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Changing Trends of Water Level and Runoff during Past 100 Years of the Yangtze River (China)

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Abstract: Changing trends and periodicities of the water level and runoff during past more than 100 years in the Yichang, Hankou and Datong stations are detected with the help of the wavelet analysis, maximum entropy spectrum analysis and Mann-Kendall analysis. The results indicate that the runoff of the Datong station is in upward trend since about 1965; this upward trend is significant at 0.95 confidence level after 1993. The runoff of the Hankou station, however, is in upward trend since 1920, and reached the 0.95 significant level at 1960. The changing features of the runoff in the Yichang station are different from Hankou and Datong stations. The runoff of the Yichang station is in downward trend after 1960. The changing trends of the water level are similar to those of the runoff. As for the periodicities, the changes of the periodicities of the runoff over time is not significant, while periodicities have the obvious changes over time, that is, the periodicities of the water level are shorter over time. This result suggests that changes of the runoff are mainly the results of the climatic changes, less impacted by the human activities. While the water level changes are results of complex factors, that is to say, the changes of the water level are not only influenced by the climatic changes but also influenced by the human activities. Wavelet analysis results, together with the maximum entropy spectrum analysis, demonstrate that the periodicities of the water level become shorter over time, which means that the occurrence possibility of the higher water level is high over time. Therefore we can say that with the development of human activities, intensifying human interference with the river channel evolution and intensified human exploitation of the land in the Yangtze catchments exert increasing influences on the water level changes. Human activities play the increasingly important role in the water level changes in the Yangtze catchments. Wavelet analysis and Mann-Kendall analysis results indicate that, except the Yichang station, the water level and runoff in the Hankou and Datong stations show upward trend. Furthermore excessive precipitation because of global warming will intensify the flood in the Yangtze catchments. Therefore, in the near future, the Yangtze catchments will encounter greater and more serious flood disasters. This result is expected to draw more attention from the local governments.

Key words: Wavelet analysis, Mann-Kendall analysis, the Yangtze catchments, water level changes, runoff changes.

Introduction

China experiences frequent natural disasters, like floods, droughts, earthquakes, snow and typhoons. Flooding is the most serious which causes considerable economic loss and serious damage to towns and farms (Zhang et al., 2002). Past researches (e.g. Mirza, 2002) suggest that global warming caused by the enhanced greenhouse effect is likely to have significant effects on hydrology and water resources of watershed. Historical flood records show that, during past 200 years, about eight floods occurred in the 3rd cold period of the Little Ice

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Age. There are about 19 floods however occurring in the warm 20th century. 1990s is the warmest period of past 1000 years (IPCC, 2001), and seven floods occurred in the 1990s, about one flood event per two years. Gao et al., (2001), with the help of the regional climatic models, suggest that under the scenario of the double carbon dioxide in 2050, the precipitation in the Yangtze catchments will increase about 10-20%, which will result in larger probability of higher water level exceeding historical recorded ones. The Yangtze catchments will face more intensifying flood conditions in the future.

Water level, runoff and flooding process are the three elements of floods. The mitigation measurements are usually decided by records of water level and runoff of historical floods and prediction of those in the future (Cai, 2002). Therefore time series analysis of water level and runoff is of great importance for Yangtze flood study (Yin, 2002; Shi et al., 1999). Some hydrological observatory stations in the Yangtze catchments have the long series of water level and runoff materials. For example, Hankou station keeps the water level and runoff records of 136 years (1865-2000). Further research of these long time series records of water level and runoff of floods will be of great significance in exploring changing principles of water level and runoff and in prediction of future changing trends of floods. The objectives of this paper have been to: (1) detect the trends of water level and runoff of the Yangtze river during past 130 years; (2) detect periodic characteristics of water level and runoff; and (3) to detect the changes of the periods of water level and runoff over time for further understanding how the human activities impact Yangtze water level and discharge changes from a long time interval. The research results of this paper may be helpful for flood mitigation of the Yangtze catchments and economic development along the Yangtze river.

Data

Water level and runoff data analyzed in this paper are from three main controlling gauging stations: Yichang station, Hankou station and Datong station (Figure 1). More detailed information concerning hydrological records of these three gauging stations is displayed in Table 1. Flood, esp. the flood disasters, refer to water level or flood discharge that overwhelmed the mitigation or flood-controlling facilities and inflicted certain losses on economy or human society, e.g. houses, human lives and so on. Therefore not the average condition of flood but maximum flood water level or maximum flood discharge is what human concern most (Adamowski, 2000). Flood mitigation measures and flood frequency analysis usually attach considerable significance to water level and discharge (Faisal et al., 1999; Heo et al., 2001). Therefore, only annual maximum water level and discharge are analyzed in this paper. The reason why Yichang, Hankou and Yichang gauging stations (Figure 1) are selected as study stations is that these three gauging stations represent the changes of water level and runoff of the Yangtze river (CWRC, 2000a, 2000b). Yichang station is the controlling station measuring the discharge from upper Yangtze river. Hankou station is the main mandatory station in the middle Yangtze river. All discharge from upstream of the main Yangtze river are from Hankou and the largest tributary of the middle Yangtze river—Hanjiang river—is passing through the Hankou station. And also, Hankou station is the important reference station for the flood mitigation and flood controlling activities in Jingjiang and Wuhan river reach (These two river reaches are the major flood-affected regions in the Yangtze catchments). Datong station is the monitoring station for the lower Yangtze catchments, accepting the discharge from the trunk stream of the Yangtze river and Poyang water systems. Therefore, the changes of water level and discharge of these three gauging stations represent the fundamental principles of the whole Yangtze river.

Methods

The trend testing method used in this paper is a nonparametric Mann-Kendall test (Kendall, 1938; Claudia, 2002), which is commonly applied for hydrologic data analysis (Helsel & Hirsch, 1992;

Table 1: Detailed Extreme Hydrological Records of Yichang, Hankou and Datong Gauging Stations

Station name	*Warning water-level (m)*	*Safe water-level (m)*	*Max. water level (m)*	*Occurrence time of max. water level*	*Max. runoff (m^3/s)*	*Occurrence time of max. runoff*	*Time series of data*	
							Water level	*runoff*
Yichang	52	55.73	55.92	1896.09.04	71100	1896.09.04	1877-2000	1877-2000
Hankou	27.3	29.73	29.73	1954.08.18	76100	1954.08.14	1865-2000	1865-2000
Datong	14.5	16.64	16.64	1954.08.01	92600	1954.08.01	1922-2000	1951-2000

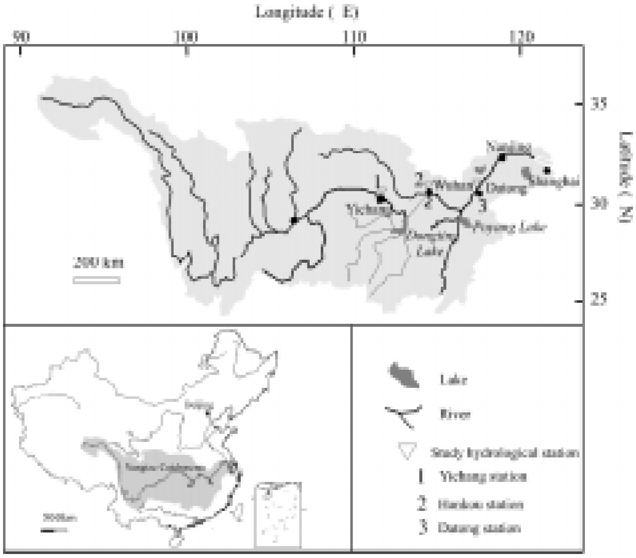

Figure 1: Location of three study hydrological stations.

Kundzewicz & Robson, 2004; Ercan et al., 2004). This method is a rank-based procedure, suitable for non-normally distributed data, censored data and nonlinear trends.

MK method assumes the times series under research stable, independent and random with equal possibility distribution. We assume the time series under study is x_1, x_2, x_3……x_n, m_i denotes the accumulative total of samples that $x_i > x_j$ ($1 \le j \le i$), n is the number of the samples.

Definition of the statistic parameter of d_k is as follows:

$$d_k = \sum_{i=2}^{n} \sum_{j=1}^{i-1} \mathrm{sign}(X_i - X_j)$$

where sign () is the sign function.

On the condition that the original time series was random and independent, free from correlations between items, the variance and the mean of d_k are defined as follows:

$$E[d_k] = \frac{k\,k-}{\;}$$

$$\mathrm{Var}[d_k] = \frac{k\,k- \quad k+}{\;} \quad 2 \le k \le N$$

Under the assumption above, the definition of statistic index of UF_k is as the following equation shows:

$$Z_k = \frac{d_k - E[d_k]}{\sqrt{\mathrm{var}[d_k]}} \quad k = 1, 2, 3, \ldots\ldots, n$$

Here the Z_k satisfies the normal distribution. In a two-sided test for trend, the null hypothesis is rejected at significance level of a if $|Z| > Z_{(1-a/2)}$, here $Z_{(1-a/2)}$ is the value satisfying the standard normal distribution with a probability exceeding $a/2$. Positive Z denotes positive trend and negative Z denotes negative trend in the time series tested. In this paper, trends are identified at 90 percent, 95 percent and 99 percent level respectively.

Spectral techniques have proven, at least empirically, useful in a variety of data mining applications (Korn et al., 1998; Ghil et al., 2002). Through the analysis of the development of spectra in a composition, one gains a greater understanding of its content and development. In this paper, spectral analysis is applied to detect possible periods of changes of the water level and stream flow.

Another method applied in this paper is the wavelet transform. This method is a powerful way to characterize the frequency, intensity, time position, and duration of variations in a climate data series (Qian et al., 2003), which reveals localized time and frequency information without requiring the time series to be stationary as required by the Fourier transform and other spectral methods. We use the ‘Mexican hat’ in this study to analyze runoff and water level dataset. Details of the wavelet transform formulae and ‘Mexican hat’ functions are described in Jiang et al. (1997). Based on the definition of the wavelet transform, the scale parameter a represents the time-scale of the function. A smaller a value refers to a higher frequency. The location parameter b corresponds to the time points in a year-to-year sequence. Usage of the wavelet transform in climatic changes and hydrological changes and other fields is receiving increasing attentions (Xie et al., 2000). Margriet Nakken (1999) applied the continuous wavelet transforms (CWTs) to detect temporal changing characteristics of the precipitation and runoff process and their correlations and separate roles of human activities from climatic changes on stream flow changes. Other researchers (e.g. Liu et al., 2003) applied the wavelet transforms to the runoff analysis and make prediction of future runoff changes.

Results

Mann-Kendall analysis

Figure 2 demonstrates that changing trends of runoff in Hankou and Datong are similar in curve patterns, but are different from Yichang station. Z_1 curve in Figure 1 indicates that the runoff of Datong station is in upward trend after 1965, and in 1993 this upward trend satisfies the 95 percent confidence level. As for Hankou station, however, this upward trend occurred since approximately 1920, and in 1960 this upward trend reaches the 95 percent confidence level. The runoff changes in Yichang station, however, present different features. The runoff of Yichang station is in downward trend since 1960. The intersection point of Z_1 and Z_2 indicates possible jump time of analyzed time series. The intersection point of Datong runoff time series occurred to about 1990, for this point lies between lines showing the 95 percent confidence level, the jump time of stream flow in Datong occurred to about 1990. Similarly, the jump time of runoff changes of the Yichang station occurred during 1982-1983. While the jump time of runoff of Hankou station is not significant.

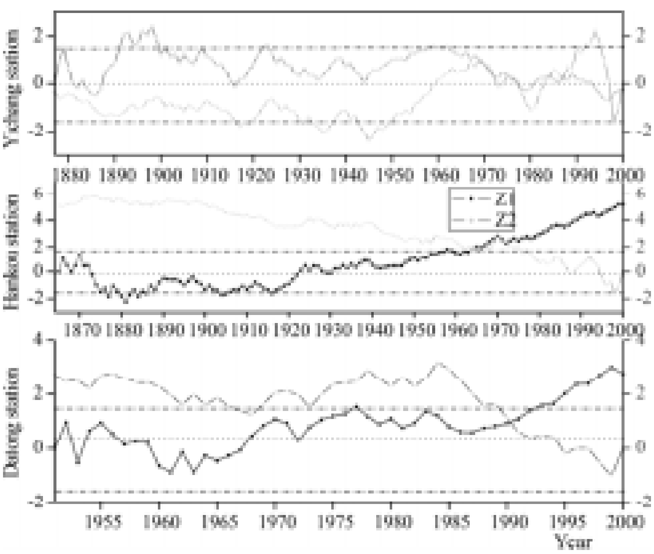

Figure 2: Mann-Kendall trends of the runoff changes in the Yichang, Hankou and Datong stations.

Mann-Kendall analysis results of water level (Figure 3) show that the water level of the Datong station is in upward trend since 1935-1937 and reaches the 95 percent confidence level since 1968. From the intersection point of Z_1 and Z_2, the water level of the Datong station has no significant jump time. At Hankou station, however, the water level is in upward trend since 1915, and reaches the 95 percent confidence level since 1990 with the jump time in about 1989. As for the Yichang station, the Mann-Kendall analysis of the water level changes is similar to that of runoff.

Wavelet Transforms

Figure 4A demonstrates that the periodicity of discharge changes of Yichang station is dominated by 3-4 years and 7-8 years. Comparison between wavelet transform

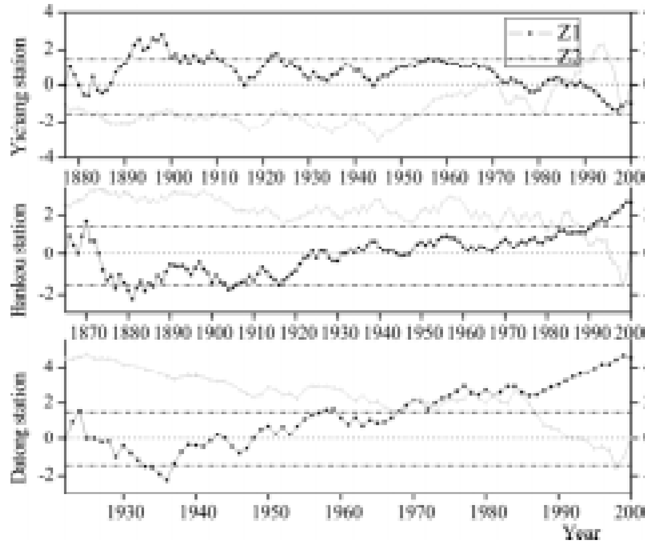

Figure 3: Mann-Kendall trends of the water level changes in the Yichang, Hankou and Datong stations.

and Mann-Kendall analysis indicates that positive wavelet coefficient (negative wavelet coefficient) corresponds to upward trend (downward trend) of discharge/water level changes. A part of Figure 4 indicates that the maximum value of the wavelet coefficient occurs in about 1919 with period of 13 years, demonstrating the strongest fluctuation in discharge change of Yichang in about 1919. Furthermore, whether from viewpoint of high-frequency or low-frequency fluctuation the isoline of the wavelet coefficient presents the stage features. As for the inter-annual discharge changes in Yichang station, they are in downward trend if seen from the long period changes; the discharge is in upward trend, however, if seen from the short term period. It should be mentioned here that, after 1992, the discharge in Yichang station is in downward trend from the viewpoint of long term changes with no closed area of negative wavelet coefficient, which indicates that the downward trend of the discharge in the Yichang station will continue in the near future.

Wavelet transform of discharge in Hankou station (B in Figure 4) shows the similar features as that of Yichange station. The maximum wavelet coefficient occurs in about 1923 with period of 13 years, which indicates that strongest fluctuation occurred in about 1923. It can also be seen from Mann-Kendall analysis result that 1923 also acts as the threshold time when the discharge change in Hankou station transferred from downward trend to upward trend. The isoline of the wavelet coefficient is scarce when compared to Yichang station, showing the more even transition between upward and downward

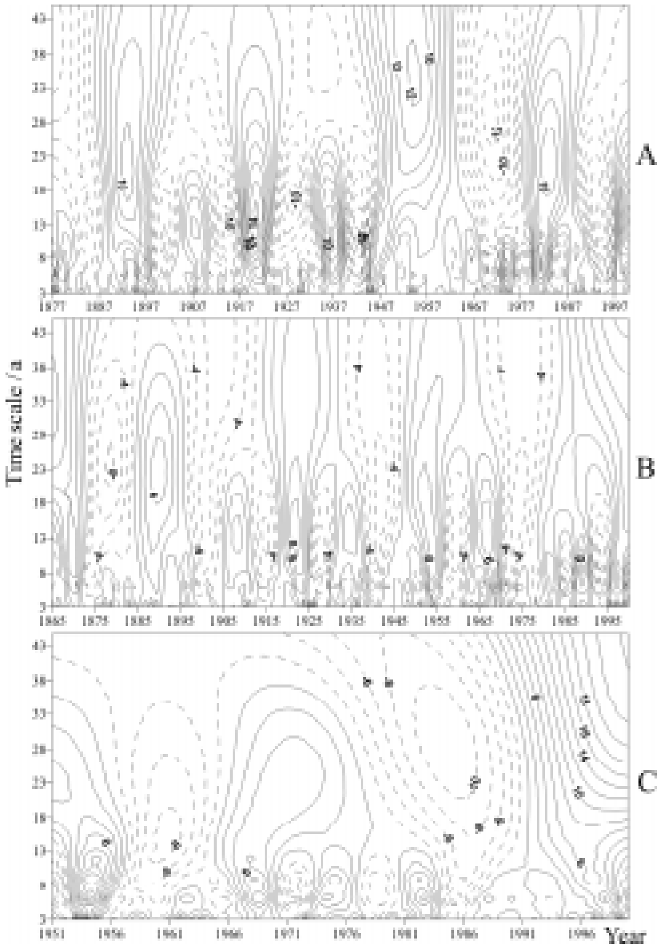

Figure 4: Wavelet analysis of the runoff changes in the Yichang, Hankou and Datong stations. A: Yichang station; B: Hankou station; C: Datong station.

trend. Furthermore, after 1980, the wavelet coefficient of discharge in Hankou station is positive value from point of long period without close region. So we can say that the discharge in the Hankou station is in upward trend in the near future, which shows the different changing features when compared to Yichang station (which is in downward trend in the near future).

Wavelet transform of discharge in Datong station (C in Figure 4) shows different changing features when compared to Yichang station and Hankou station. The low-frequent oscillations are relatively stable, but the high-frequent oscillation is strong. Different changing structures occur between low-frequent oscillation and high-frequent oscillation. It can be seen from B that the discharge changes of Datong station have the periods of about three and seven years. C also demonstrates the maximum wavelet coefficient value in about 1996 with period of 38 years, showing the strongest oscillation. During 1956-1966 and 1976-1991, the discharge of Datong station is in downward trend, during 1966-1976, however the discharge is in upward trend. After 1991, the wavelet coefficient values are positive in long period without closed area, showing that the discharge of Datong station is in upward trend in the future. These changing features are somewhat similar as those of Hankou station.

Figure 5 demonstrates the wavelet transform of water level changes in Yichang (A), Hankou (B) and Datong (C) station respectively. It can be seen from A in Figure 4 and A in Figure 5 that the wavelet transform of water level and discharge is similar in changing trends and structure. So we made no comments on wavelet transform of water level in Yichang station. As for Hankou station, the density of the isoline of wavelet coefficient of water level changes in Hankou station is larger than that of discharge changes, demonstrating that changes of water level are moderate way if compared to the discharge changes in Hankou station. B part in Figure 5 also shows that the maximum wavelet coefficient value occurs in about 1923 with period of 12 years, indicating the strongest oscillation of water level changes in about 1923. After 1923, the water level of Hankou station is in obvious upward trend with decreasing major periods, which also means that the occurrence frequency of higher water level is increasing. It should be mentioned here that, after 1995, the positive wavelet coefficient value occurs without closed area, showing that this upward trend of the water level will go on during the next several years.

The wavelet transform fabric of water level is somewhat the same as that of discharge in Datong station. After 1952, however, the wavelet transform fabrics are different. The maximum wavelet coefficient value occurs in about 1954 with period of nine years. This means that strongest oscillation occurred in nearly 1954. From the point of inter-annual changes of the water level, during 1922-1937, the water level is in downward trend; during 1937-1957, the water level is in upward trend; during 1957-1990, the water level changes are dominated by downward trends. As for the high-frequent oscillation, the changing fluctuations are quick and intensive without obvious phase features. All these results demonstrate the complexity of the water level changes and they also indicate that the factors influencing the water level changes are multiple. After 1992, the wavelet coefficient value is positive without close area, indicating that the upward trend will dominate the water level changes in Datong station in the near future.

Maximum Entropy spectrum analysis results indicate that the water level changes in Hankou station have the major periods of 2.3 years, 3.8 years and 6.2 years. The major periods of water level changes in Yichang station

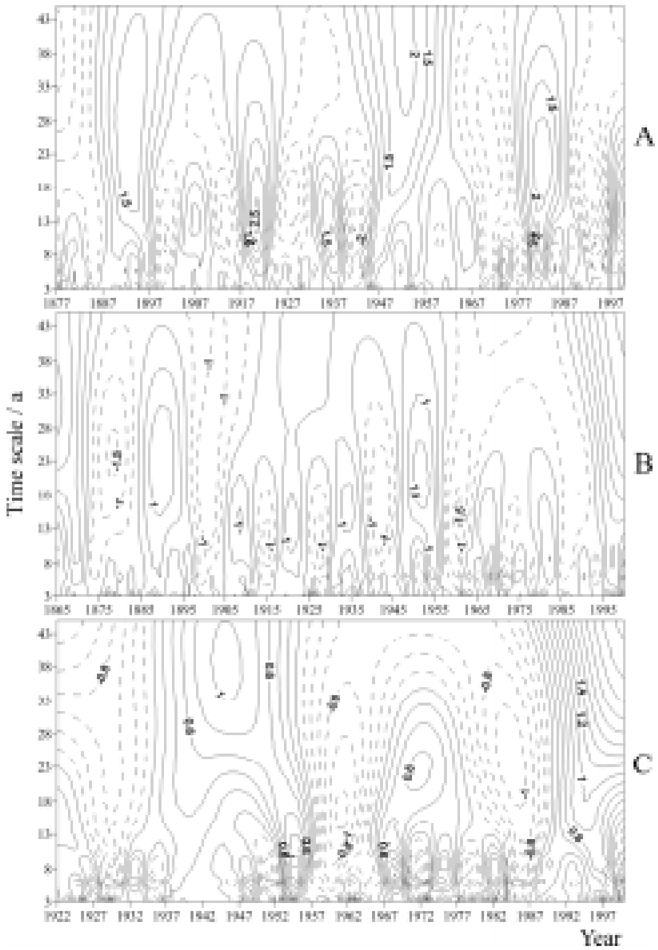

Figure 5: Wavelet analysis of the water level changes in the Yichang, Hankou and Datong stations. A: Yichang station; B: Hankou station; C: Datong station.

are of 17.7 years. Maximum Entropy spectrum analysis results, together with the wavelet transform analysis results mentioned above, indicate that discharge is in not obvious changes over time; the water level, however, is in obvious changes over time. As for the water level alone, the water level changes of Yichang station are fluctuating with no obvious trends and principles. As for the Hankou station and Datong station, the periods of water level changes are decreasing over time. This phenomenon is more obvious in Datong station if compared with Hankou station. This means that the occurrence frequency of high water level is increasing in Hankou and Datong station over time.

Summary

1. Mann-Kendall analysis of discharge in Yichang, Hankou and Datong station indicates that the changing trends of discharge in Hankou and Datong station are similar. The discharge in Datong station is in upward trend since 1965 and after 1993, this upward trend reached the 0.95 confidence level. The upward trend of discharge in Hankou station occurred since 1920, and after 1960, this upward trend reached the 0.95 confidence level. As for Yichang station, however, the changing trends of discharge are different from those of Hankou and Datong stations. The discharge of Yichang station is in downward trend since 1960. Wavelet transform analysis results of discharge of these three stations indicate that in the next several years the discharge of Yichang station is in downward trend and that of Hankou and Datong stations is in upward trend.
2. As for the changes of water level, during 1935-1937 the water level in Datong station is in upward trend; after about 1968, this upward trend reached 0.95 confidence level. As for the Hankou station, the water level is in upward trend since 1915; and after 1990, this trend reached the 0.95 confidence level. But for the Yichang station, the water level is in downward trend after 1960.
3. Wavelet transform analysis and Maximum Entropy spectrum analysis combine to show that the changes of discharge over time are not obvious, but the changes of water level over time are easily seen. Wavelet transform and period analysis results indicate that the periods of water level changes are decreasing over time. This means that water level changes are not influenced by single factor like climatic change, but by multiple factors like human activities, etc. Furthermore, decreasing periods of water level changes over time (higher occurrence possibility of maximum water level in the Yangtze River over time) mean that with the growth of population and intensifying human intervention in river channel, land use and flood mitigation, human impacts on water level will be intensifying over time.
4. 1998 floods have the “smaller discharge but more serious hazard” (Zeng et al., 1999), exemplifying the human impacts on water level changes. People built levee for flood mitigation and reclamation of lacustrine areas for agriculture aim, leaving decreasing rooms for floods. Another intensifying soil erosion because of unreasonable land use fill in the river channel leads to the decreasing storage capacity of river channel for more water. All these factors result in increasing water level though some times the discharge is small. Therefore, the middle and lower Yangtze River will face increasingly serious flood-mitigation situations in the future.

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