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Understanding Seasonal Water Clarity Dynamics of Lake Dahuchi from In Situ and Remote Sensing Data

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Abstract Obtaining, analyzing and understanding the seasonal dynamics of water clarity is of importance for understanding and managing lakes and sustaining their ecosystem services. This study aimed to explore the seasonal dynamics of water clarity and to analyze how water level, wind velocity and total precipitation influence this dynamics in Lake Dahuchi, China. The Secchi disk depths recorded in the field and derived from Moderate Resolution Imaging Spectroradiometer (MODIS) images together demonstrated a seasonal pattern of water clarity, which was lower in winter and spring, increased in April or May to reach the highest values in summer, upon which it gradually declined from September onward. Piecewise linear regression analysis between water clarity and water level showed that water level could explain 70% of the variation of the logarithm of Secchi disk depth. The water clarity of Lake Dahuchi was primarily controlled by suspended sediment, while the seasonal variation of water level induced different sediment resuspension, thus we concluded that the water clarity seasonal dynamics of Lake Dahuchi was mainly regulated by seasonal variation of water level.

Keywords Water clarity · Seasonal dynamics · MODIS · Water level

1 Introduction

Poyang Lake National Nature Reserve of China is a globally important wetland (Wu and Ji 2002), which provides multiple functions in commerce, aesthetics, tourism,

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recreation and biodiversity conservation. The provisions of these functions are to a great extent influenced by water quality. As water clarity is a indicator widely used to describe a lake's overall water quality (Li and Li 2004; Shaw et al. 2004), obtaining, analyzing and understanding the seasonal dynamics of water clarity is of importance for understanding and managing lakes and sustaining their ecosystem services.

The water clarity is generally measured in situ using a Secchi disk, one of the most commonly used tools for measuring water clarity (Duane Nellis et al. 1998; Kloiber et al. 2002a; Preisendorfer 1986). Similarly, the water clarity has been measured using Secchi disk in three lakes within the nature reserve since 1999. The in situ measurements, however, were only carried out from April to October, and they do thus not describe adequately the integrated seasonal dynamics of water clarity over a whole year. Moreover, this method may be costly for intensive sampling within the water bodies in which the water clarity fluctuates highly in time and space scales (Brezonik et al. 2002; Hakanson and Boulion 2003; Kloiber et al. 2002b).

Remote sensing techniques hold potential to infer water clarity from the captured reflectance (Harma et al. 2001; Li and Li 2004; Liu et al. 2003). The potential has been explored since the launch of the first Landsat satellite in the 1970s, and various sensors have been employed such as Landsat (Giardino et al. 2001; Hellweger et al. 2004; Lathrop and Lillesand 1986), IKONOS (Sawaya et al. 2003), QuickBird (Sawaya et al. 2003), Sea-viewing Wide Field-of-view Sensor (SeaWiFS; Chen et al. 2007) and Moderate Resolution Imaging Spectroradiometer (MODIS; Lillesand 2004; Lillesand and Chipman 2001). Wu et al. (2008) compared MODIS and Landsat Thematic Mapper (TM) for estimating water clarity in the Poyang Lake National Nature Reserve, and concluded that MODIS would be more suitable to this region due to its daily and near-daily coverage (Lillesand 2004), better spectral sensitivity (Li and Li 2004) and cost-free distribution. Thus, MODIS could complement the in situ measurement of water clarity for exploring its integrated seasonal dynamics.

The water clarity is determined by water column constituents such as chlorophyll a, inorganic suspended solid and coloured dissolved organic matter (Choubey 1998; Hakanson and Boulion 2003; Swift et al. 2006). The variations (type, particle or concentration) of these constituents might result in different water clarity. External factors, such as wind, precipitation, waste water discharge or dredging, could modify the compositions of these water constituents, and further change the water clarity (Chen et al. 2007; Cozar et al. 2005; Wu et al. 2007). However, how these potential factors affect the seasonal dynamics of water clarity is still unknown in the nature reserve.

This study aimed to explore the seasonal dynamics of water clarity using the Secchi disk depths measured in the field and derived from the MODIS surface reflectance product together, and to analyze how water level, wind velocity and total precipitation influence its dynamics in Lake Dahuchi within the nature reserve.

2 Materials and Methods

2.1 Study Area

The study was carried out in Lake Dahuchi within the nature reserve, which is located between 115° 55′ and 116° 03′ E, 29° 05′ and 29° 15′ N in the northwest of Poyang

Lake (Fig. 1). The nature reserve was established in 1988 to conserve the endangered Siberian crane (Li et al. 2005), as more than 95% of its world population winter here (Wu and Ji 2002). It connects to the Poyang Lake during high water levels in summer but disconnects when water levels are low in spring, autumn and winter.

2.2 Landsat TM Image

One Landsat TM5 image (path 121/row 40) captured on 29 November 2004 was obtained from the Chinese Remote Sensing Satellite Ground Station for describing the general spatial pattern of vegetation distribution in Lake Dahuchi. Topographic maps with scale 1:50,000 were employed to register the image to the Beijing 54/Gauss-Kruger projection using a first-order polynomial and nearest neighbour

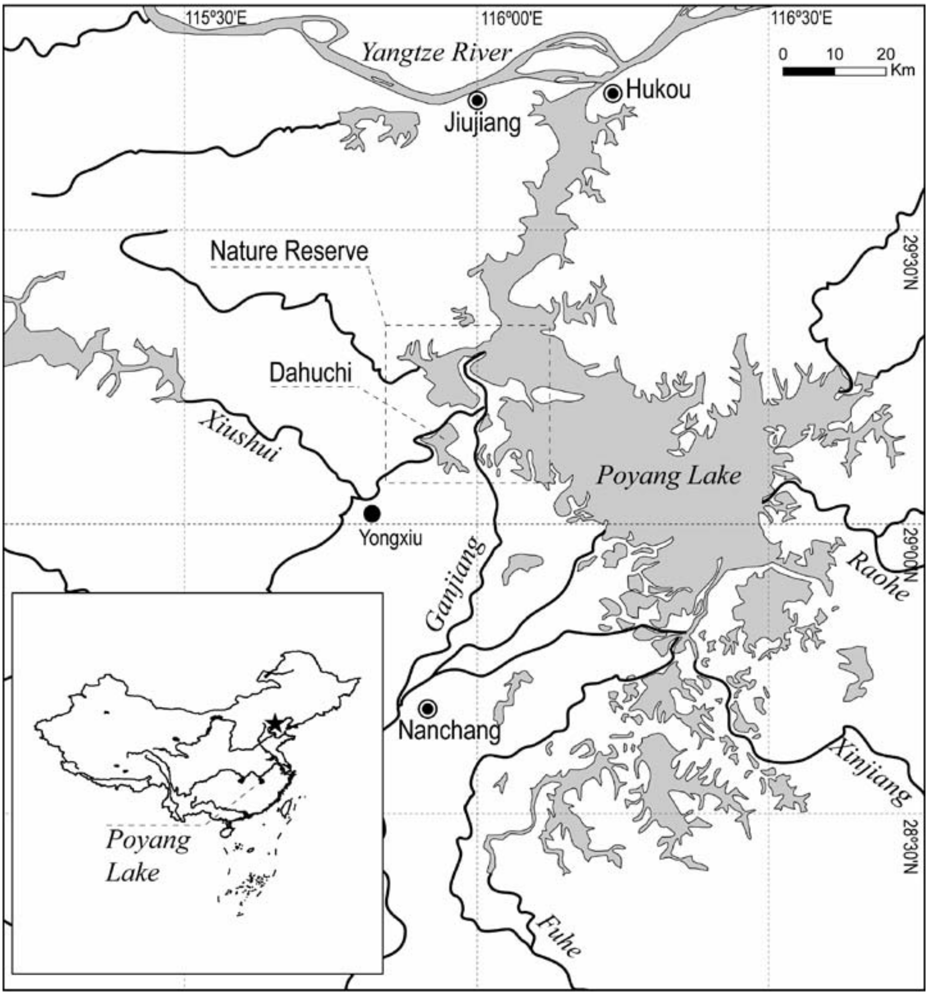

Fig. 1 Locations of Poyang Lake National Nature Reserve (nature reserve), Lake Dahuchi and Yongxiu meteorological station

approach, and the root mean square error (RMSE) for positional accuracy was within half a pixel.

2.3 Water Level and Water Clarity

The water level and water clarity (Secchi disk depth) of Lake Dahuchi were regularly measured by the Bureau of Jiangxi Poyang Lake National Nature Reserve and the International Crane Foundation from 2003 to 2006. Daily water level was recorded using a water level gauge, and Secchi disk depth was measured using a standard 20 cm Secchi disk at five locations at weekly intervals from April to October.

2.4 Wind Velocity and Total Precipitation

Yongxiu meteorological station is the closest station to Lake Dahuchi around 20 km away (Fig. 1). Given this distance, we considered that the meteorological environment at this station might reflect that over the Lake Dahuchi. Thus, the daily wind velocity and total precipitation from 2003 to 2006 at this station were obtained for further analysis.

2.5 MODIS Data

Two MODIS instruments onboard the US National Aeronautics and Space Administration (NASA) Terra and Aqua spacecraft platforms are operational for global remote sensing of the land, ocean, and atmosphere. MOD09GQK/ MYD09GQK is a surface reflectance product computed from MODIS-Terra/ MODIS-Aqua level 1B bands 1 and 2 with 250 m spatial resolution, which are centred at 645 nm (red) and 858 nm (infrared) respectively. The data have been corrected for the effect of atmospheric gases, aerosols and thin cirrus clouds and thus provide an estimate of the spectral reflectance as it would be measured at ground level in the absence of atmospheric scattering or absorption (http://modis-land.gsfc.nasa.gov/surfrad.htm, accessed 26 July 2007).

For each month from 2003 to 2006, one good-quality MOD09GQK or MYD09GQK covering the study area was downloaded from the NASA's Earth Observing System (EOS) data gateway (http://edcimswww.cr.usgs.gov/pub/imswelcome, accessed 26 July 2007). All downloaded images were first transformed from the Integerized Sinusoidal (ISIN) projection into the WGS 84/UTM zone 50N using nearest-neighbour resampling method. Then, to each image, a sub-image covering the study area was clipped from the larger original image. Finally, the area above 12.5 m was removed from further analysis with the support of digital elevation model (DEM).

2.6 Estimating Water Clarity

Wu et al. (2008) explored the relations between the visible bands of time-series MOD09GQK/MYD09GQK data and Secchi disk depth, and reported that the red band (R) could explain 85% of the variance of the logarithm of Secchi disk depth (SDD): $\ln(\mathrm{SDD}) = 0.76 - 14.72 \times R$, $R^2 = 0.85$. Therefore, we first implemented this model to estimate Secchi disk depths from the processed MODIS images using

ERDAS software (ERDAS Inc.), and created time-series Secchi disk depth maps with ArcGIS software (ESRI Inc.). Then, we obtained all the Secchi disk depth values within a circle with a radius of 750 m in the central lake from the developed maps. Finally, the mean of these obtained values was calculated to describe the seasonal water clarity pattern.

2.7 Exploring and Analyzing Seasonal Pattern of Water Clarity

We first combined the Secchi disk depths derived from time-series MODIS images and historically measured in the field, and explored the seasonal dynamics of water clarity. Then, ANOVA test was used to analyze the differences in water clarity against year and month respectively. Next, the average water level, maximum wind velocity and total precipitation of 3 days previous to each Secchi disk measurement were calculated, and a linear regression analysis of Secchi disk depth against the 3-day average water level, maximum wind velocity and total precipitation was carried out to explore the important variables affecting water clarity dynamics using Statistica (StatSoft Inc.). Finally, piecewise linear model was applied to analyze the relation between water clarity and water level.

3 Results

A false colour composite of the Landsat image combined with contour lines (Fig. 2) describes the general spatial pattern of vegetation distribution in Lake Dahuchi. The brownish region above 14 m corresponds to the zones of *Phragmites australis*

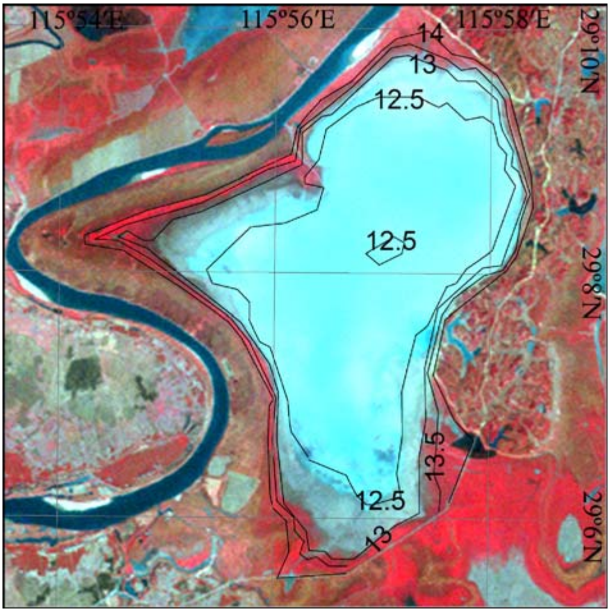

Fig. 2 A false colour composite of Landsat Thematic Mapper (TM) image captured on 29 November 2004 showing living (*red*) and dead (*brown-grey*) vegetation, bare soil (*light grey*), sediment-rich water (*light blue*) and contour lines in meter (National Vertical Datum 1985) in Lake Dahuchi

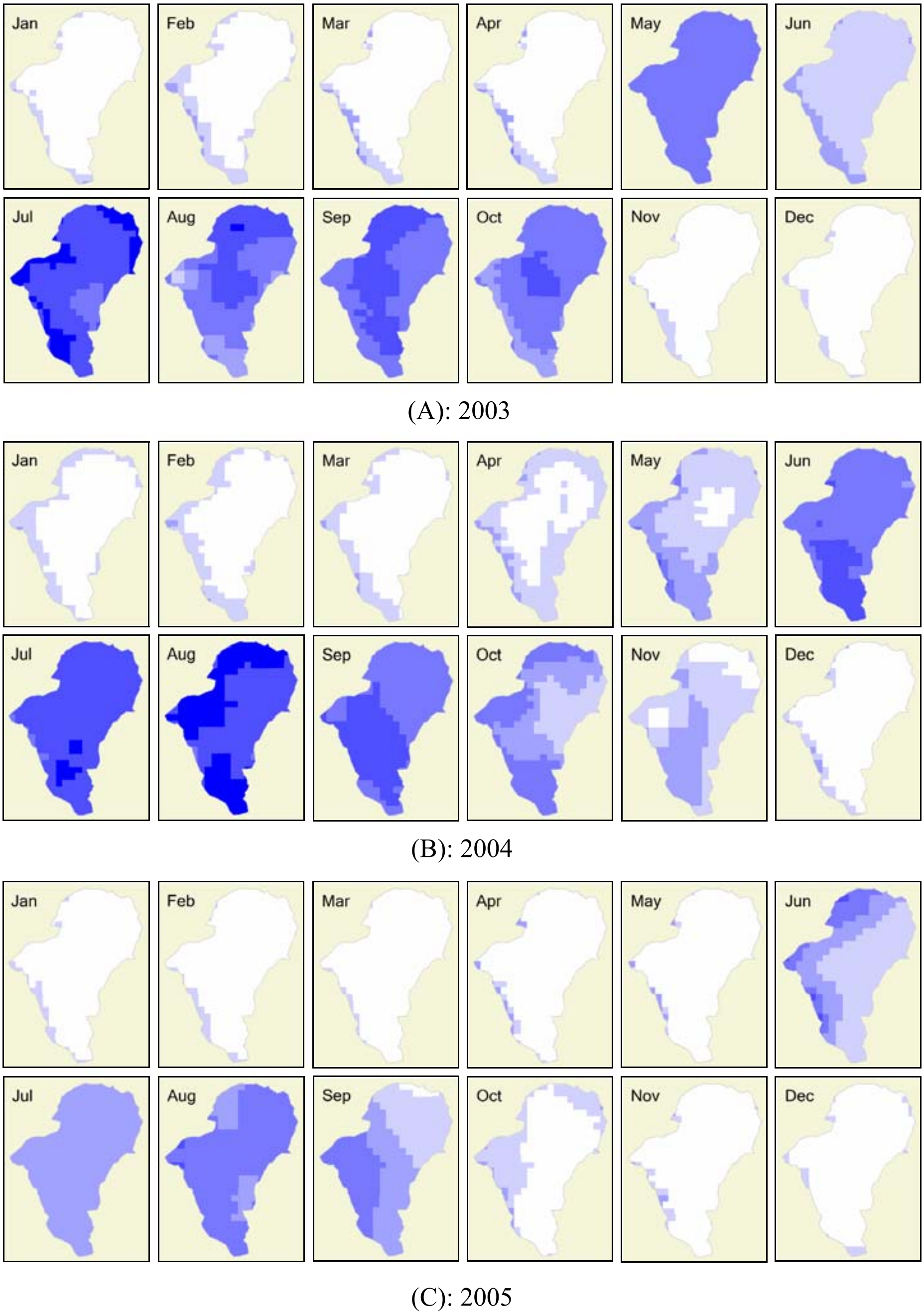

Fig. 3 Time-series Secchi disk depth maps derived from Moderate Resolution Imaging Spectroradiometer images for Lake Dahuchi from 2003 to 2006

and *Triarrhena lutarioriparia*. The red narrow belt between 13 and 14 m consists of winter-green grasses such as *Carex*. The area below 13 m showing up as bare soil and open water in November is vegetated in the summer by floating and submerged

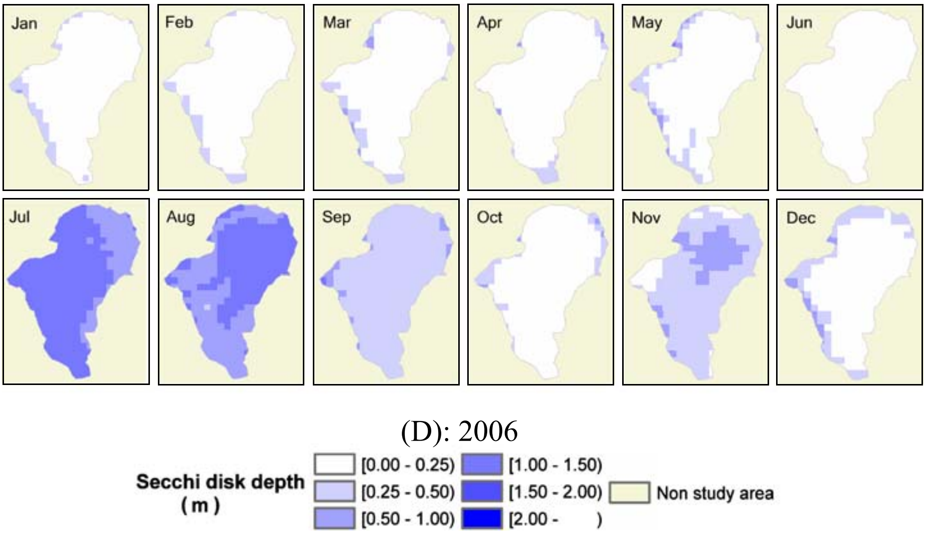

Fig. 3 (Continued)

aquatic plants, among which *Vallisneria spiralis L.* is dominant. The aboveground parts die off in late autumn leaving the below ground storage organs, the tubers, a staple food of three wintering bird species, Swan, Swan goose and Siberian crane.

Time-series of Secchi disk depth maps derived from the MODIS images (Fig. 3) reveal that Secchi disk depth was relatively homogeneous within Lake Dahuchi, with virtually no spatial difference in winter and spring and some variation in summer and autumn. The maps also suggest a seasonal pattern of water clarity, clear in summer (around June–August) and early autumn (around September–October) while turbid in spring (around March–May) and winter (around December–February). In the summer of 2006 lower water clarity occurred and the period with high clarity persisted for shorter duration than that in previous years.

Figure 4 (A) shows the Secchi disk depths of 2003–2006 derived from MODIS images and measured in the field, in which the number of MODIS image-derived Secchi disk depths account for around 28% of the total number. The figure reveals a general seasonal pattern of water clarity in Lake Dahuchi, namely, water clarity was lower in winter and spring, increased in April or May to reach the highest value in summer, upon which it gradually declined from September onward.

Figure 4 (B) also depicts the fluctuation of water level from 2003 to 2006 in Lake Dahuchi, and it reveals a general seasonal pattern of water level dynamics. The water level was lower in winter and early spring, and increased from late spring. It reached the highest level in summer, and began to decline gradually from late autumn. The increasing and decreasing trends in spring and autumn appeared regular. The water level fluctuated slightly in winter but widely in summer. The daily wind velocity is shown in Fig. 4 (C), which was weaker in summer, stronger in winter and moderate in spring and autumn. The precipitation mainly concentrated from April to June, and heavier precipitations occurred occasionally (Fig. 4 (D)).

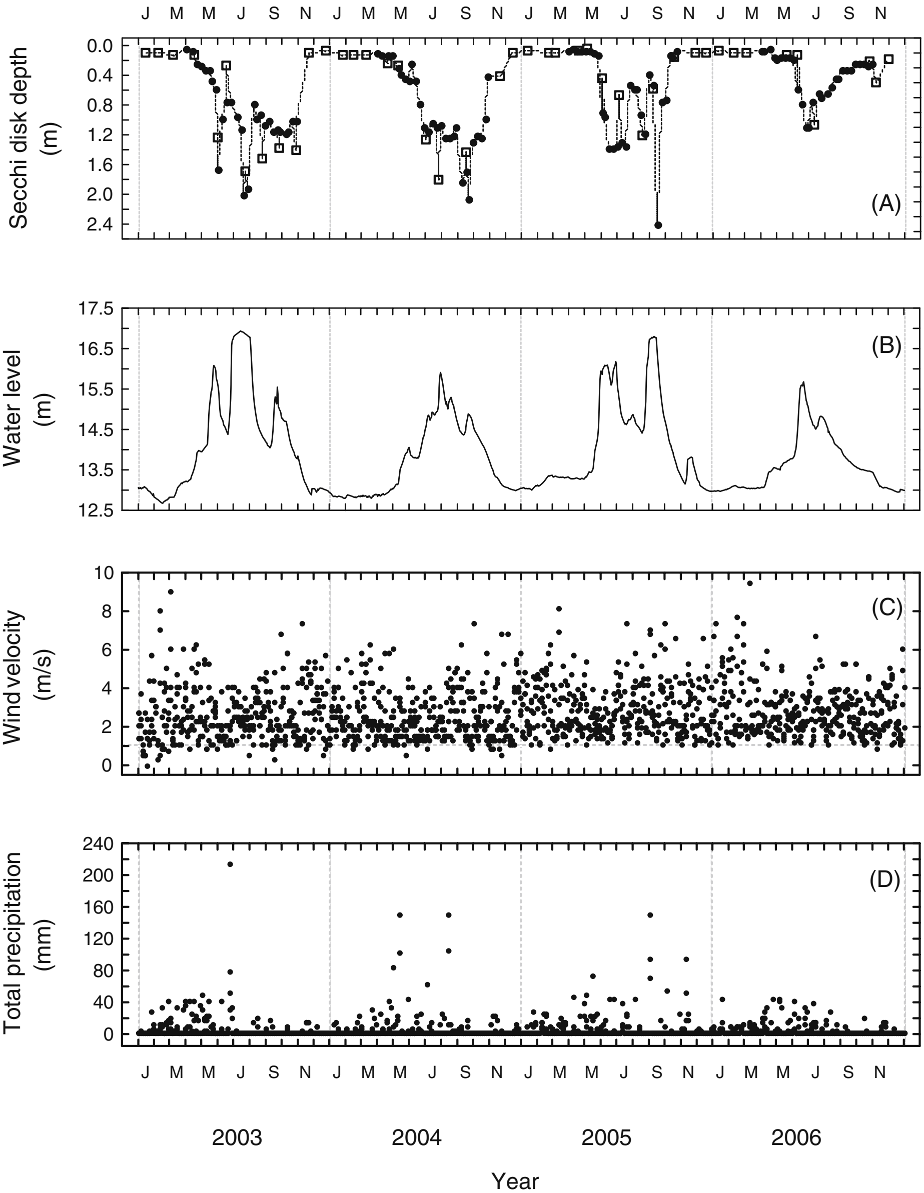

Fig. 4 (*A*): Secchi disk depth measured in the field (*filled circles*) and estimated from Moderate Resolution Imaging Spectroradiometer images (*empty squares*), (*B*): daily water level of Lake Dahuchi (National Vertical Datum 1985), (*C*): daily wind velocity, and (*D*): daily total precipitation at Yongxiu meteorological station

Figure 5 shows the Secchi disk depth averaged by year and month respectively, and ANOVA revealed that Secchi disk depth differed significantly between years ($F = 7.057$, $df = 3, 151$, $P < 0.001$) and months ($F = 13.707$, $df = 11, 143$, $P < 0.001$)

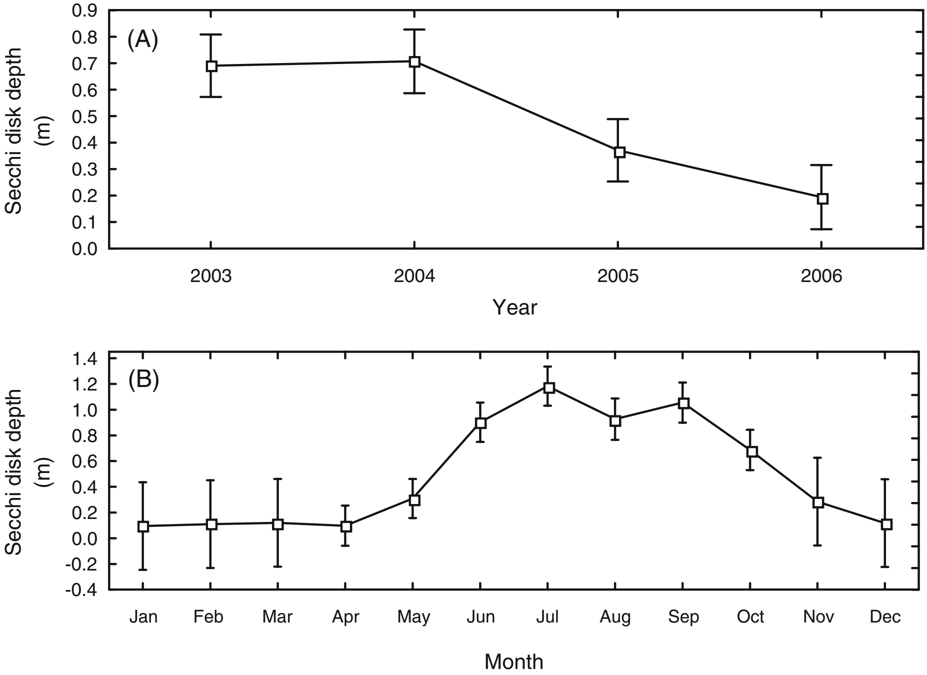

Fig. 5 Secchi disk depth averaged by year (**a**) and month (**b**). *Vertical bars* indicate 95% confidence intervals

respectively, which confirmed the above-mentioned yearly and seasonal variations of water clarity.

The multiple linear regression analysis of Secchi disk depth against water level, wind velocity and total precipitation revealed that the water clarity was significantly related to water level and wind velocity, but not to total precipitation.

Figure 6 revealed that the water level could explain 70% of the variation of the logarithm of Secchi disk depth (ln(SDD)) with the following piecewise linear model:

$$\ln(\mathrm{SDD}) = \begin{cases} -20.067 + 1.363 \times \mathrm{WL} & (\mathrm{WL} \leq 14.75) \\ -0.222 + 0.018 \times \mathrm{WL} & (\mathrm{WL} > 14.75) \end{cases} \left(R^2 = 0.70,\ F = 241.352,\ n = 155,\ P < 0.005\right)$$

The inclusion of wind velocity (WV) in the model improves the prediction of the model with R^2 from 0.70 to 0.72:

$$\ln(\mathrm{SDD}) = \begin{cases} -19.887 + 1.393 \times \mathrm{WL} - 0.217 \times \mathrm{WV} & (\mathrm{WL} \leq 14.75) \\ -0.712 + 0.093 \times \mathrm{WL} - 0.278 \times \mathrm{WV} & (\mathrm{WL} > 14.75) \end{cases} \left(R^2 = 0.72,\ F = 154.721, n = 155,\ P < 0.005\right)$$

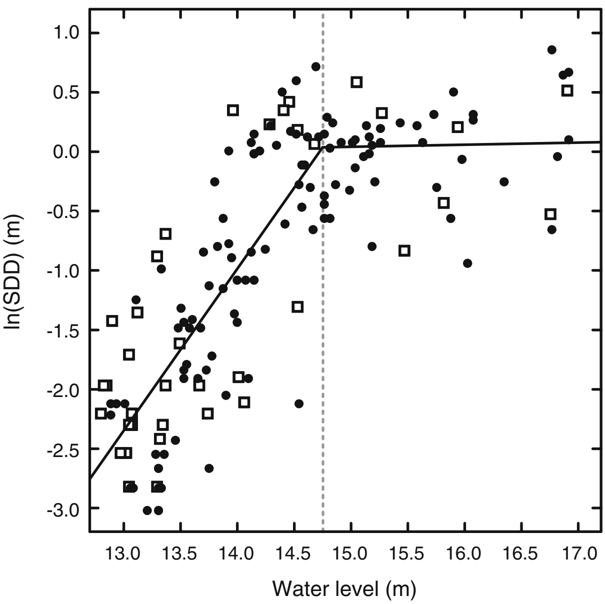

Fig. 6 Regression between the natural logarithm of Secchi disk depth (ln(SDD)) and water level of Lake Dahuchi from 2003 to 2006. Secchi disk depth: *filled circles*, measured in the field; *empty squares*, estimated from Moderate Resolution Imaging Spectroradiometer images

4 Discussion

It is difficult to describe and understand the seasonal pattern of water clarity in Lake Dahuchi using the in situ measurements alone, for they were only recorded from April to October and represented discrete data over a large, varying area. The combination of Secchi disk depth recorded in the field with that derived from MODIS images improved the understanding of seasonal water clarity variation.

Water clarity is regulated by chlorophyll a, inorganic suspended solid and coloured dissolved organic matter within the water column. The detailed information on these constituents is unknown in our study area. However, previous research showed that the water clarity of Poyang Lake was primarily controlled by suspended sediment concentration (Jin et al. 1990), and the sediment was composed of very fine silt and clay (Wu and Ji 2002).

The Secchi disk depth recorded in the field and derived from MODIS images together demonstrated that Lake Dahuchi had a seasonal pattern of water clarity. Water was turbid in late autumn, winter and spring when water levels were below around 13.5 m and clear in summer with levels above about 14.5 m. We attribute this pattern to sediment resuspension by wind-induced waves occurring when the scouring effect of waves exceeds the resistance of the soil to erosion. Given the wind speeds and fetch of the lake, waves with wavelength of 10–20 cm are likely to occur. These may scour the sediment up to 20 to 40 cm depth or more depending on the resistance of the sediment. The bare sediment was restricted to the region below 13 m in winter and spring seasons, waves thus may scour the sediment up to water levels of 13.2 to 13.4 m. This corresponds remarkably well with the water levels above which waters become less turbid according to Fig. 6. When the lake extends with the increasing water level in later spring, its shallow fringe where waves scour the bottom most intensively moves outward from the bare sediments to the grassland belt shown in Fig. 2, which will limit the wave-induced sediment resuspension, and as a result the turbid water becomes clear. Therefore, we suggest that these grasses reduce the resuspending impact of waves and cause the lake water to switch from turbid to clear. In Poyang system there are many lakes similar to Lake Dahuchi while being surrounded by vegetation and having fluctuating water levels, and we suggest that the same variation in water clarity would appear in these lakes with similar controlling processes. It would be interesting to further study the role of this vegetated fringe in controlling water clarity dynamics of these peripheral lakes of Poyang.

Above we attributed the declined water clarity at low water levels to the effects of wind. Biotic factors may, however, also resuspend the sediments in shallow lakes. Fish tend to stir up sediment while foraging on the lake bottom, causing an increase in suspended solids and decline in water clarity (Scheffer 1998) due to their spawning and feeding activities in shallow water, which not only causes re-suspension of bottom soils, but is detrimental to shallow water vegetation that helps protect shorelines from wind-induced wave action. So, it cannot be excluded that fish resuspend sediment in Lake Dahuchi as the lake is rich in fish. In addition, tens thousands of waterfowl winter in Lake Dahuchi every year. Among these are the three species of tuber feeders which actively reduce the density of tubers and rhizomes of *Vallisneria* while the swan goose forages on the rhizomes of *Carex* species which stabilize the substrate in the vegetated fringe. We postulate that the birds might reduce the resistance of the sediments against the sheer stress of the waves of the lake, and suggest that their foraging might enhance the resuspension of sediment in Lake Dahuchi and similar lakes.

5 Conclusion

In this study, we explored the seasonal dynamics of water clarity using the Secchi disk depths recorded in the field and derived from MODIS images together and analyzed how water level, wind velocity and total precipitation influenced this dynamics in Lake Dahuchi, China. The principal results obtained can be summarized as follows:

1. The Secchi disk depths recorded in the field and derived from MODIS images together demonstrated a seasonal pattern of water clarity.
2. The seasonal dynamics of water clarity was mainly regulated by seasonal variation of water level, which influences the resuspension of sediment, a dominant factor controlling the water clarity in Lake Dahuchi.
3. The combination of Secchi disk depth recorded in the field with that derived from MODIS images improved our understanding to the seasonal dynamics of water clarity.

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