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ORIGINAL PAPER

Long-term periodic structure and seasonal-trend decomposition of water level in Lake Baiyangdian, Northern China

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Abstract Water level, as an intuitive factor of hydrologic conditions, is of great importance for lake management. In this study, periodic structures of water level and its fluctuations in Lake Baiyangdian are analyzed based on wavelet analysis and seasonal-trend decomposition using local error sum of squares (STL). Data of monthly time series are divided into three types with emphasis on anthropogenic influence from water allocation. It is found that intra-annual characteristics of water level fluctuations are the common periodic structures. Water allocation alters the periodic structures by decreasing and weakening the oscillations of water level, compared with the slight effects of natural hydrologic water supplies and short-term climate changes. An irregular water level decline and short-term oscillation with irregular periodicity are deduced from seasonal-trend decomposition analysis using STL. With seasonality depicted monthly, the influence of water allocation implies irregular oscillations with high-frequency components, especially for monthly changes. The water level fluctuations are influenced by seasonal changes, as demonstrated by three types of time series. The impacts of water allocation on seasonality show the differences with continuous single-peak oscillations representing no influences and continuous double-peak oscillations representing frequent influences. Furthermore, the accumulation of water allocation shows a slight rising trend in average monthly level fluctuations over the last several years. The study helps understand periodic structures and long-term trend changes of water level fluctuations, which will facilitate lake management of Lake Baiyangdian.

Keywords Periodic structure · Water level fluctuation · Wavelet analysis · Seasonal-trend decomposition analysis using local error sum of squares · Lake Baiyangdian

Introduction

As one of several hydrologic factors, water level is an important indicator in lake management (Angel and Kunkel 2010; Leeben et al. 2012) and is an intuitive factor indicating water availability for shallow lakes. Water level fluctuations are decisive elements in hydrology, especially for shallow lakes embedded in wetlands that are particularly sensitive to any rapid change in water level and input (Coops et al. 2003). Therefore, water level fluctuations may have an overriding effect on the ecology, functioning, and management of such lakes. Water levels in shallow lakes naturally fluctuate intra- and inter-annually depending largely on regional and global climate changes, seasonal variations in meteorological conditions, and human activities (Keenlyside et al. 2008; Küçük et al. 2009; Omute et al. 2012). Actually, water level fluctuations are induced by change to the water budget, such as the amounts of precipitation and evaporation, catchment size and characteristics, and water inflow and outflow conditions of the

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basin. Water level fluctuations are considered as an intuitive factor of early warning for lake health that link climate changes and anthropogenic interferences.

Such fluctuations are not a recent phenomenon and have varied for a long time (Jay Baedke and Alan Thompson 2000; Chenini et al. 2008; Liu et al. 2013). The fluctuations and their ecological and socioeconomic consequences have been investigated in many large lakes (Chowdhury and Rahman 2008; Wang and Yin 2008; Saleh et al. 2011). Lake Baiyangdian is the largest shallow freshwater lake in North China. In recent decades, it has shrunk and dried up several times since 1980s, as the result of climate changes and human activities. Thus, water allocations are important for water balance of the lake. These have been implemented over decades, especially during the last one. However, it is unclear whether such allocations have the potential to threaten the natural periodic structures of water level fluctuations. Therefore, it is necessary to clarify the periodic structures and to assess potential effects of disturbances in water allocation..

With respect to inter-annual water level fluctuations of lakes, the influences of hydrologic, meteorological, and geophysical processes are usually negligible. This is because their amplitudes are generally less then 10 cm and only slightly increase the scatter of water level time series (Cengiz 2011). In fact, in mean water level computation, most of these local processes approach zero at the scale of selected time series of the lake, assuming homogeneous sampling of surface patterns (Hofmann et al. 2008; Shirmohammadi et al. 2013). Thus, to better understand the long-term complex nature of water level fluctuations, the wavelet transform method is a powerful tool for analyzing nonstationary time series, as well as an exploration of interest changes with inner/over the last few years in water resources. Wavelet analysis and global spectrum methods have been applied in hydrologic and meteorological systems in multivariate phenomena for many studies (Labat et al. 2005; Küçük and Agiralioglu 2006; Wang et al. 2012a). The wavelet spectrum based on continuous wavelet transform is three-dimensional, in that energy is manifests as contour lines plotted in the time–frequency domain (Rajaee et al. 2010). This of course provides an ideal opportunity to examine energy variations in terms of location and timing of hydrologic events (Labat 2008).

As for intra-annual level fluctuations of lake level, all external natural superimposed factors are usually considered negligible, since their amplitudes are generally less than 20 cm and thus only slightly increase the scatter of water level time series. The variability of water level responses significantly changes in water supply from water allocation or the China South-to-North Water Transfer Project (Cui et al. 2010), as well as from rainfall or cyclical modifications to the evapotranspiration regime. Such variability results from the customary seasonal oscillation and from the superimposed effect of several nonseasonal forcing factors. Variation of the seasonal cycle has been studied using seasonal-trend decomposition using loess (local error sum of squares) (STL) method for water level (Lenters 2001; Sellinger et al. 2007) and nutrient trend (Qian et al. 2000; Wang et al. 2012b). In this case, the trend of water level fluctuations in Lake Baiyangdian can be decomposed to depict intra-annual water level variation, using STL method. Furthermore, unusual water level fluctuations are often discernible in spite of the time that water resides in the lake. This residence time usually strongly modulates the hydrologic regime. The resulting high- and/or low-frequency oscillations may turn water level fluctuations into indicators of recent historical climate changes (Jöhnk et al. 2004; Kebede et al. 2006; Zhao et al. 2013). Therefore, it is important to study the periodic structure of water level fluctuations over both long-term period and a seasonal short-term periods, which can help understand the mechanism of lake hydrologic cycle.

In this paper, long-term time series data of water level during 1950–2009 are used to inspect trends and harmonic behavior in water level time series of Lake Baiyangdian, Northern China. To investigate the characteristics of water level fluctuations, we propose three intervals of time series: integrate full, interceptive less anthropogenic influence, and increased anthropogenic disturbance. Our main objectives are to (1) describe long-term periodic structural characteristics of water level fluctuations in the time domain, with an emphasis on interferences of water allocation; (2) reveal the characteristics of seasonal water level variation, incorporating effects of nature and human activity; and (3) propose an effective assessment method for periodic structures of water level fluctuations.

Materials and methods

Study site and background

Lake Baiyangdian, in the central North China Plain, is located 130 km south of Beijing (48°43′–39°02′N and 115°38′–116°07′E) (Fig. 1). The lake consists of more than 100 small and shallow lakes, linked by thousands of ditches. The lake surface area is 366 km^2, with the catchment area of 31,200 m^2. Lake depth varies with hydrologic conditions, but is usually less than 2.0 m (Xu et al. 1998). Annual mean precipitation is less than 450 mm, and annual mean ambient temperature is less than 17 °C under climate changes. With average annual runoff of 3.57×10^9 m^3, the lake has a vital roles in flood reservation, environmental pollution decomposition, and others. However, Lake Baiyangdian has shrunk and dried

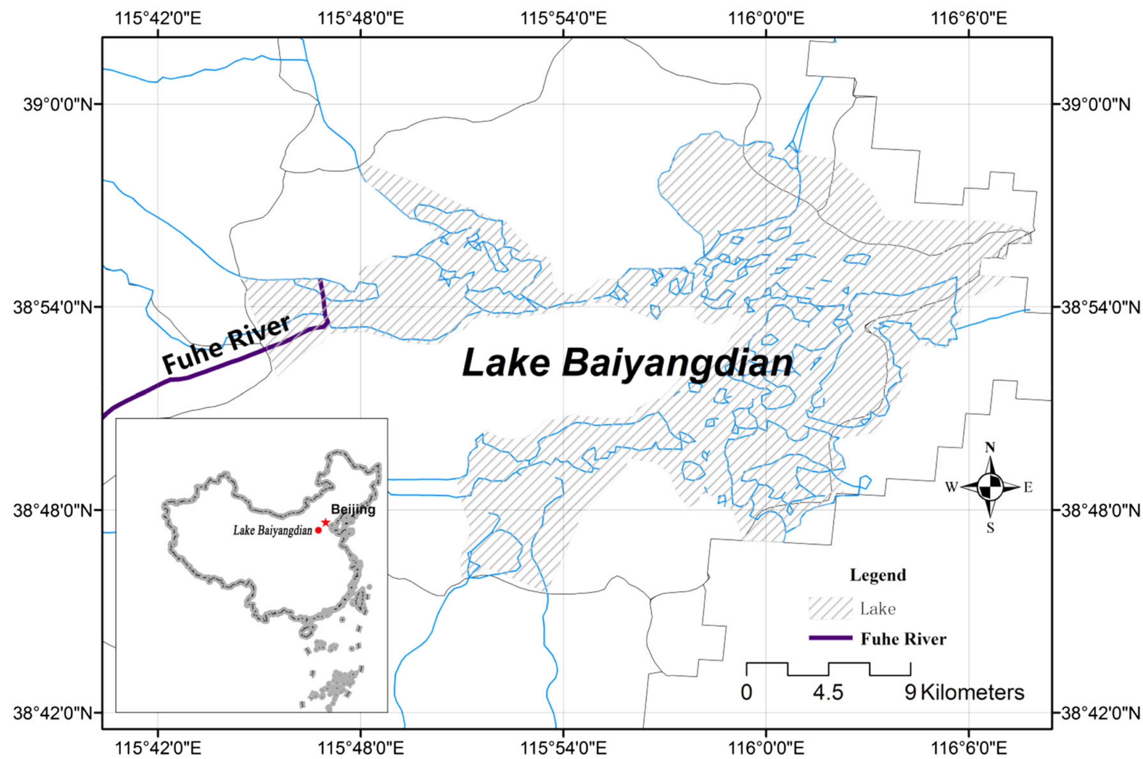

Fig. 1 Geographical location of Lake Baiyangdian, North China

Table 1 Recent implementations of water allocations to Lake Baiyangdian (2000–2009)

Time period of water allocation	Reservoir	Discharge out of the reservoir (10^4 m^3)	Discharge flow into the lake (10^4 m^3)
Jul 2000	Angezhuang	3,111	1,800
Dec 2000–Jan 2001	Wangkuai	7,902	4,060
Feb 2001–Mar 2001	Angezhuang	3,287	2,164
Jun 2001–Jul 2001	Wangkuai	9,079	4,513
Feb 2002–Mar 2002	Xidayang	5,015	3,501
Apr 2002–May 2002	Xidayang	3,873	1,974
Jul 2002–Aug 2002	Wangkuai	6,108	3,104
Jan 2003–Ma 2003	Wangkuai	20,000	11,634
Feb 2004–Jun 2004	Yuecheng	39,000	16,000
Mar 2005–Apr 2005	Angezhuang	5,863	4,251
Mar 2006	Angezhuang	3,200	828
Mar 2006–Apr 2006	Wangkuai	9,000	4,844
Nov 2006–Mar 2007	The Yellow River	20,000	10,010
Jan 2008–Jun 2008	The Yellow Rive	31,200	15,660
Jun 2009–Jul 2009	Angezhuang	6,974	1,725
Nov 2009	The Yellow Rive	20,000	10,000

up frequently since the 1980s, when the water level is less than 5.5 m. Moreover, the lake is a monomictic lake with only one entrance receiving pollutant emissions from Fuhe River (Fig. 1). Recently, the lake has suffered eutrophication and much of the area has been converted to swamps because of nutrient overload. Consequently, water resources of the lake benefit substantially from China South-to-North Water Transfer Project. In addition, water allocation scheme has been implemented at least once per year in Lake Baiyangdian since 1990s (Cui et al. 2010). In the period of 2000–2009, water level of the lake is frequently influenced by such water allocations (Table 1), which has significantly changed natural patterns of water level fluctuations.

Data sources and classification of water level time series

Monthly hydrologic data of water level time series from 1950 to 2009 were obtained from the Agency of Environmental Protection of Anxin County, Hebei Province. Considering the influences of artificial dam in upstream of the lake since 1980s, three intervals of water level time series data are representative of different scenarios. Water level I covers the entire time series from 1950 to 2009, and water level II (intercepted from water level I) represents the time series with no anthropogenic disturbances by water allocation (1950–1959), while water level III time series is characterized by various and frequent anthropogenic water allocations (2000–2009).

Methods

To analyze the temporal variability of long-term water level fluctuations, we use continuous wavelet transform and Fourier power spectrum analysis.

Spectrum analysis deals with the identification of cyclical patterns in data. Data windowing is used to smooth the power spectrum, thereby reduce its variance and increase statistical confidence, although this may cause spectral leakage (Cazelles et al. 2008). To reach a compromise between strong smoothing (more confidence but stronger bias) and weak smoothing (less confidence but less bias) with acceptable spectral leakage, power spectrum estimations are generated by applying a smoothing Hamming window of variable length (Torrence and Compo 1998).

To investigate periodic structures of lake water level fluctuations, monthly time series data were selected. Two harmonic tools were applied to these data series: classical Fourier analysis and continuous wavelet transform. The classical Fourier transform uses sine and cosine base functions of infinite span. It is globally uniform in time, and only reveals the presence of spectral components (Lau and Weng 1995). We used the conventional power of two fast Fourier transform procedures. Decomposition of time series into time–frequency space permits determination of both the dominant modes of variability and their temporal variation. Water level time series were analyzed by classical Fourier analysis and continuous wavelet transform using the Morlet wavelet (Meyers et al. 1993).

Assuming a continuous time series $x(t)$, $t \in [\infty, -\infty]$, a wavelet function $\psi(\eta)$ that depends on a nondimensional time parameter η can be written

$$\Psi(\eta) = \Psi(\tau, s) = s^{-1/2}\Psi\left(\frac{t-\tau}{s}\right) \tag{1}$$

where t is time, τ is the time step over which the window function is iterated, $s \in [0, \infty]$ is for the wavelet scale. $\psi(\eta)$ must have zero mean and be localized in both time and Fourier space.

The continuous wavelet transform is expressed by convolution of $x(t)$ with a scaled and translated $\psi(\eta)$:

$$\Psi(\tau, s) = s^{-1/2} \int_{-\infty}^{+\infty} x(t)\Psi^*\left(\frac{t-\tau}{s}\right)\mathrm{d}t \tag{2}$$

where * denotes complex conjugate. By changing varying both s and τ values gradually, one can construct a two-dimensional picture of wavelet power.

As for global wavelet spectrum, if a vertical slice through a wavelet plot is a measure of the local spectrum, then the time-averaged wavelet spectrum over all periods or all the local wavelet spectra is

$$\bar{W}^2(s) = \frac{1}{T}\sum_{t=0}^{T-1} |W_t(s)|^2 \tag{3}$$

where T is number of points in the time series, $|W_t(s)|$ denotes wavelet modulus or wavelet absolute value, $|W_t(s)|^2$ is the wavelet power, indicating the frequency (or scale) of peaks in the spectrum of $x(t)$, and how these peaks change with time.

The time-averaged wavelet spectrum is generally called the global wavelet spectrum (Torrence and Compo 1998). The frequency (or scale) and temporal changes of peaks in the spectrum of $x(t)$ can be indicated with $|W_t(s)|^2$, showing how these peaks change with time (Eq. 3).

The smoothed Fourier spectrum approaches the global wavelet spectrum as the amount of necessary smoothing decreases with scale. The latter spectrum provides unbiased and consistent estimation of the true power spectrum and is a useful tool for nonstationary time series analysis. The global spectrum is compatible with a power spectrum. In the latter, spectral components are defined as frequency, and periodic components are ordered according to period scales within a global wavelet spectrum. In addition, since a global spectrum is calculated using a continuous spectrum, the starting and finishing time of the periodic components can be obtained.

To evaluate overall patterns within intra-annual variations for the entire water level series (1950–2009), we use a graphically based approach, i.e., the STL method. The method is an iterative nonparametric procedure using repeated loess fitting (Sellinger et al. 2007). A time series of monthly monitoring data may be considered a sum of three components: high-frequency seasonal, low-frequency, long-term (or trend), residual (variation not explained by time). These are expressed as

$$Y_{\text{year,month}} = T_{\text{year,month}} + S_{\text{year,month}} + R_{\text{year,month}} \tag{4}$$

where $Y_{\text{year,month}}$ is the observed value for a given year and month, $T_{\text{year,month}}$ is the trend component, $S_{\text{year,month}}$ is the seasonal component, and $R_{\text{year,month}}$ is the residual term.

Although the median polish process uses median values for the trend and seasonal components, the STL method uses one continuous loess line for the long-term trend component and 12-month-specific loess lines for the seasonal component. As with median polishing, fitting is done on each component iteratively, until the resulting trend and seasonal components are no longer different from the estimates of the previous iterations. The nonparametric nature of the STL makes it flexible in revealing nonlinear patterns in seasonal data. Because each month is a subseries in the fitted loess model, the seasonal pattern can evolve with time, thus revealing changes in timing, amplitude, and variance in the seasonal cycle. As with all nonparametric regression methods, the STL requires subjective selection of smoothing parameters. There are two smoothing parameters in the model, representing the window widths of the seasonal and long-term components. We chose window widths of 21 and 61 months, respectively, to visually elucidate trends.

Results and discussion

Descriptive statistics

Descriptive statistics (maximum, minimum, mean and standard deviation) of three time intervals of monthly water level are shown in Table 2. Intuitively, compared with water level II, water level III indicates decline values, indicating possible disturbance by upstream anthropogenic artificial dams. This is because that the frequently water allocations during 2000–2009 became important in the water supply of Lake Baiyangdian (Table 1).

Wavelet analysis

Continuous wavelet transform

To analyze time-scale localization of the periodical signals in the water level series, we used continuous wavelet transform analysis. Figure 2 shows the real part of the continuous Morlet wavelet spectra for the water level time series. Figure 2a shows with confidence intra-annual (<12 month) and near-half-decadal ($\sim$60 month) oscillations in water level I. The intra-annual structure persists through the entire record period, whereas the near-half-decadal signal was stronger since beginning in the 1950s. In the periods of water levels I and II, both intra-annual (<12 month) and $\sim$20-month periodic structures are obvious throughout the entire records (Fig. 2b, c). The real part of wavelet spectra in the three intervals time series shows the common characteristic of intra-annual water level fluctuations. The results indicate that intra-annual water level change is the inherent periodic structure that is unaffected by the anthropogenic influences. This is the possible explanation of short-term influences of climatic changes.

The wavelet power spectrum

Power of the wavelet transform ($|W_t(s)|^2$ in Eq. 3) for the monthly water level fluctuations in Lake Baiyangdian is shown in Fig. 3. The square of absolute value gives information on relative power at a certain scale and period. Figure 3a–c shows the actual oscillations of wavelets in three time intervals, rather than just their magnitude. The wavelet power spectrum reveals that the highest energy occurs for water level time series. Periods of greater energy changes for water level I are from 6–16 and 16–32 months (Fig. 3a). Global variance of water level shows that the periodic structures of 6 and 16 months are above the 95 % confident level (Fig. 3d). For water level II and III, the wavelet power spectra reveal an obvious difference of the highest energy appearance, relative to the results from real part of continuous wavelet transform. The period of the greatest energy occurring for water level II is centered on 12 months, and there are relatively weaker periods of 2 and 6 months that persist for very short period (Fig. 3b). However, there are no higher energy periods for water level III, only several weak and short time periods scattered throughout the entire time series (Fig. 3c). The global variance indicates that the periods of 6 and 12 months are above 95 % confident level for water level II (Fig. 3e), as is the periods of 6 months for water level III (Fig. 3f). The results of both wavelet power spectrum and global variance indicate the periodic coherence with water levels II and I. The wavelet power spectrum for water level III shows less obvious differences, and the global variance only shows the common 6-month periodic changes. Moreover, the durations of higher energy oscillations for water level III appear shorter.

Intra-annual fluctuations

Although above wavelet analysis shows multiple time-scale variations in water level, intra-annual variations were

Table 2 Descriptive statistics for water level time series

Variables	Duration time	Unit	Max.	Min.	Mean	SD
Water level I	Jan 1950–Dec 2009	m	11.15	3.24	7.61	±1.27
Water level II	Jan 1950–Dec 1959	m	11.15	7.49	8.90	±0.78
Water level III	Jan 2000–Dec 2009	m	7.57	5.70	6.75	±0.46

Water levels I, II and III are measured referencing DaGu elevation as a benchmark

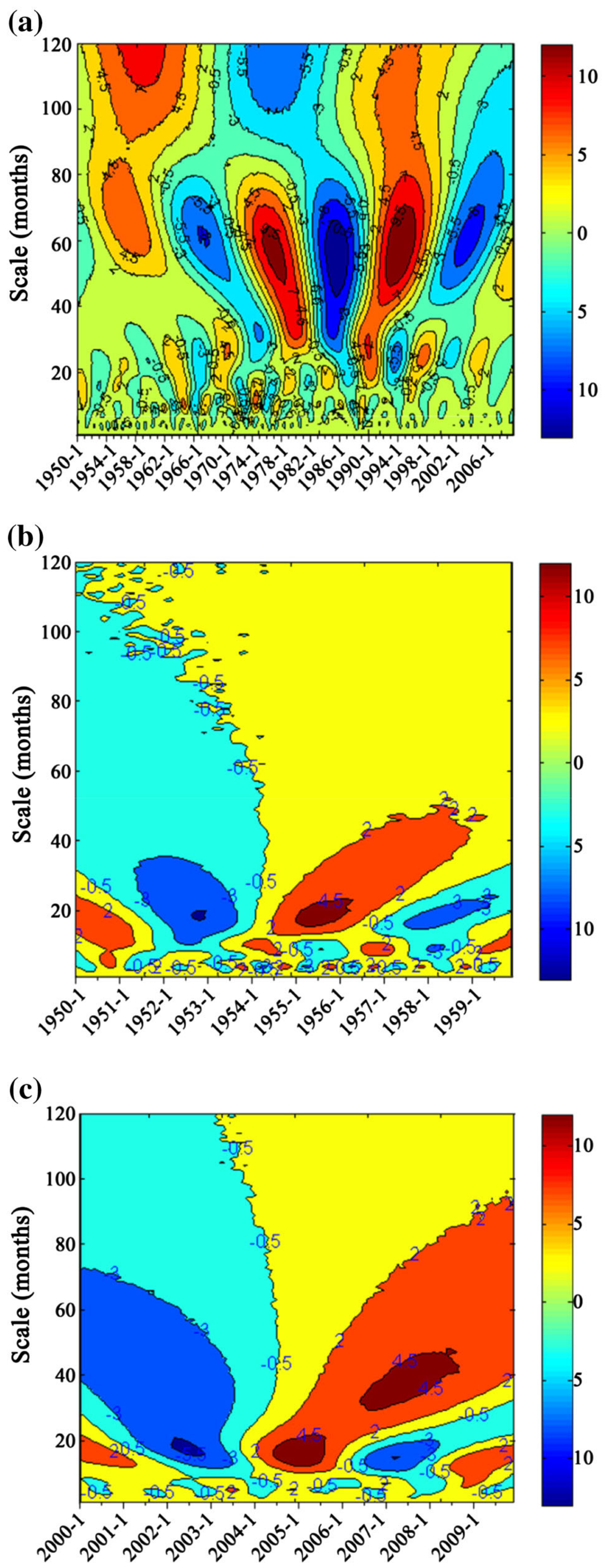

Fig. 2 Real part of the continuous Morlet wavelet spectra for water level I (**a**), water level II (**b**), and water level III (**c**)

detected for all three interval time series. We are also mainly interested in intra-annual fluctuations (<12 months), which correspond to periodic management decisions in practice. Consequently, we determined the global average variance to the interested component. Figure 4 shows the intra-annual average variances of three interval water level time series. For water level I, there were high-confidence, intra-annual water level variations from the beginning of the 1950s to the end of the 1980s (Fig. 4a). For a long time, there were fewer fluctuations with confident levels above 95 % in period of water level III, but clear fluctuations in the period of water level II (Fig. 4a). There were similar results from the separate analysis in water level II and water level III (Fig. 4b, c). Regarding the recent insufficient water resources and frequent water recharges, water level variations in Lake Baiyangdian are largely modulated by discharges from upstream reservoirs, in addition to the quantity of water resources. Both natural hydrologic water supplies and short-term climate changes contribute less to the water level fluctuations in the period of water level III.

STL results

Seasonal water level change is one of the main types of intra-annual water level fluctuations. We know that intra-annual water level fluctuations in recent years demonstrate an negligible effect on natural hydrologic water supplies and short-term climate changes. Thus, we studied long-term and seasonal trends in water level fluctuations using the STL method in the last decade. The nonparametric nature of the STL approach makes it possible to identify nonlinear trends and seasonal interactions that would be missed by traditional trend detection methods. STL decomposes the water level time series into three components: a smoothed long-term trend (Fig. 5a), a seasonal cycle of varying amplitude (Fig. 5b), and residuals (Fig. 5c). The long-term trend line indicates an irregular water level decline occurring before the end of 1980s and a short-term oscillation with an irregular periodicity (Fig. 5a). After the end of 1980s, there was an irregular water level rise. This is consistent with events during the late 1980s, when water allocation gradually became a vital inflows to Lake Baiyangdian. Similar timing nodes also occur in seasonal cycles of variable amplitudes (Fig. 5b). With seasonality depicted by month (Fig. 5d), we see that the overall pre-1980s decline is accentuated in autumn, indicated by declining seasonal components from September to November. There is dampening in spring–early summer, indicated by increasing components from March to July. Continuous monthly average water levels in the period of water level

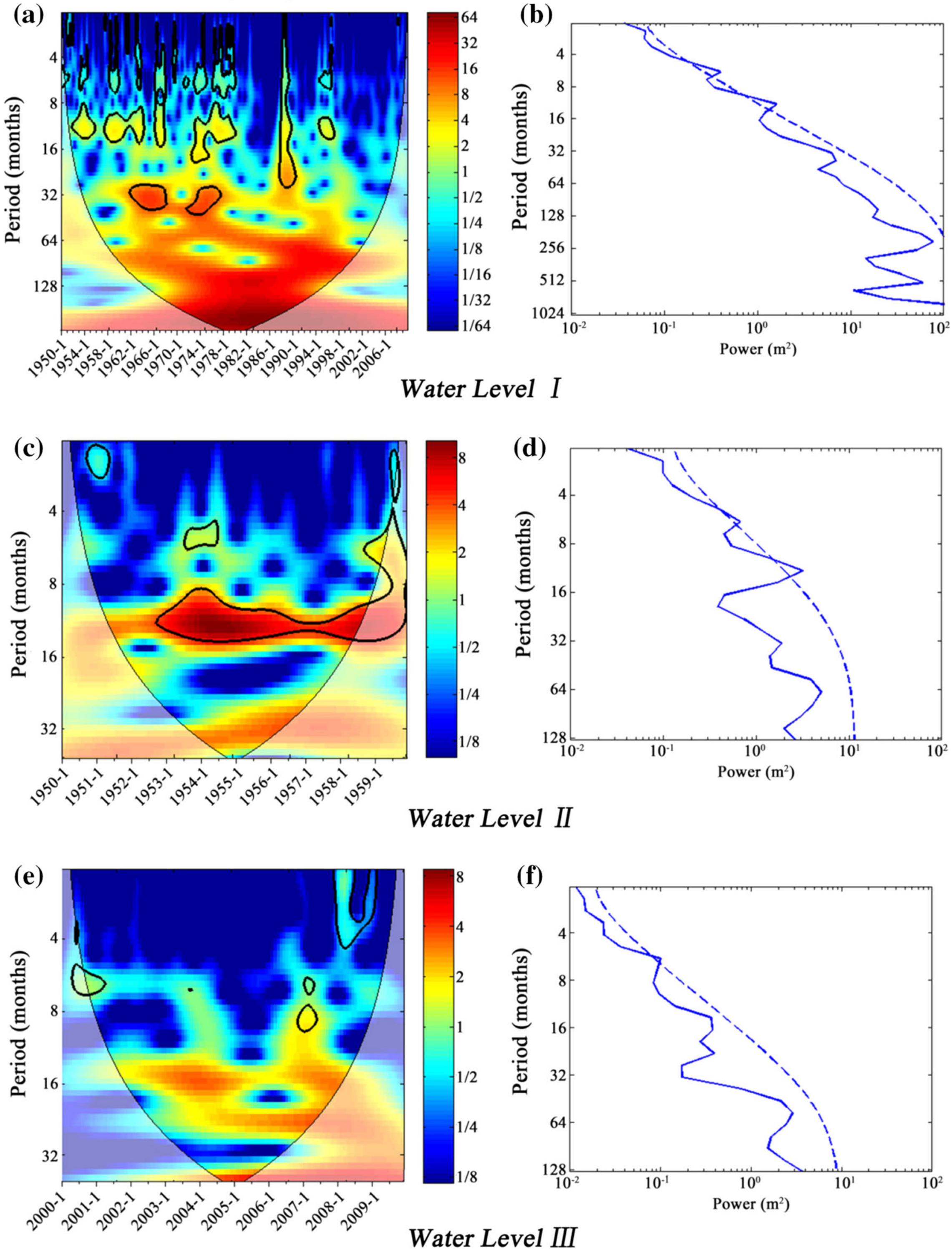

Fig. 3 Wavelet power spectrum using Morlet mother wavelet for water level I (**a**), water level II (**c**), and water level III (**e**). The relative low-resolution region is the cone of influence, where zero padding has reduced the variance. *Black contour* is the 5 % significance level, using a white-noise background spectrum. The global wavelet variance (*solid line*) for water level I (**b**), water level II (**d**), and water level III (**f**), and the *dashed line* is the confidence for the global wavelet variance, assuming the same confidence level and background spectrum as in power spectrum

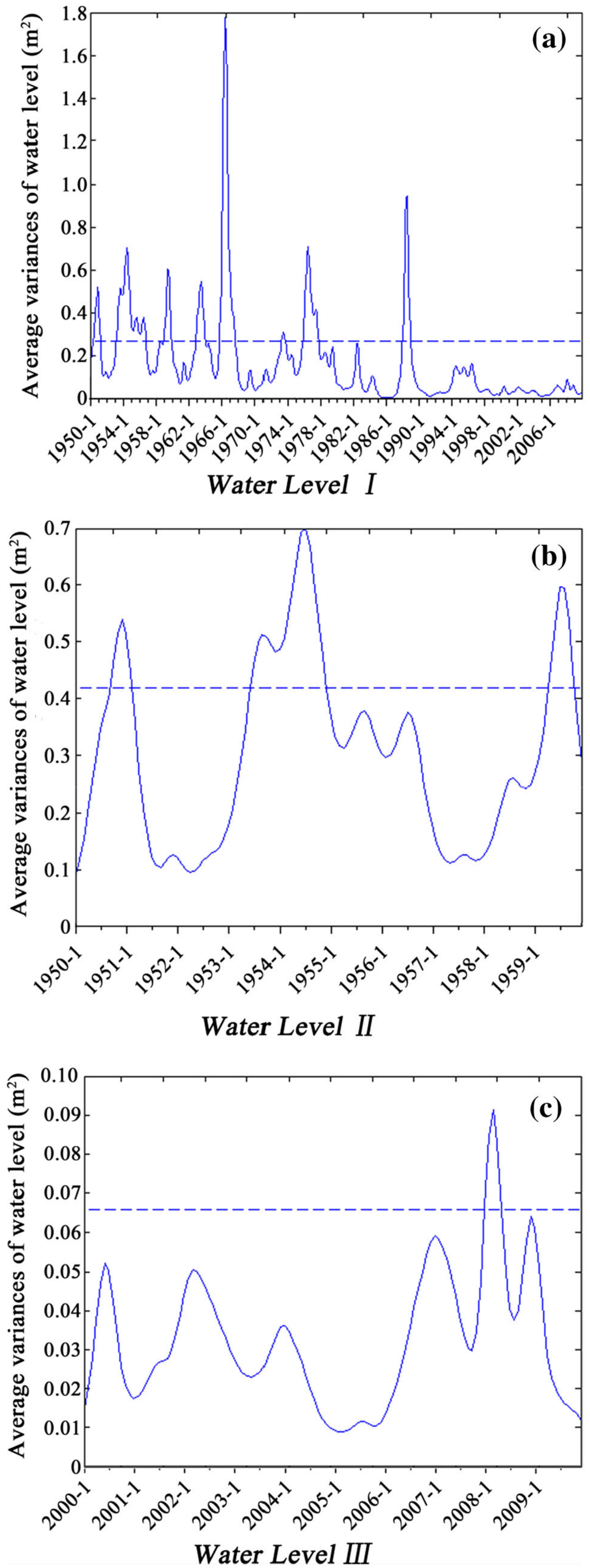

Fig. 4 Intra-annual average fluctuations for water level I (**a**), water level II (**b**), and water level III (**c**) based on wavelet global variance. The *dash line* means 95 % confident level

I indicate a decrease trend from January to June and an increase from July to September (Fig. 5d), which indicate clear variation of seasonal fluctuation ranges (Fig. 5b). The monthly average water level decline in spring points to a huge water demand for use on land. Integrated water recharge via precipitation and evaporation causes water level increasing in summer, with a subsequently decline because of less precipitation in the fall. The fluctuation mode for the water level I period implies a response to climate changes. Variations of the seasonal component can be adequately depicted by monthly changes. However, obvious changes in the seasonal fluctuation range can be a possible interpretation for increasing effects of water allocation or anthropogenic interferences after 1980s.

To investigate differences of natural fluctuations and disturbing fluctuations, STL analysis was done for water level II and water level III. The smoothed trend of water level II is consistent with the trend of water level III during first 6 years. The curves show completely different trends in the remaining periods, with declining in water level II (Fig. 6a) and rise in water level III (Fig. 6d). With seasonality depicted by month, the differences lie in changing frequencies. In the period of water level II, seasonality is shown by single-peak changes (Fig. 6b). However, for the water level III period, there are double-peak changes in seasonality curves (Fig. 6e). Continuous monthly average water level trends in the water level II period are coincident with those in the water level I period (Fig. 7a), which implies influences from climate changes. However, seasonal fluctuations in the water level III period have different trends, with drastic changes in spring and slight ones in fall (Fig. 7b). Nevertheless, very weak trends of seasonal level fluctuations in the water level III period still show the potential influence of climate changes. These results demonstrate the effects of water allocation on water level fluctuations. There was frequent water allocation in winter to guarantee the maximum water level in spring (Cui et al. 2010). The water level was affected by intra-annual climate changes until the following water allocation.

Long-term periodic structure of water level fluctuations

Three long-term time series data with emphasis on anthropogenic disturbances were used to detect periodic structures of water level fluctuations in Lake Baiyangdian. From the real part of the wavelet analysis, there was intra-annual periodic structure (<12 month) in all three time series. This result is similar to those of Cengiz, which demonstrated that annual cycle events are generally characterized by periodicities in water level fluctuations

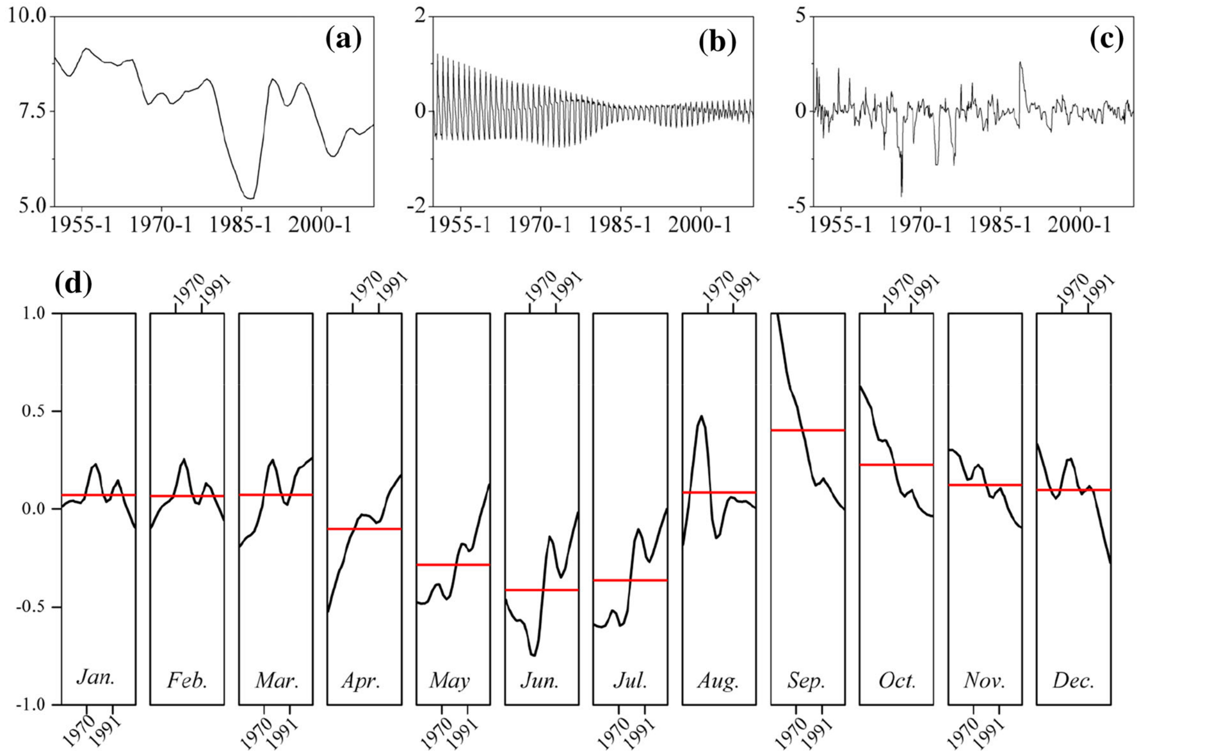

Fig. 5 Results of the STL method with depicting the long-term water level I component (**a**), seasonal component (**b**), and residuals (**c**). *Red Solid horizontal line* in the (**d**) is the long-term mean of monthly trends for each month from 1950 to 2009

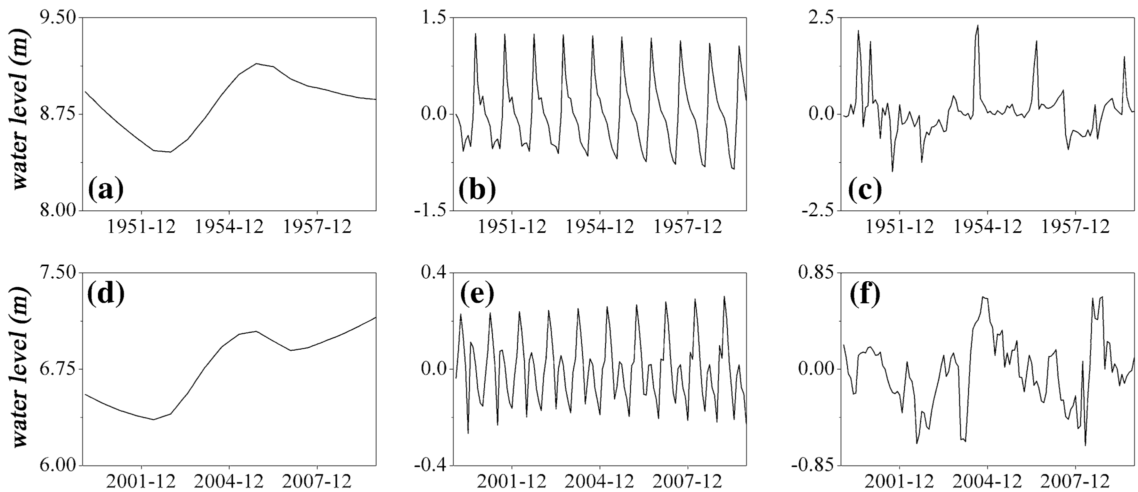

Fig. 6 Results of STL method with depicting trend component (**a**), seasonal component (**b**), residuals (**c**), for water level II and trend component (**d**), seasonal component (**e**), residuals (**f**) for water level III

(Cengiz 2011). This inherent periodic structure is less affected by anthropogenic disturbances. However, power spectrum analysis indicates the accurate oscillations of water level fluctuations. The consistent results in water level I and water level II periods demonstrate that the periodic structures of 6–16 months are natural structures of water level fluctuations, whereas approximate 6-month periodic structures in the water level III period indicate the influence of water allocation on water level periods. These results can also be shown by intra-annual fluctuations analysis. Although precipitation and evaporation were correlated with water level fluctuations, precipitation changes had less impact on water level relative to human activities (Zhuang et al. 2011). For a long-term, water level modified by water allocation can decrease frequencies with greater than 95 % confident level, which means

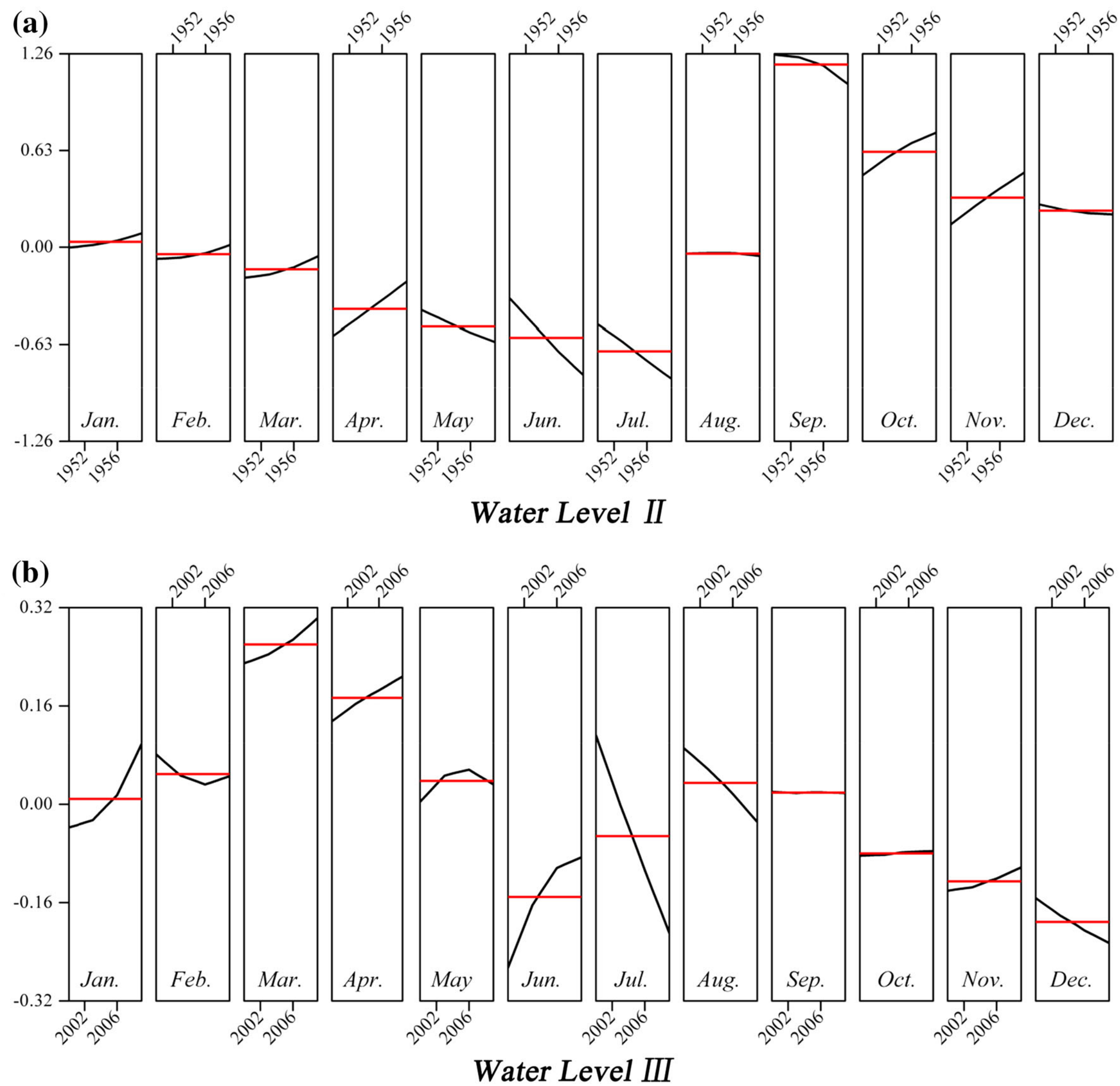

Fig. 7 Results of STL method with depicting mean of monthly trends for each month in period of water level II (**a**) and water level III (**b**). *Red Solid horizontal line* is the long-term mean of monthly trends

water level fluctuations are deeply influenced by such allocation. For intra-annual water level fluctuations, water allocations are far more important than the climate changes.

Seasonal trends of water level fluctuations

Although intra-annual water level fluctuations in recent decade have a faint effect on natural hydrologic water supplies and short-term climate changes, the STL method further analyzes seasonally varying amplitudes responding to the water level trend, as well as the monthly water level depicting by seasonality. Based on the STL method, the long-term trend shows an irregular water level declines and short-term oscillations of irregular periodicity. However, exact short-term period is unavailable, simply because of selection of smoothing parameters in STL method to better elucidate visual trends (Cleveland et al. 1990; Qian et al. 2000). For seasonality variations, there was a salient time node at the end of 1980s, consistent with the result of long-term trend variations. However, in seasonality depicted by month, coincident oscillations occurred in both periods of water level I and II periods; there was a relatively weak trend in water level III. These results show the response of climate changes to water level fluctuations. The obvious differences in seasonality depicted by month for the water level III period lie in the magnitudes of oscillations in spring and fall. For water level III, the greatest seasonal trend was in spring, in contrast to the corresponding trends in fall for the water level I and II periods. This phenomenon of water level III period gives an abnormal monthly depiction of seasonality and suggests irregular oscillations in high-frequency components, especially in monthly changes. Annual water allocation constitutes these high-frequency components, which demonstrates the changing response to water allocation. For normal water level fluctuations, seasonality can depict monthly part or completely. Similar results were reported by Lenters (2001) and Quinn (2002). Potential reasons for the differences in water level III could be from monthly water budget, which is completely different from seasonal changing mode. Assel et al. (2000) pointed out some potential influential factors could change water level fluctuations, such as monthly total lake evaporation, conversion factor, monthly mean land surface runoff flows into the lake, monthly mean outflow, monthly mean groundwater inflow/outflow, monthly mean consumptive use, monthly mean water diversions, monthly mean rate of change in volume due to thermal expansion, and dynamic monthly lake. We have not considered these factors, so they should be the focus of future research.

By comparing results for the period of water levels II and III, water allocation impacts the seasonality of water level fluctuations are shown by double-peak changes in the periodic structure variations. The smaller peaks indicate the disturbances of water allocation. Accumulation of frequent water allocation is possible primary reason for an increased trend over the last several years in the period of water level III. Therefore, water allocation is of profound significance in water level fluctuations, and future research should focus on both influencing factors and ecological risk assessment.

Conclusion

In this study, water level I (1950–2009) represented the entire time series and water level II (1950–1959) the time series with no disturbances by water allocation. The water level III time series (2000–2009) was characterized by frequent disturbances from water allocation. Long-term period structures and seasonal-trend decomposition of water level fluctuations, especially regarding effects of anthropogenic disturbances by water allocations, were analyzed with the wavelet approach and the STL method for Lake Baiyangdian for water levels I, II and III. In summary, we demonstrated the following.

1. Intra-annual fluctuations were detected in all three time series. The results of wavelet and power spectrum analyses show that there were periodic structures with 60 and 16–32 months in the period of water level I, respectively. There was an approximate 20-month periodic structure in the period of water level II, from the wavelet analysis. Inter-annual periodic structures were below the 95 % confident level for the periods of water levels II and III. Water allocation alters the periodic structures of water level by decreasing and weakening the oscillations, in contrast with the slight effects of natural hydrologic water discharges and short-term climate changes.
2. An irregular water level decline and a short-term oscillation with an irregular periodicity were determined by the STL method in the period of water level I. With seasonality depicted by month, the influence of water allocation produces irregular oscillations in high-frequency components, especially in monthly changes. The long-term trend for the period of water level II appears valid trend and is consistent with the result of the water level I period. Despite the slight trend in seasonality depicted by month in the water level III period, seasonal change is suggested. Moreover, water allocation acting on seasonality shows double-peak oscillations from 2000 to 2009, contrasting with single-peak oscillations from 1950 to 1959. The accumulation of water allocation shows a slight rise in average monthly level fluctuations over the last several years.

To better understand water level fluctuations from water allocation disturbances, detailed study should be made of other influencing factors and long-term ecological impacts on lake ecosystem from such allocations. Future research should also focus on the effects of hydrologic processes on water level fluctuations.

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