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Impact assessment of climate change and human activities on annual highest water level of Taihu Lake

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Abstract: The annual highest water level of Taihu Lake (Z_m) is very significant for flood management in the Taihu Basin. This paper first describes the inter-annual and intra-annual traits of Z_m from 1956 to 2000. Then, using the Mann-Kenall (MK) and Spearman (SP) nonparametric tests, the long-term change trends of area precipitation and pan evaporation in the Taihu Basin are determined. Meanwhile, using the Morlet wavelet transformation, the fluctuation patterns and change points of precipitation and pan evaporation are analyzed. Also, human activities in the Taihu Basin are described, including land use change and hydraulic project construction. Finally, the relationship between Z_m, the water level of Taihu Lake 30 days prior to the day of Z_m (Z_0), and the 30-day total precipitation and pan evaporation prior to the day of Z_m (P and E_0, respectively) is described based on multi-linear regression equations. The relative influence of climate change and human activities on the change of Z_m is quantitatively ascertained. The results demonstrate that: (1) Z_m was distinctly higher during the 1980-2000 period than during the 1956-1979 period, and the 30 days prior to the day of Z_m are the key phase influencing Z_m every year; (2) P increased significantly at a confidence level of 95% during the 1956-2000 period, while the reverse was true for E_0; (3) The relationship between Z_m, P and E_0 distinctly changed after 1980; (4) Climate change and human activities together caused frequent occurrences of high Z_m after 1980; (5) Climate change caused a substantially greater Z_m difference between the 1956-1979 and 1980-2000 periods than human activities. Climate change, as represented by P and E_0, was the dominant factor raising Z_m, with a relative influence ratio of 83.6%, while human activities had a smaller influence ratio of 16.4%.

Key words: *climate change; human activities; annual highest water level; Taihu Lake*

1 Introduction

Climate and human activities are two elementary factors in the hydrologic process. Climate determines the main inputs to the hydrologic circle, such as rainfall and radiation. Human activities have persistent influences on the land surface or directly interfere with the transformation and distribution of runoff, sediment and so on, so the hydrologic process becomes more complicated.

In the past fifty years, both global climate change and intensive human activities have

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caused a remarkable influence on hydrology and water resources all over the world (IPCC WGI 2007; Ding 2008; Wang et al. 2004). Detecting and evaluating these changes, and especially scientifically distinguishing the impacts of climate change and human activities, is a challenge for hydrologists and meteorologists. Many approaches and models have been established for the purpose of investigating the operating mechanisms among hydrologic processes, climate change and human activities and predicting the future hydrologic scenario under changing conditions. These range from complicated atmospheric-hydrologic coupled models and distributed hydrologic models (Milly et al. 2005; Mori et al. 2008) to relatively simple lumped hydrologic models (Guo et al. 2002; Wang et al. 2006) and statistical methods (Burn and Hag Elnur 2002; Xu 2005; Zhang et al. 2001; Liu 2007).

This study aimed to investigate climate change and human activities in the Taihu Basin from 1956 to 2000 and assess their impacts on Z_m. The value of Z_m is of great importance for flood control and management of this basin, so its variability in response to climate change and human activities is worth our attention. This paper begins with a brief description of the Taihu Basin and the data used in this study. Then the main methods used to analyze variation of precipitation and pan evaporation in the Taihu Basin and the quantitative assessment of their influence on Z_m are presented. Finally, the results are discussed and some conclusions are summarized.

2 Study area and data availability

2.1 Study area

The Taihu Basin, which has an area of about 36 895 km^2, is located in the Yangtze River Delta in southeast China (Fig. 1). The climate is a typical semi-tropical monsoon climate with an annual pan evaporation fluctuating around 820 mm and annual rainfall varying from 1 050 mm to 1 800 mm. About 60 percent of the annual precipitation is concentrated in the rainy season from May to September. As one of the most developed regions in China, its population density exceeds 1 000 persons per km^2 and its urbanization ratio reached 66.5% in 2000.

Located in the center of the basin, Taihu Lake is the third largest fresh water lake in China with a surface water area of about 2 338 km^2. The storage capacity of Taihu Lake makes up about 80 percent of that of all the lakes in this basin, so it is the most important flood storage reservoir in the basin.

2.2 Data availability

There is a an extensive rainfall monitoring network composed of 115 rain gauges in the Taihu Basin (Fig. 1). From these gauges, area rainfall data over the basin from 1956 to 2000 at a daily temporal resolution can be obtained. There are nine total pan evaporation stations providing daily pan evaporation data. The daily series of Taihu Lake’s water level is computed by the five gauges shown in Fig. 1. However, daily water level records are missing for some of the years from 1956 to 2000, namely 1961-1963, 1974, 1981 and 1988-1990, so the available water level data actually covers thirty-seven years. This is true for daily precipitation and pan evaporation, but the annual and rainy season total values of them for these years are available.

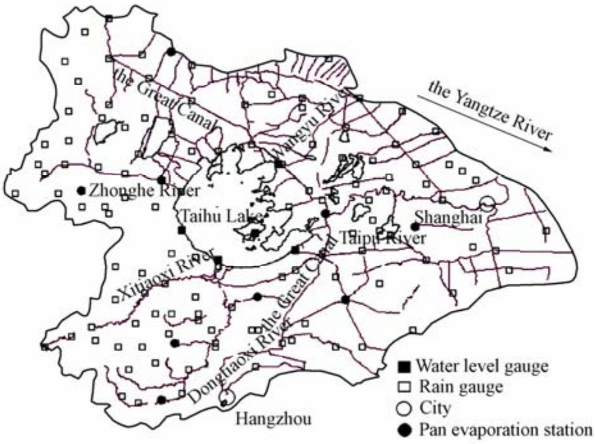

Fig. 1 River network and hydrometric stations in Taihu Basin

Land use data and socioeconomic indexes from the 1950s were also collected. The land use area data of three different periods are shown in Table 1, while population and the gross domestic product (GDP) can be seen in Table 2. Generally, changes of land use and socioeconomic indexes manifest the strength of human activities which have become more and more intense since the 1950s.

Table 1 Land use type in Taihu Basin over different periods

Period	Area (km^2)				Ratio (%)			
	Paddy field	Dry land and non-plowland	Construction land	Surface water area	Paddy field	Dry land and non-plowland	Construction land	Surface water area
1950s	10 880	16 950	2 550	6 515	29.5	45.9	6.9	17.7
1980s	11 930	15 010	3 780	6 175	32.4	40.7	10.2	16.7
2000	11 558	13 183	6 630	5 551	31.3	35.7	17.9	15.1

Table 2 Socioeconomic indexes in Taihu Basin

Period	Population (10^4)	Urbanization ratio (%)	GDP (10^8 RMB)
1950s	—	< 25.0	—
1980s	3 168.6	35.5	1 081.3
1990s	3 493.0	47.2	2 582.6
2000	3 887.0	66.5	9 716.6

3 Methodology

3.1 MK and SP nonparametric tests

The MK and SP nonparametric tests are two effective approaches for detecting possible trends of hydrologic and climatologic variables (Ding and Deng 1988; Yue et al. 2002; Liu 2007; Burn and Hag Elnur 2002). These two methods were used to inspect the trends of precipitation and pan evaporation in the Taihu Basin.

3.2 Wavelet transformation

Wavelet transformation is a multi-time-scale analysis method for time series (Wang et al. 2005), which can be used to analyze evolutionary oscillations at various time scales. Kumar and Foufoula-Georgiou (1993) introduced this method into spatial rainfall field analysis. It has been widely used to analyze the variation traits of different hydrologic factors, such as runoff, precipitation, sediment flux, and water level. In our study, we applied the Morlet continuous wavelet (Kumar and Foufoula-Georgiou 1993; Wang et al. 2005) to identify the breakpoints and periodicity of precipitation and pan evaporation series.

3.3 Ordinal clustering

Regarding the intervention of climate change and human activities, the relationship between Z_{m}, basin precipitation, and potential evapotranspiration (represented by pan evaporation) changed during the period from 1956 to 2000. Therefore, identifying the change point is important for reasonable evaluation of the impact on Z_{m} of climate change and human activities. This could be considered an ordinal clustering process for multi-dimensional time series.

There are many kinds of ordinal clustering methods for multi-dimensional time series clustering, including the fuzzy set analysis (Chen 1998) and Fisher's method (Liu et al. 2007). Here, a system clustering method is proposed to search for the change point for the relationship between Z_{m}, precipitation and pan evaporation. For the 4D time sequence consisting of the four variables below, the splitting point is determined by Eq. (1):

$$S(t) = \min_{1 \le t \le n-1} \left(\sum_{i=1}^{t} \left| \boldsymbol{Y}_i - \overline{\boldsymbol{Y}}_t \right|^2 + \sum_{i=t+1}^{n} \left| \boldsymbol{Y}_i - \overline{\boldsymbol{Y}}_{n-t} \right|^2 \right) \tag{1}$$

where $\left| \boldsymbol{Y}_i - \overline{\boldsymbol{Y}}_t \right|$ and $\left| \boldsymbol{Y}_i - \overline{\boldsymbol{Y}}_{n-t} \right|$ represent the Euclidian distance, n is the number of total samples amounting to 37, $S(t)$ is the variance summation of the two classes partitioned by point t, and $\boldsymbol{Y}_i$ is a 4D vector defined as follows:

$$\boldsymbol{Y}_i = \left(Z_{\mathrm{m}i}, P_i, E_{0i}, Z_{0i} \right)^{\mathrm{T}} \tag{2}$$

where $Z_{\mathrm{m}i}$ is the highest water level in year i; P_i is the total precipitation for the 30 days prior to the day of $Z_{\mathrm{m}i}$; E_{0i} is the total pan evaporation spanning the same period as P_i; and Z_{0i} is the water level of Taihu Lake 30 days prior to the day of $Z_{\mathrm{m}i}$. The mean values of these two classes are calculated as follows:

$$\overline{\boldsymbol{Y}}_t = \frac{1}{t} \sum_{i=1}^{t} \boldsymbol{Y}_i \tag{3}$$

$$\overline{\boldsymbol{Y}}_{n-t} = \frac{1}{n-t} \sum_{i=t+1}^{n} \boldsymbol{Y}_i \tag{4}$$

The reason that Z_0, P and E_0 are chosen as the main factors influencing Z_{m} will be illustrated in the following section. According to Eq. (1), when $S(t)$ reaches the minimum value, the splitting point t is chosen and the relationship between Z_m and the three influencing factors is distinctly different before and after t.

3.4 Multi-linear regression

Multi-linear regression is a classical statistical approach principally based on the least squares approach and the Gauss-Markov assumption (Wang 1999). A prerequisite for employing multi-linear regression is that the correlation between the selected variables is weak. After the splitting point t described above is selected, using this method, the quantitative relationship between Z_m and the three influencing factors before and after t is established through the following equation:

$$Z_{mi} = \beta + \alpha_1 P_i + \alpha_2 E_{0i} + \alpha_3 Z_{0i} \tag{5}$$

where α_1, α_2, and α_3 are the regression coefficients of P_i, E_{0i} and Z_{0i}, respectively, and β is a constant. Eq. (5) can be further written in vector form:

$$\boldsymbol{Z}_m^{\ *} = \left(\boldsymbol{I}, \boldsymbol{P}^*, \boldsymbol{E}_0^{\ *}, \boldsymbol{Z}_0^{\ *}\right)\boldsymbol{A} \tag{6}$$

where $\boldsymbol{E}_0^{\ *} = \left(E_{01}, E_{02}, \cdots, E_{0n}\right)^{\mathrm{T}}$, $\boldsymbol{Z}_0^{\ *} = \left(Z_{01}, Z_{02}, \cdots, Z_{0n}\right)^{\mathrm{T}}$, $\boldsymbol{Z}_m^{\ *} = \left(Z_{m1}, Z_{m2}, \cdots, Z_{mn}\right)^{\mathrm{T}}$, $\boldsymbol{I} = \left(1, 1, \cdots, 1\right)^{\mathrm{T}}$, $\boldsymbol{P}^* = \left(P_1, P_2, \cdots, P_n\right)^{\mathrm{T}}$, and $\boldsymbol{A} = \left(\beta, \alpha_1, \alpha_2, \alpha_3\right)^{\mathrm{T}}$.

Based on Eq. (5) and Eq. (6), the individual effects of P, E_0 and Z_0 on Z_m can be assessed and compared. The regression coefficients and constants are derived with the following equation:

$$\boldsymbol{A} = \left\{\begin{bmatrix} \boldsymbol{I}^{\mathrm{T}} \\ \boldsymbol{P}^{*\mathrm{T}} \\ \boldsymbol{E}_0^{\ *\mathrm{T}} \\ \boldsymbol{Z}_0^{\ *\mathrm{T}} \end{bmatrix} \left(\boldsymbol{I}, \boldsymbol{P}^*, \boldsymbol{E}_0^{\ *}, \boldsymbol{Z}_0^{\ *}\right)\right\}^{-1} \begin{bmatrix} \boldsymbol{I}^{\mathrm{T}} \\ \boldsymbol{P}^{*\mathrm{T}} \\ \boldsymbol{E}_0^{\ *\mathrm{T}} \\ \boldsymbol{Z}_0^{\ *\mathrm{T}} \end{bmatrix} \boldsymbol{Z}_m^* \tag{7}$$

For the purpose of illustration, cm is uniformly adopted as the unit of P, E_0, Z_0 and Z_m. The constant β also has a unit of cm while the other three coefficients are dimensionless. Physical meanings of the four regression coefficients can be interpreted by deconstructing Eq. (5) into two functions as follows:

$$f = \beta + \alpha_3 Z_{0i} \tag{8}$$

$$\varphi = \alpha_1 P_i + \alpha_2 E_{0i} \tag{9}$$

The function f describes the relation between Z_m and Z_0 when P and E_0 approximate zero. The parameters β and α_3 together reflect the integrative relation between Z_m and Z_0 under the influence of other implicit factors, especially water concentration and drainage of Taihu Lake due to human regulation. The function φ stands for the contribution of P and E_0 to Z_m under certain land surface and human activity conditions. The meaning of α_1 can be explained as the increment of Z_m with just 1 cm change of P while other factors remain constant. The parameter α_2 has a meaning similar to that of α_1.

3.5 Evaluation method for driving factors of Z_m

The driving factors of Z_m can be generally classed into climate change and human activities as stated above. In this paper, the influence of climate change is mainly considered P and E_0 while other influences are all considered human activities. As a statistical model, the regression equation is still useful for evaluating the impacts of climate change and human activities and can estimate future changes of Z_m under certain P and E_0 scenarios. Actually, regression coefficients of Eq. (5) implicitly and synthetically describe the interaction mechanisms between the land surface, human activities and Z_m under certain P and E_0 conditions. If the linear regression functions of the two different periods before and after t are respectively denoted by F_1 and F_2, then the total difference in the mean Z_m ($\bar{Z}_\mathrm{m}$) between the two periods is calculated as:

$$\varDelta = F_2\left(\bar{\boldsymbol{X}}_2\right) - F_1\left(\bar{\boldsymbol{X}}_1\right) \tag{10}$$

where

$$\bar{\boldsymbol{X}}_1 = \left(\bar{P}_1, \bar{E}_{01}, \bar{Z}_{01}\right)^\mathrm{T} \tag{11}$$

$$\bar{\boldsymbol{X}}_2 = \left(\bar{P}_2, \bar{E}_{02}, \bar{Z}_{02}\right)^\mathrm{T} \tag{12}$$

The variables $\bar{P}_1$, $\bar{E}_{01}$ and $\bar{Z}_{01}$ respectively indicate the mean values of P_i, E_{0i} and Z_{0i} $\left(i = 1, 2, \cdots, t\right)$ during the first period, and $\bar{P}_2$, $\bar{E}_{02}$ and $\bar{Z}_{02}$ respectively indicate the mean values of P_i, E_{0i}, and Z_{0i} $\left(i = t+1, t+2, \cdots, n\right)$ during the second period. The partial difference of Z_m caused by climate change and by human activities can be respectively calculated as follows:

$$\varDelta_\mathrm{c} = \varphi_2\left(\bar{P}_2, \bar{E}_{02}\right) - \varphi_2\left(\bar{P}_1, \bar{E}_{01}\right) \tag{13}$$

$$\varDelta_\mathrm{h} = \varDelta - \varDelta_\mathrm{c} \tag{14}$$

where $\varDelta_\mathrm{c}$ is the increment exerted only by climate change, $\varDelta_\mathrm{h}$ is the increment exerted only by human activities, and φ_2 is the function of φ in the second period. Thus, the relative influence of climate change and human activities on $\bar{Z}_\mathrm{m}$ can be computed with the following formulas:

$$\rho_\mathrm{c} = \frac{\varDelta_\mathrm{c}}{\left|\varDelta_\mathrm{c}\right| + \left|\varDelta_\mathrm{h}\right|} \tag{15}$$

$$\rho_\mathrm{h} = \frac{\varDelta_\mathrm{h}}{\left|\varDelta_\mathrm{c}\right| + \left|\varDelta_\mathrm{h}\right|} \tag{16}$$

where ρ_c and ρ_h are the relative influence of climate change and human activities, respectively. From Eq. (15) and Eq. (16), we can postulate that if ρ_c is positive, climate change raises $\bar{Z}_\mathrm{m}$; and if ρ_c is negative, climate change reduces $\bar{Z}_\mathrm{m}$. This situation is true for human activities and for ρ_h.

4 Results and discussion

4.1 Variability of water level of Taihu Lake

Based on the water level records at a daily resolution from 1956 to 2000, intra-annual and inter-annual variability of Taihu Lake was investigated and summarized. Water level variation of Taihu Lake is rather complicated. The duration of the water level rise and the date of Z_m were different every year. However, through analysis of the water level curves of 37 years, it was found that the dominant period of water level rise started about 30 days before Z_m. This is especially true for some typical flood years (Fig. 2) and it is the reason why we conclude that P, E_0 and Z_0 are the main factors influencing Z_m.

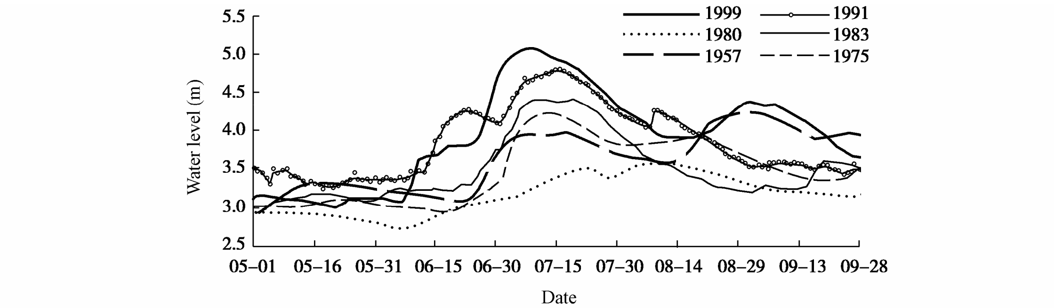

Fig. 2 Rising process of water level of Taihu Lake in typical years

The $\overline{Z}_m$ value of the period from 1956 to 2000 was 3.74 m, calculated with the 37-year available records. Anomalous values of Z_m are shown in Fig. 3(a). Although the records of Z_m for several years were missing, we can still see that Z_m had an evident ascending trend over these years. High Z_m values mostly appeared after 1980. The $\overline{Z}_m$ value of the latter period was 0.42 m higher than that of the previous period. Z_m was particularly high in the 1990s, indicating that the Taihu Basin suffered severe flood hazards. Additionally, the initial water level Z_0 is shown in Fig. 3(b). With almost no trend, the annual variation of Z_0 is distinctly different from that of Z_m.

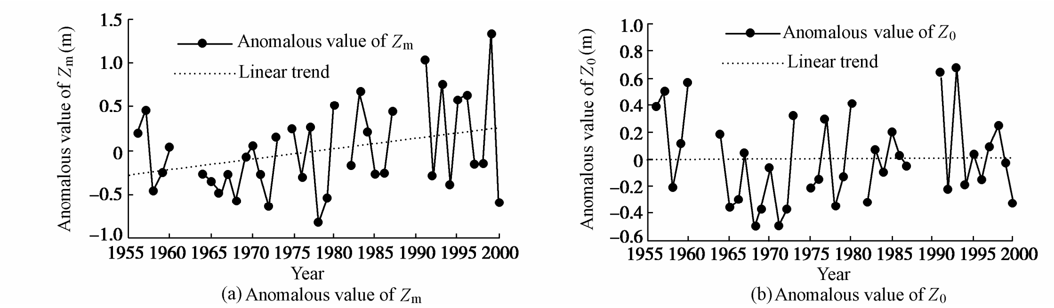

Fig. 3 Anomalous values of Z_m and Z_0 of Taihu Lake from 1956 to 2000

4.2 Dynamics of precipitation and pan evaporation

Time series of precipitation and pan evaporation in the Taihu Basin are presented in Fig. 4. Annual precipitation and pan evaporation are denoted by PY and EY while rainy season precipitation and pan evaporation are denoted by PX and EX, respectively. It can be seen in Fig. 5 that precipitation at different time steps varied with an upward incline from 1956 to 2000, while the reverse was true for pan evaporation. Also, standardized curves of precipitation and pan evaporation are drawn in Fig. 5. The standardization formula used is

$$P_{si} = \frac{P_i - \overline{P}}{\sigma_P} \tag{17}$$

where P_{si} is the standardized P_i, and $\overline{P}$ and σ_P are the mean and standard deviation of P, respectively. Eq. (17) is also adapted for standardizing PY, EY, PX, EX and E_0. After the effects of mean value and standard derivation are eliminated, we can see that although there are some differences, the main changes of P are consistent with PY and PX. This is similarly true for E_0, EX and EY (Fig. 5).

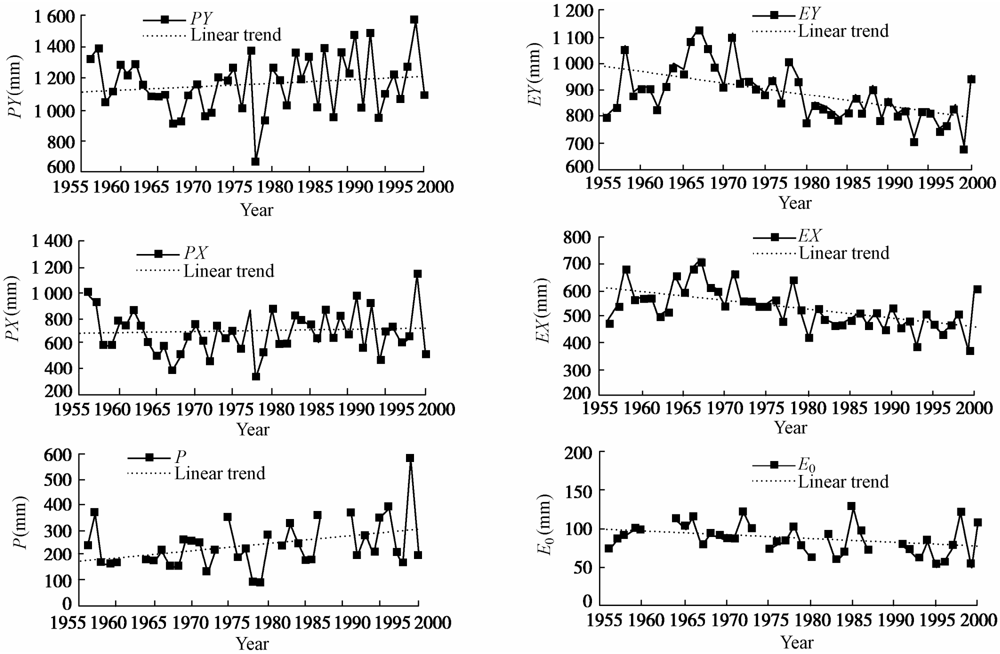

Fig. 4 Time series of precipitation and pan evaporation and their linear trends from 1956 to 2000

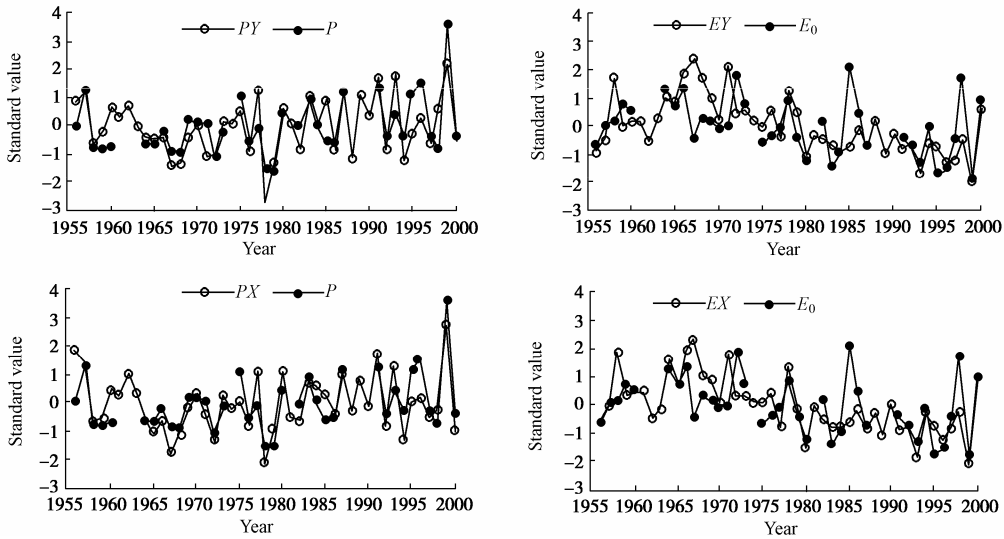

Fig. 5 Standardized curves of precipitation and pan evaporation from 1956 to 2000

By means of MK and SP nonparametric tests and Morlet wavelet transformation, the dynamics of precipitation and pan evaporation were further analyzed. Table 3 shows the test results of these series. Change trends of precipitation and pan evaporation were rather different. For precipitation series, only P had a significant trend at a confidence level of 95%, though all of them tended to ascend. However, the pan evaporation series all had significantly descending trends at the confidence level of 95%, which was almost the opposite of what was observed of the precipitation sequences. At annual and rainy season resolutions, the absolute change ratio of pan evaporation even exceeded that of precipitation. This demonstrates the fact that the decrease of pan evaporation was a crucial aspect of climate change in the Taihu Basin from 1956 to 2000.

Table 3 Nonparametric tests for change trends of precipitation and pan evaporation

Category	Series	Series length (year)	Mean (mm)	Change ratio (mm/year)	MK trend	SP trend
Precipitation	PY	45	1 167	1.9	0	0
	PX	45	698	0.9	0	0
	P	37	242	2.5	1	1
Pan evaporation	EY	45	884	– 4.3	1	1
	EX	45	534	– 3.4	1	1
	E_0	37	87	– 0.5	1	1

Note: The confidence level of nonparametric tests is 95%; 1 means the trend is statistically significant and 0 means the trend is statistically insignificant.

Fig. 6 presents the Morlet wavelet transformation coefficients of PY, PX, EY and EX. Fig. 7 is the wavelet variance curve of the four sequences. Wavelet coefficient maps clearly describe the fluctuation process of precipitation and pan evaporation at different time scales from 1 to 45 years, and also detect the possible change points with zero isolines. Wavelet variance curves of the four series manifest the principal periods that correspond to local peaks. Together with these, a basic evolutionary pattern is deduced, that PY and PX approximately traversed three different phases at time scales of 33 years and 28 years, respectively. The two change points emerged in the initial years of the 1960s and the 1980s. Similarly, it can be inferred that both EY and EX varied through two different phases at a time scale of 42 years. The years 1980 and 1979 are the corresponding change points of EY and EX. Considering these findings, PY and PX will possibly go through a dry phase after 2003, while EY and EX will presumably go through a phase of abundant rainfall after 2006. Detailed summaries of the wavelet analysis are provided in Table 4.

Wavelet analysis of P and E_0 was not conducted for missing data. However, the evolutionary rules and future scenario are likely similar to the annual and rainy season series due to their consistency (Fig. 5). The evolution of P and E_0 over the 45 years is also shown in Table 4. To sum up, the abundance of precipitation and diminishment of pan evaporation from the 1980s to 2000 likely together brought on higher Z_{m}.

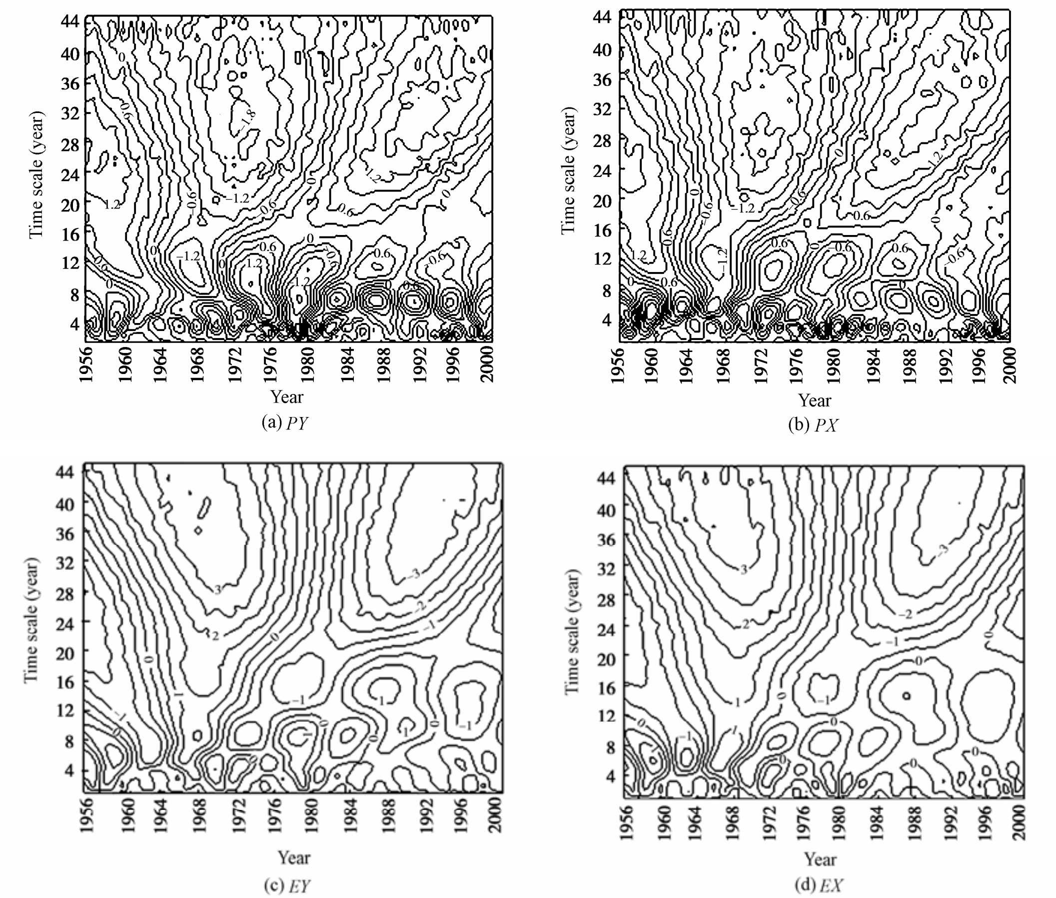

Fig. 6 Wavelet coefficient isolines of precipitation and pan evaporation from 1956 to 2000

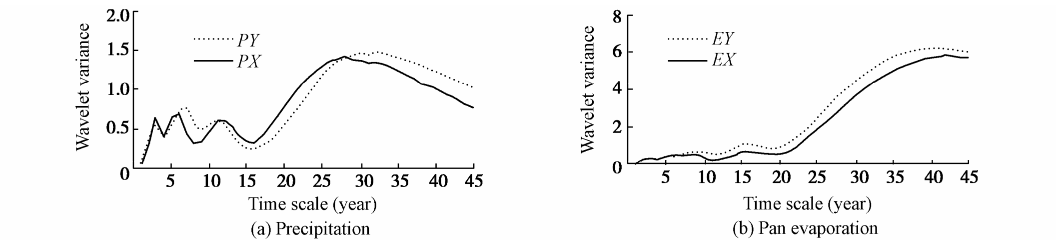

Fig. 7 Wavelet variance curves of precipitation and pan evaporation

4.3 Effects of human activities

The effects of human activities on Z_m are rather complicated, but can be analyzed from two perspectives. On the one hand, with the persistent industrialization and urbanization process of the Taihu Basin, land use types were considerably transformed and the flood storage capacity was reduced. Apparently, these changes of land surface conditions in the Taihu Basin were important reasons for the frequent high value of Z_m from the 1980s to 2000. On the other hand, with extensive construction of hydraulic projects and alteration of the river system, the modes of flood concentration and discharge were altered. Particularly with the establishment of many pumping stations and drainage canals, the water quantity relationship between Taihu Lake and the other parts of the basin was adjusted. Generally, this helped to keep Z_m fluctuating within a proper range.

As illustrated in Table 1, the main feature of land use change is that the area of dry land and non-plowland has been decreasing whereas construction land area has been increasing. From the 1950s to 2000, the ratio of dry land and non-plowland to the basin area decreased by about 10%. Conversely, the construction area showed a considerable increase of 11% relative to the basin area. Therefore, the runoff amount increased even if precipitation and potential evapotranspiration did not change. From 1980 to 2000, the runoff volume increased by 4.11% because of land use change (Li et al. 2007). At the same time, the water area of the Taihu Basin showed a considerable reduction because of the vanishing of lakes. Thus, the flood storage space was cut down. This was also an important factor in high Z_m values. As shown in Table 5 (Li et al. 2006), the total water area of nine major lakes decreased by 189.9 km^2 from 1971 to 2002.

Table 4 Results of Morlet wavelet analysis of precipitation and pan evaporation

Phase	*PY*				*PX*				*P*			
	P scale (year)	Change point	Period	Mean (mm)	P scale (year)	Change point	Period	Mean (mm)	P scale (year)	Change point	Period	Mean (mm)
1			1956-1962	1 246			1956-1963	786			1956-1963	255
2	33	1963, 1983	1963-1982	1 081	28	1964, 1983	1964-1982	616	—	1963, 1983	1964-1982	208
3			1983-2000	1 231			1983-2000	744			1983-2000	286
Phase	*EY*				*EX*				E_0			
	P scale (year)	Change point	Period	Mean (mm)	P scale (year)	Change point	Period	Mean (mm)	P scale (year)	Change point	Period	Mean (mm)
1			1956-1979	947			1956-1978	583			1956-1978	95
2	42	1980	1980-2000	811	42	1979	1979-2001	483	—	—	1964-1982	88
3			—	—			—	—			1983-2000	80

Note: P scale refers to principal scale time.

Table 5 Water area of major lakes in Taihu Basin in 1971 and 2002

Period	Water area (km^2)									Summation (km^2)
	Taihu Lake	Ge Lake	Yangcheng Lake	Dingshan Lake	Tao Lake	Cheng Lake	Kuncheng Lake	Yuandang Lake	Dushu Lake	
1971	2 425.3	194.9	122.6	63.6	87.8	45.7	18.3	15.5	10.7	2 984.4
2002	2 313.0	141.9	116.5	61.4	81.2	40.6	18.0	12.6	9.4	2 794.5

Simultaneously, the appearance of flood control systems entirely changed from the 1950s to 2000. Thus, the water balance relation between Taihu Lake and the other parts of the basin was distinctly changed. In the western mountainous regions, several large-scale reservoirs were established with total flood control storage of about 0.594 billion m^3, while drainage systems composed of pumping stations, floodgates and canals were gradually developed in the plains region. Particularly after the great flood disaster of 1991, eleven key projects for flood regulation and drainage were established or reconstructed, including some important drainage projects around Taihu Lake and in other sub-regions. The drainage capability of the plains region exceeded 10 000 m^3/s and floods could more rapidly discharge into the sea. Therefore, the regulation ability of the entire basin was substantially intensified, helping to keep Z_m within an appropriate range.

4.4 Relation between Z_m, P and E_0 during different periods

In order to quantitatively analyze the influence of precipitation and pan evaporation on Z_m by means of ordinal clustering and least squares regression, two equations were derived from Eq. (5).

First, the 37 available samples of 4D vectors composed of Z_m, P, E_0 and Z_0 were divided into two sections according to the ordinal clustering method referred to in Section 3.3. The year 1979 was selected as the splitting point (Fig. 8), so the 20 available samples from the period of 1956-1979 were grouped together in one part while the other 17 samples from the period of 1980-2000 were grouped together in another part. The rationality of choosing 1979 as the splitting point can be illustrated by Fig. 9, where dZ represents the difference between Z_m and Z_0. The scatter plot of dZ against P for the 1956-1979 period is distinct from that of the 1980-2000 period. This situation is likewise true for the scatter plot distribution of dZ against E_0.

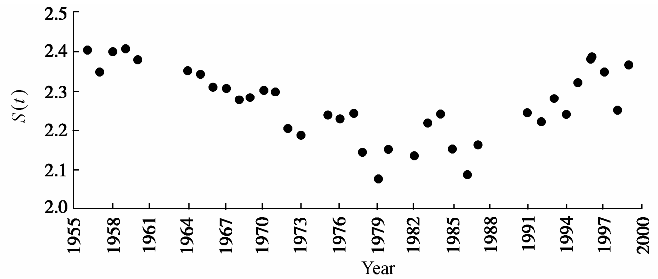

Fig. 8 Splitting points selected by ordinal clustering

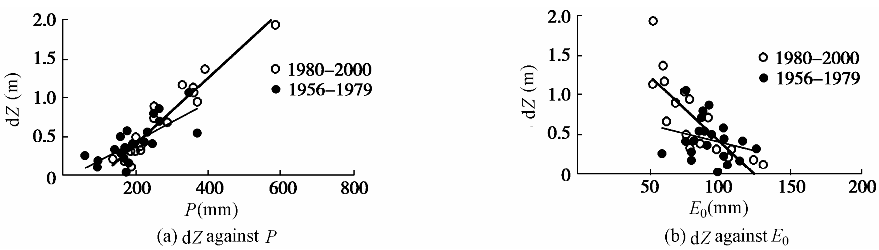

Fig. 9 Scatter plots of dZ against P and dZ against E_0 during different periods

Table 6 presents regression coefficients of the linear regression equations for the 1956-1979 and 1980-2000 periods. Also, a comparison of observed and simulated values of Z_m is shown in Fig. 10, which verifies that the linear regression equations can well express the relation between Z_m and the three influencing factors. The obvious difference of regression coefficients between the two periods indicates that water quantity relationships in the Taihu

Basin have changed due to human activities. Another point worth our attention is that the absolute partial differential of Z_m against E_0 exceeds P.

Table 6 Regression coefficients of linear regression equations

Period	Regression coefficient				Nash coefficient
	β (cm)	α_1	α_2	α_3	
1956-1979	163.72	3.084	–3.948	0.529	0.941
1980-2000	79.76	3.691	–4.840	0.779	0.968

The evaluation results of effects on Z_m of climate change and human activities are shown in Table 7. Between the two periods, the total difference of $\bar{Z}_m$ caused by P and E_0 change and human activities together was 42.4 cm. Both climate change and human activities during the 1980-2000 period generally raised $\bar{Z}_m$ as compared with the 1956-1979 period. Climate change partially increased $\bar{Z}_m$ by 35.5 cm while the corresponding value was only 6.9 cm for human activities. Their relative influence on the change of $\bar{Z}_m$ was, respectively, 83.6% and 16.4%, so climate change was evidently the dominant influencing factor of Z_m change. The net influence of human activities on Z_m was rather small relative to their high intensity. However, it can be seen through the interaction among land use change, flood regulation measures and other factors introduced by human society.

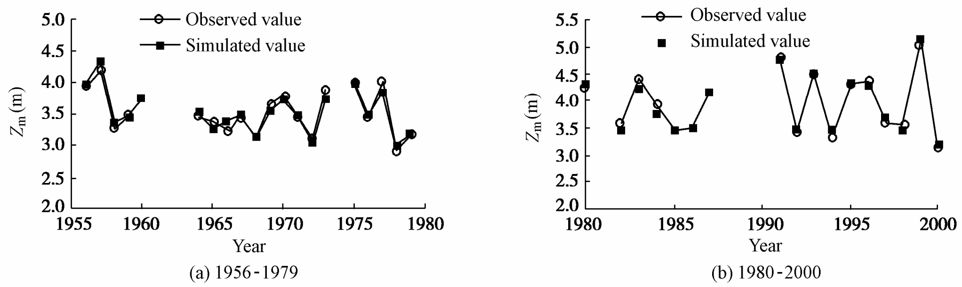

Fig. 10 Scatter plots of observed and simulated Z_m during different periods

Table 7 Evaluation results of effects on Z_m of climate change and human activities

Period	$\bar{P}$ (cm)	$\bar{E}_0$ (cm)	$\bar{Z}_0$ (cm)	$\bar{Z}_m$ (cm)	Δ (cm)	Δ_c (cm)	Δ_h (cm)	ρ_c (%)	ρ_h (%)
1956-1979	20.6	9.4	310.0	354.3	42.4	35.5	6.9	83.6	16.4
1980-2000	28.4	8.0	322.0	396.7					

5 Conclusions

Climate change and human activities have significantly influenced the annual highest water level of Taihu Lake from 1956 to 2000. This study demonstrates that precipitation and potential evaporation in the Taihu Basin substantially changed after 1980. Meanwhile, human activities also had important impact on Z_m. Some conclusions can be summarized:

(1) The mean annual highest water level of Taihu Lake after the 1980s was higher than the mean value from 1956 to 2000. The converse was true for the mean annual highest water level before the 1980s. $\bar{Z}_m$ from 1980 to 2000 was 0.42 m, higher than that from 1956 to 1979. The

30 days prior to the day of Z_m are the key phase of the water level rise process in the rainy season every year, but the initial water level 30 days prior to the day of Z_m showed a rather weak incline from 1956 to 2000.

(2) Precipitation at different time resolutions showed an ascending trend from 1956 to 2000, while pan evaporation showed a descending trend. Based on the MK and SP nonparametric tests, the change trend of P, E_0, EY, and EX was proven to be significant at a confidence level of 95%. The Morlet wavelet transformation detected the annual change point. The main change point of rainy season precipitation and pan evaporation mostly occurred in the initial years of the 1980s. After 2000, precipitation in the Taihu Basin will gradually enter a dry period, while pan evaporation will have the reverse evolutionary rule. Also, P_0 and E_0 have similar evolution traits to PX and EX, respectively.

(3) Human activities in the Taihu Basin have intensified. On the one hand, human activities have transformed land use from surface water area and dry plowland into construction land, which is an important factor in frequent occurrences of high Z_m. On the other hand, the extensive construction of flood drainage projects helps to maintain a proper value of Z_m. These two effects of human activities counteract each other, so the net influence of human activities on Z_m actually weakened over the study period.

(4) The influence of climate change and human activities on Z_m was evaluated and assessed by means of multi-linear regression. Selecting P, E_0 and Z_0 as independent variables and Z_m as the determined variable, regression equations for the two periods of 1956-1979 and 1980-2000 were established. Based on these, it was determined that the partial difference of $\bar{Z}_m$ between these two periods caused by climate change is 35.5 cm while the corresponding value is just 6.9 cm for human activities. With a relative influence level of about 83.6%, climate change was evidently the dominant driving factor of Z_m change from 1956 to 2000.

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