. In the Chaohu Lake, macrophytes mainly germinated in February–March. Submergence depth during this time could limit the range of germination, and further limit the development of macrophytes. The maximum germination depth of emergent, floating and submerged macrophytes was about 0.8, 1.1 and 1.2 m, respectively (Fig. 4). It seemed that macrophytes could not germinate in areas where water depth exceeds 1.2 m during February–March under current water regime.

Macrophytes coverage area was also found to be negatively correlated with water level difference between April–June and January–March (Table 1). The decrease of water level in April–June had destructive effects on macrophytes (Fig. 5). According to field monitoring data, abundant seedlings of a submerged species (*P. wrightii*) and a floating species (*N. peltatum*) were found in area above the water surface during May. In June, most seedlings (about 90%) of both species were found to be shrunken or death, and in July, none was in the plots.

3.3. Requirements of WLF and regulation strategies

The life history of macrophytes in the Chaohu Lake could be classified into three stages, i.e. germination, fast growing, and flowering and fruiting periods. For most species, germination period is February–March, fast growing period is April–June, and flowering and fruiting period is July–October. Because the macrophytes have adapted to the natural WLF, so we considered the pattern of WLF before the building of Chaohu sluice was the best for macrophytes. Water level requirements of macrophytes in different life history stages were shown in Fig. 6. During February–March, species need low water level to improve light availability and to promote germination. In April–June, they have a greater demand for water and space. Gradually increase of water level during this time can promote their growth. Generally, water level of Yangtze lakes maximizes in July–August, and then decreases gradually to the minimum of the year. Such water regime can promote mature of macrophytes and is beneficial for propagules and seeds dispersion.

Combined WLF requirements of macrophytes with other demands such as agriculture, industry, shipping, and so on (Appendix A), we proposed water level regulation strategies for the restoration of aquatic vegetation (Table 2). The main regulations were to lower down January–March water level and to gradually increase April–June water level. According to water budget equation, such regulation is feasible by discharging the lake water to the Yangtze mainstem in certain months (Appendix C).

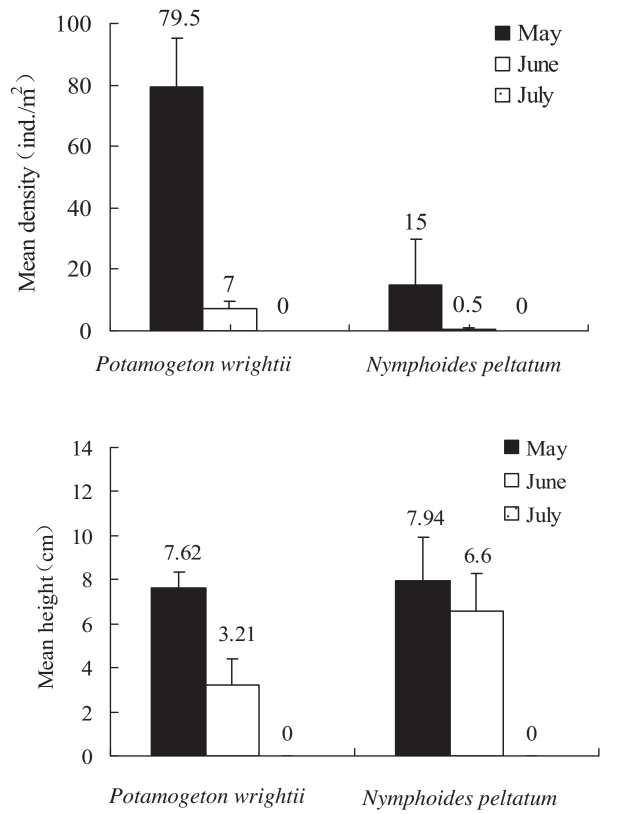

Fig. 5. Comparison of mean density and mean height of macrophytes in different months.

4. Discussion

Before 1960, macrophytes of the Chaohu Lake distributed all over the lake, and its coverage was about 25%. After the building of Chaohu sluice, the coverage had sharply dropped to 1.73% in the

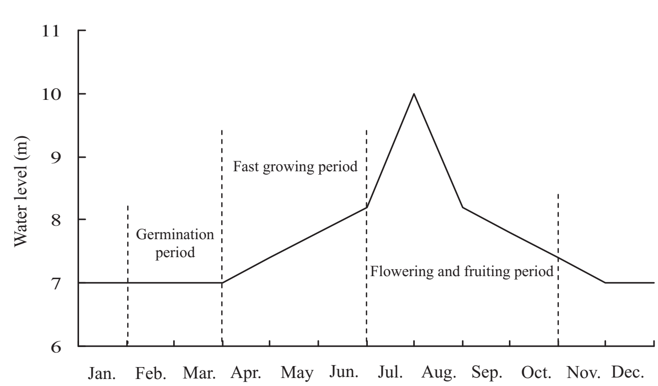

Fig. 6. Water level requirements of macrophytes in different life history stages.

Table 1
Spearman corrections between water level and coverage area of macrophytes. Significant correlations were in bold letters.

	FA	MAW	WLD	WLE	MWL
Coverage area					
r	0.30	−0.40	−0.90	−0.30	−0.70
n	5	5	5	5	5
P	0.624	0.505	**0.037**	0.624	0.188

	January	February	March	April	May	June
Coverage area						
r	−0.90	−0.90	−0.90	−0.70	−0.50	−0.30
n	5	5	5	5	5	5
P	**0.037**	**0.037**	**0.037**	0.188	0.391	0.624

	July	August	September	October	November	December
Coverage area						
r	−0.10	−0.10	−0.30	0	0	−0.30
n	5	5	5	5	5	5
P	0.873	0.873	0.624	1	1	0.624

Note: FA, fluctuation amplitude; MAW, mean annual water level; WLD, water level difference between January–March and April–June; WLE, water level difference between June and July; MWL, mean water level from October to December.

year of 1963 (Compilation Commission of Chaohu Local Records, 1988). In 1980s, the coverage was raised to 2.54% (Lu, 1984). In recent years, with the increasing human activities, macrophytes of the Chaohu Lake are nearly extinct; the total coverage was less than 1%. Compared with the study of 1980s, we found that the species number has decreased obviously, but the dominant species changed little. Some pollution-sensitive species (e.g. *Utricularia vulgaris*) or species without canopy (e.g. *Vallisneria natans*) have disappeared.

Hydrological alteration, lake reclamation, eutrophication and extreme flooding events were usually being considered as main factors affecting macrophytes in the Yangtze floodplain lakes. Which one is the most important in the Chaohu Lake? In the present study, we found hydrological alteration had significantly adverse effects on the germination and fast growing of macrophytes, and might be the primary factor leading to the sharp degradation of macrophytes in 1963. Other factors had also contributed to the degradation of macrophytes in certain degrees. Lake reclamation had a long history (since 1700 years ago) in the lake, with a large amount of lake areas being transformed to farmlands. Although it had reduced habitat area, lake reclamation seemed not the main reason for sharp and rapid degradation of macrophytes in a short time. Eutrophication was usually regarded as an important factor for the degradation of macrophytes in freshwater ecosystems, but its effects in this lake should be limited. Hutchinson (1975) considered that under extremely turbid conditions, submerged macrophytes could also grow at shallow sites where the water depth is lower than 1 m. Macrophytes coverage was at a higher level (25%) during 1950s when the Chaohu Lake was already eutrophic and water blooms occurred every year (Compilation Commission of Chaohu Local Records, 1988). It indicated that a certain area of macrophytes could also be maintained under eutrophic condition. Such evidence was already found in other eutrophic lakes. The TN concentration of Taihu Lake was higher than the Chaohu Lake, but the macrophytes coverage was about 20% (Xie, 2009). According to Jeppesen et al. (1990), substantial macrophytes could also be found in lakes the TP concentration was about 0.7 mg/L. Therefore, we agreed with Xie (2009) that eutrophication was not the direct cause of vegetation recession in this lake. Dou and Jiang (2003) thought the devastating flood in 1954 led to the degradation of macrophytes in the Chaohu Lake, but the coverage had restored to 25% before 1960. The flood destroyed the aboveground parts of macrophytes, but left the seed banks and propagules alive for further recovery.

In the Chaohu Lake, coverage area of macrophytes was significantly negative correlation with January–March mean water level and water level difference between January–March and April–June (Table 1). The influences of altered WLF on macrophytes were mainly demonstrated in two aspects. First, the maximum germination depth of macrophytes in January–March was 1.2 m, but the water level increased about 1.8 m in recent years, which lowering the availability of lights, leading to the original seed bank or propagules difficult to germinate and the distribution range shifted to higher elevation. Second, after shifted to higher elevation, floating and submerged macrophyte seedlings germinated in shallow water areas would be exposed to air in April–June because of the gradually decreased water level during that time. Seedling stage is usually accompanied by extremely high mortality due to the lower resistance to external interference (Silvertown and Dickie, 1980; Mauchamp et al., 2001; Nishihiro et al., 2004). The drought caused by low water level in April–June would be destructive

Table 2
Water level requirements of macrophytes in the Chaohu Lake.

Month	Hydrological events	Suggested water level (m)	Implications
January	Low water level	7.5	Improving the sediment physical and chemical conditions
February–March	Low water level	7.5	Increasing light availability, promoting the germination of macrophytes
April–June	Gradually increased water level	7.5–9	Providing sufficient water and space, promoting the fast growing of macrophytes
July–September	High water level	9–10.5	Expanding the distribution area of macrophytes, excluding exotic species, preventing the shrink of the lake area
October	Gradually decreased water level	8.0–9.0	Promoting mature and seeds dispersion of macrophytes
November–December	Low water level	7.5–8.5	Maintaining sufficient habitat, promoting the germination and growth of *Potamogeton crispus*

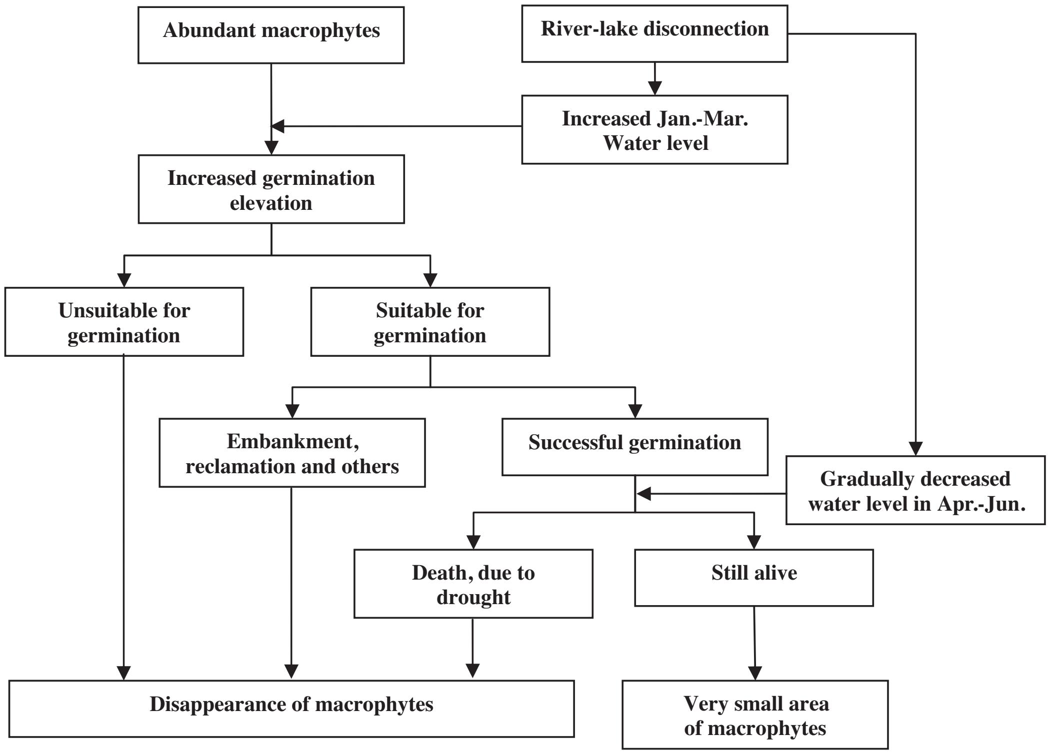

Fig. 7. Degeneration mechanisms of macrophytes in the Chaohu Lake.

to the floating and submerged macrophyte seedlings. Emergent macrophytes have higher tolerance to drought. However, if we take into consideration of embankment which prevented the germination in higher elevations, the negative effects of altered WLF would be appeared. Therefore, the alteration of natural WLF was the main driving factor for serious decline of aquatic vegetation, which could not satisfy the water level requirements of macrophytes during germination (February–March) and fast growing (April–June) period. We concluded the degradation mechanisms of macrophytes in the Chaohu Lake in Fig. 7.

The key point to restore macrophytes of the Chaohu Lake was to restore the natural water regime, meeting the water level requirements of macrophytes in different life history stages. Xu et al. (1999) suggested keeping January–March water level at 7.5 m with considerations of successful germination. In our research, we proposed water level regulation strategies based on water level requirements of macrophytes over different life history stages. Both lowering January–March water level and making April–June water level an increasing tendency are very important for the restoration of macrophytes. Under current transparency (about 50 cm) of the Chaohu Lake, the maximum water depth for macrophytes to germinate was 1.2 m in February–March. When water level is lowered to 7.5 m, about 20% of lake area would become potentially recoverable for macrophytes.

In this paper, we demonstrated the effects of WLF alterations on macrophytes and proposed feasible regulation strategies for macrophytes restoration in the Chaohu Lake. The results had significant implications for the decision support schemes, and were also useful for other lakes with similar water level alterations in this region. However, water level regulation is a large engineering; water level requirements of many others such as agriculture, industry, and fishery should also be considered. This concerns the departments of environmental protection, water conservancy, fishery administration, and so on, making the regulation difficult to be implemented. To solve this problem, we suggest that the coordination and cooperation should be strengthened for multiple management departments, holding joint meetings at regular intervals or establishing a special organization composed of different departments. Besides this, efforts should also be paid to strengthen the control of point and non-point pollution. Because of the low coverage of vegetation in this lake, active plantation is also required to restore the macrophytes in a short time. After doing this, the Chaohu Lake can change back to macrophytes dominated state.

Acknowledgements

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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.2014.03.087.

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