Temporal and spatial variation of water level in urbanizing plain river network region

Guanglai Xu, Youpeng Xu, Xian Luo, Hongliang Xu, Xiaohua Xu and Chunsheng Hu

ABSTRACT

As one of the most developed regions in China, the plain of East China is undergoing gradually increased flooding under the obvious urbanization process. This paper mainly analyses the trend of water level time series in the region during the past decades, and assesses the temporal and spatial variation of water level and indicators of hydrological alteration. The results show that there is a trend of increasing water level. Bigger slope and higher significant level can be observed in monthly minimum than in monthly maximum water level, in peri-urban than in urban areas. Meanwhile, it is observed that the mean monthly minimum and maximum water level increased in both urban and peri-urban regions, while decreased coefficients of variation (C_v) in urban and increased C_v in peri-urban regions were calculated. Most indicators of hydrologic alteration in urban stations are concentrated to the range of variability approach target, while most indicators are discrete in peri-urban stations. And the degree of hydrologic alteration is higher in peri-urban than in urban regions.

Key words | hydrologic alteration, peri-urban, temporal and spatial variation, water level, urbanization, Yangtze River Delta

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INTRODUCTION

Urbanization represents a dramatic example of human interference on the hydrological cycle (Barco *et al.* 2008). An increasing proportion of resident area has significant impacts on hydrologic and ecosystem functions and often results in excess runoff, increases in water level and diffuse pollution, and severe groundwater depletion, and thus increases the vulnerability of these areas to floods, droughts and water quality problems (Hirsch *et al.* 1990; Harden 2006).

Peri-urban catchments have complex features and dynamics (i.e. hydrological, sociological and geographical processes, etc.) (Perrin *et al.* 2001; Aragón-Durand 2007). Especially, flood prevention and control in a plain river network region (PRNR) are more difficult than in mountain areas for the flood is easy to rise and difficult to recede due to the low and flat topography, gentle slope, variable flow direction and cross-river network. Previous studies showed that human activities have strong influences on the hydrological process, and most studies focus on the response of runoff on urbanization (Burns *et al.* 2005; Barnett *et al.* 2008). However, in PRNR, the water level becomes an important basis for flood control and the final object of prediction because of runoff monitoring is difficult taking account of the complex flow convergence, low runoff velocity, and small discharge. Therefore, studies of water level in the changing environment of an PRNR are particularly necessary.

Currently, research of water level variation under urbanization is increasing, and most research has focused on the statistical methods and related spatial analysis (Yang *et al.* 2002; Chen *et al.* 2004, 2009; Yin *et al.* 2009; Zhang *et al.* 2009). Research has analyzed the changes of water levels and possible causes such as in Zhujiang Delta. However, the Yangtze River Delta is one of the biggest plains and one of the most developed economic regions in China, and studies focussing on this area are insufficient. This study attempts to analyse the variation of water level in

doi: 10.2166/wst.2014.133

both temporal and spatial scale and reveals its hydrologic alteration in the regions under rapid urbanization (PRNR) in the Yangtze River Delta. A time series analysis of water level change of the whole region under urbanization processes, a comparison of the trend of monthly water level time series, and a spatial analysis of time series slope are undertaken. Meanwhile, a comparison of the mean, coefficient of variation (C_v) and hydrologic alteration of water level before and after urbanization is made. This study tries to find the differences between urban and peri-urban regions through spatial analysis. This study is scientifically and practically helpful for flood control and sustainable development of the region under urbanization.

STUDY AREA, DATA AND METHODOLOGY

Study area

The Hang-Jia-Hu (HJH) plain is an urbanizing region in the Yangtze River Delta, located in Eastern China (Figure 1). The HJH region is about 7,607 km^2 with a mean elevation of 1.6–2.2 m above sea level and belongs to subtropical monsoon climate zone. There are dry seasons in spring, autumn and winter, and the flood season (from May to September) is during the long summer period. Under the increasing population, about 12.67 million people in 2007, the region has become intensively urbanized with an annual average population increase of approximately 0.85% during 1978–2007 (Zhejiang Provincial Bureau of Statistics 2008). Therefore, land use patterns in the HJH region have changed obviously under the impact of human activities during recent years, such as impervious areas increasing from 353 to 1,630 km^2, water area reducing from 450 to 307 km^2 during 1991–2006, and river network density reducing from 3.75 to 2.30 km/km^2 from the 1960s to the 2000s (Xu *et al.* 2010; Xu *et al.* 2013).

Hydro-meteorological data

Daily water level data during the past five decades have been collected from 16 gauging stations in study area (Table 1). Missing data are interpolated based on data at neighboring stations using regression method (10 years' data missing and accounting for 1.3% of the total number of records). In order to enable the comparability of water levels of different gauging stations, the original base surface of the water level has switched to a uniform datum, taking the elevation of the benchmark of 1985 Yellow Sea as the unified base surface.

Because the water level in the HJH region is revised by the base surface and ground subsidence (Ou & Wu 2000; Mao *et al.* 2007), the water level of the region can be obtained from the average value of water levels of each station. Regional water level data are obtained from the average value of 16 meteorological stations from 1960 to 2007. With the Pearson two-tailed test, all correlation coefficients computed between regional average and individual station are significant under the 0.001 significance level. It is seen that the mean value series can represent the changes of water level in the whole region and are even more

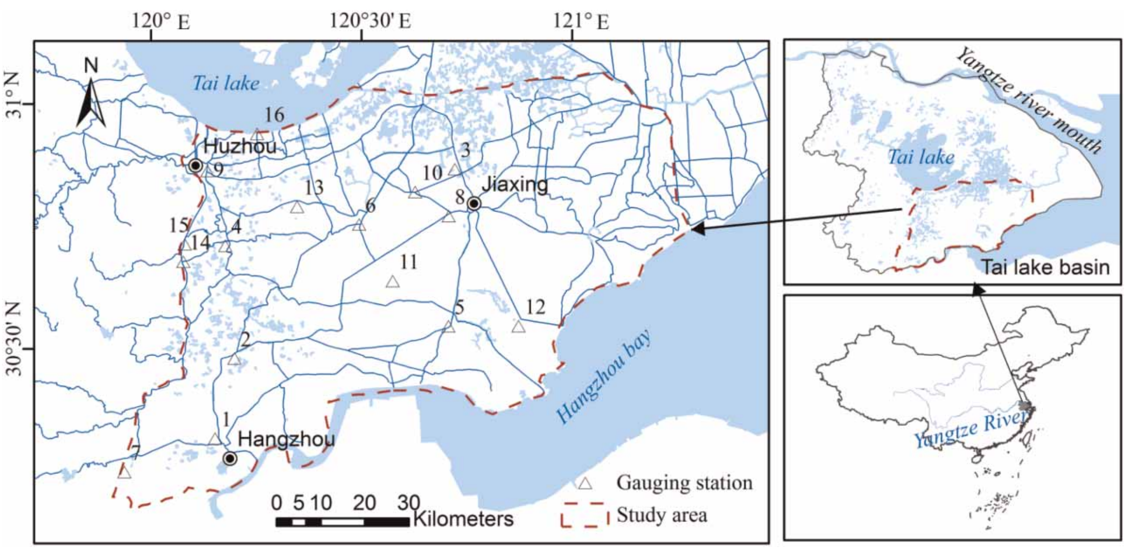

Figure 1 | Location of the HJH region and the gauging stations.

Table 1 | Location of gauging station and series length of the water levels in the HJH region

Ordinal number	Station name	Series length	E longitude	N latitude
1	GongChengqiao	1950–2007	120°08′	30°20′
2	Tangxi	1955–2007	120°11′	30°29′
3	Wangjiangjing	1955–2007	120°42′	30°53′
4	Linghu	1955–2007	120°10′	30°43′
5	Xiashi	1955–2007	120°42′	30°32′
6	Wuzhen	1955–2007	120°29′	30°46′
7	Yuhang	1951–2007	119°56′	30°18′
8	Jiangxing	1950–2001	120°45′	30°46′
9	Sanliqiao	1971–2007	120°07′	30°51′
10	Xinteng	1966–2007	120°37′	30°48′
11	Tongxiang	1961–1967,1971–2007	120°33′	30°39′
12	Yucheng	1955,1956,1964–2007	120°50′	30°32′
13	Shuanglin	1968–2007	120°19′	30°47′
14	Lianyukou	1964–2007	120°04′	30°40′
15	Jingshan	1964–2007	120°04′	30°42′
16	Huanglou	1964–2007	120°18′	30°56′

comprehensive and reliable than individual station of discontinuous distribution (Xu & Sun 2007).

Time series analysis

The simple linear regression method with parametric *t*-test method is used for trend detecting. It consists of two steps: first, fitting a linear simple regression equation with the time T as independent variable and the hydrological variable to be tested as the dependent variable, Y, (i.e. $Y_i = \alpha + \beta T_i$), and second, testing whether the slope β of the regression equation is statistically different from zero (trend exists) or not statistically different from zero (no trend exists) under a certain significance level. The parametric *t*-test requires that the data to be tested is normally distributed. The normality of the data series can be tested by applying the Kolmogorov–Smirnov test (Zhang *et al.* 2006).

Assessment of hydrologic alteration

As one set of proposed hydrologic indices, the indicators of hydrologic alteration (IHA) concept is commonly used worldwide (Shiau & Wu 2004; Magilligan & Nislow 2005; Yang *et al.* 2008; Zhang *et al.* 2009). IHA considers a full range of natural flow variability, including magnitude, frequency, timing, duration and rate of change. Thirty-one IHA parameters are categorized into these five groups of hydrologic features. In order to determine the flow regime target using IHA, the range of variability approach (RVA) has been established (Richter *et al.* 1998).

In this study, the RVA target range for each parameter is bracketed by the 25th and 75th percentile values of the pre-impact daily water level, as suggested by Richter *et al.* (1998). The degree of hydrologic alteration, D, is defined as

$$D = (N_0 - N_\xi)/N_\xi \times 100\% \tag{1}$$

$$N_\xi = p \times N_T \tag{2}$$

where $N_0 =$ observed number of post-urbanization years for which the value of the hydrologic parameter falls within the RVA target range; and $N_\xi =$ expected number of post-impact years for which the parameter value falls within the RVA target range. N_ξ can be estimated by Equation (2), where $p =$ percentage of pre-impact years for which the parameter value falls within the RVA target range, and $N_T =$ total number of post-impact years.

A positive deviation indicates that annual parameter values fell inside the RVA target range more often than expected; while negative values indicate that annual values fell within the RVA target range less often than expected (Hu *et al.* 2008); and the absolute value of D ranging between 0 and 33% represents low alteration, 33–67% represents medium alteration, and 67–100% represents high alteration.

Spatial interpolation

Besides the temporal analysis for detecting abrupt changes of water level series, the spatial patterns of water level characteristics before and after change points are analysed for understanding the spatial–temporal dynamics of hydrologic alternations over the entire study region. To generate water level surface from point-based values, the ordinary kriging method, a commonly used geostatistical technique, is employed for spatial interpolation (Chen *et al*. 2009; Zhang *et al*. 2009).

RESULTS AND DISCUSSION

Trend and change-point detection of annual water level series

The annual water level of the HJH region shows an increasing trend (Figure 2(a)). The change points of highest, mean and lowest water level all appear in 1982 (Figure 2(b)–(d)), and the change-point of mean and lowest water level reached 0.05 significance levels.

Taking 1982 as the change point of the series, the annual water level series is divided into two parts: 1960–1982 and 1983–2007. The average highest water level is 2.06 m during 1960–1982 and 2.33 m during 1983–2007 (increased 13.1%). The average mean is 1.08 m during 1960–1982 and 1.26 m during 1983–2007 (increased 16.7%). The average lowest is 0.52 m during 1960–1982 and 0.79 m during 1983–2007 (increased 51.9%).

Maximum and minimum water level

Slope of time series of individual stations

The results of the parametric *t*-test indicate that there are 321 positive slopes in all 384 maximum (minimum) monthly water level series (accounting for 83.6%). And more stations show higher slope in terms of monthly minimum water level when compared with monthly maximum water level (89.6 and 77.6% respectively). Meanwhile, 148

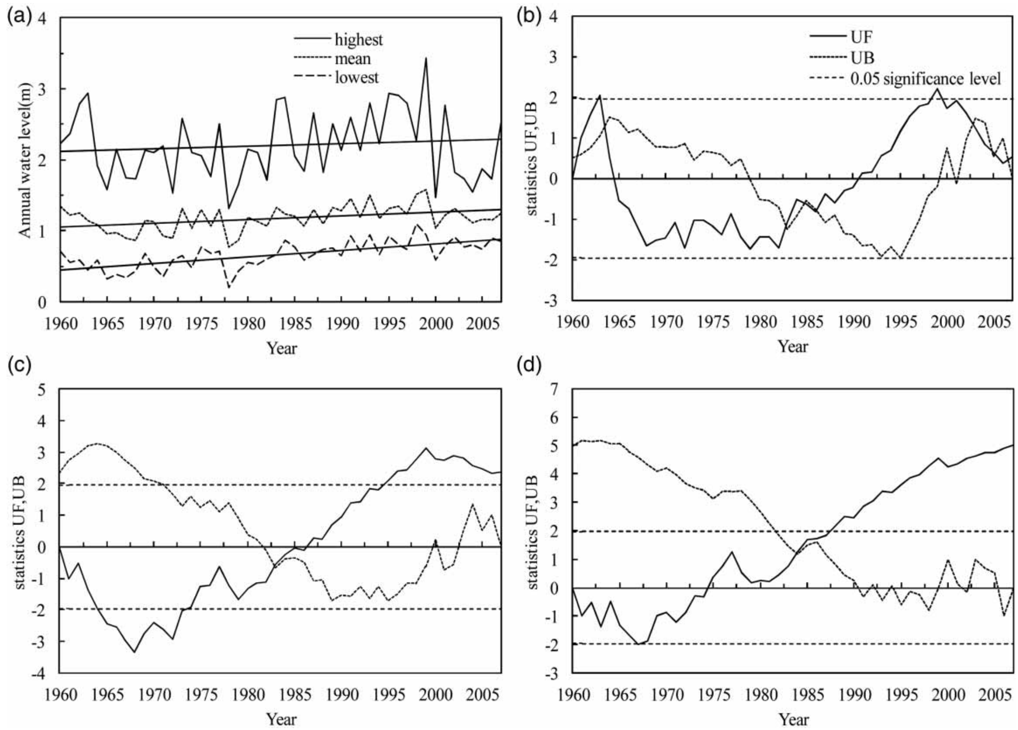

Figure 2 | Water level series of HJH region during 1960–2007: (a) linear trend of annual water level series, (b) Mann–Kendall method test of (b) annual highest water level, (c) mean water level, and (d) lowest water level. UF line: a statistic index series based on original time series; UB: a statistic index series based on adverse time series. The two lines, UF and UB, will make an intersection point during a certain time interval. If the intersection point is significant at 95% level, we say that the critical point occurred in the analysed time series at that time (Zhang *et al*. 2006).

water level series show an increasing trend under the 0.05 significance level (accounting for 38.5%). And more stations have an increasing trend in terms of monthly minimum water level compared with monthly maximum water level under the 0.05 significance level (51.0 and 26.0% respectively).

As for the specific time, the higher significant increase of monthly minimum water level at more than 10 stations can be observed in January, February, March, April, and December (dry season). And the higher significant trend of monthly maximum water level at more than seven stations can be observed in January, March, and December.

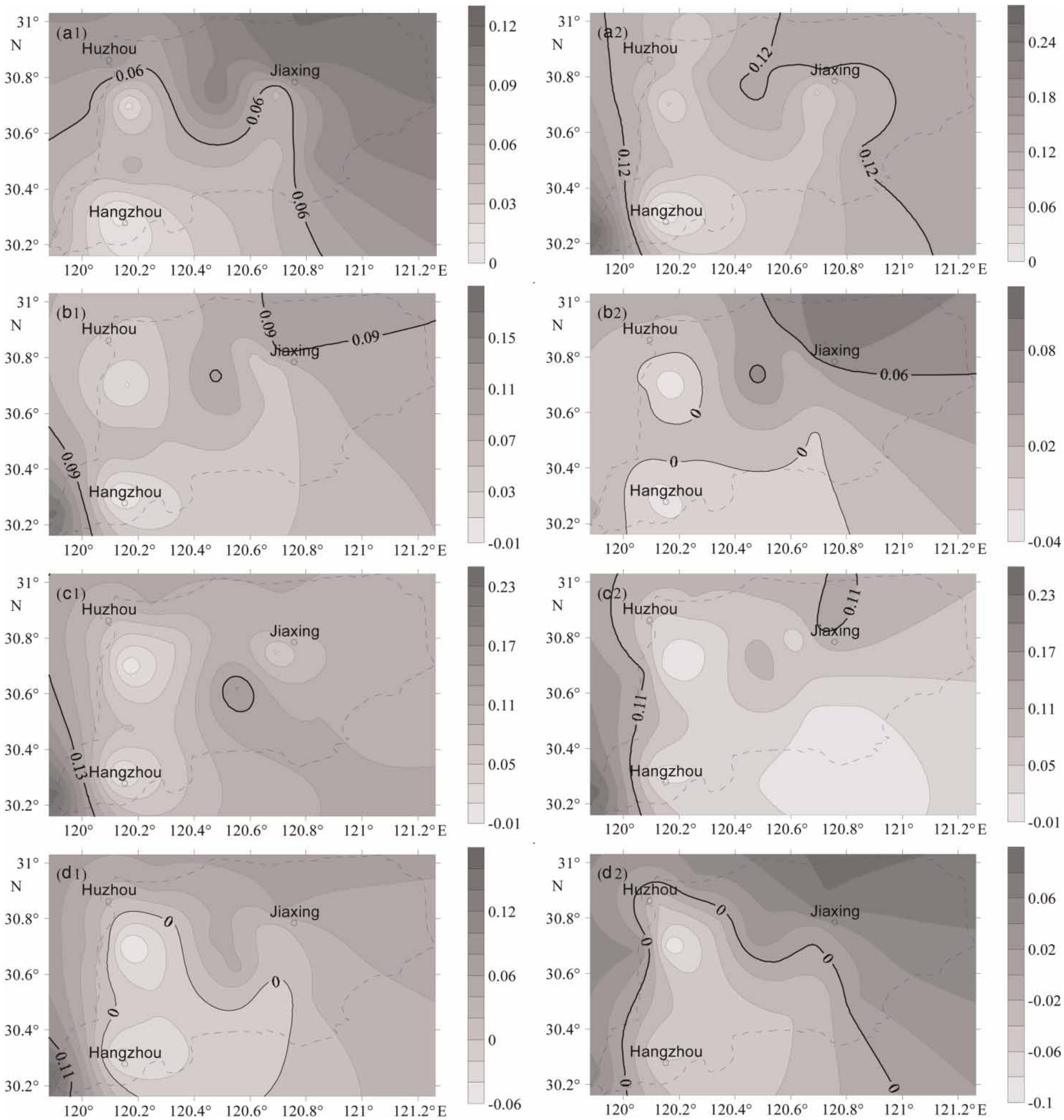

Figure 3 | Spatial distribution of linear slope of time series of water level: (a1), (a2) minimum and maximum in January; (b1), (b2) minimum and maximum in April; (c1), (c2) minimum and maximum in July; (d1), (d2) minimum and maximum in October.

Spatial distribution of time series slope of individual month

It can be observed in Figure 3 that the majority of the region is characterized by a positive slope of minimum and maximum water level. A smaller slope is detected near Hangzhou City, Jiaxing City and Huzhou City. The peri-urban region between the three cities is characterized by a larger slope of monthly minimum and maximum water levels.

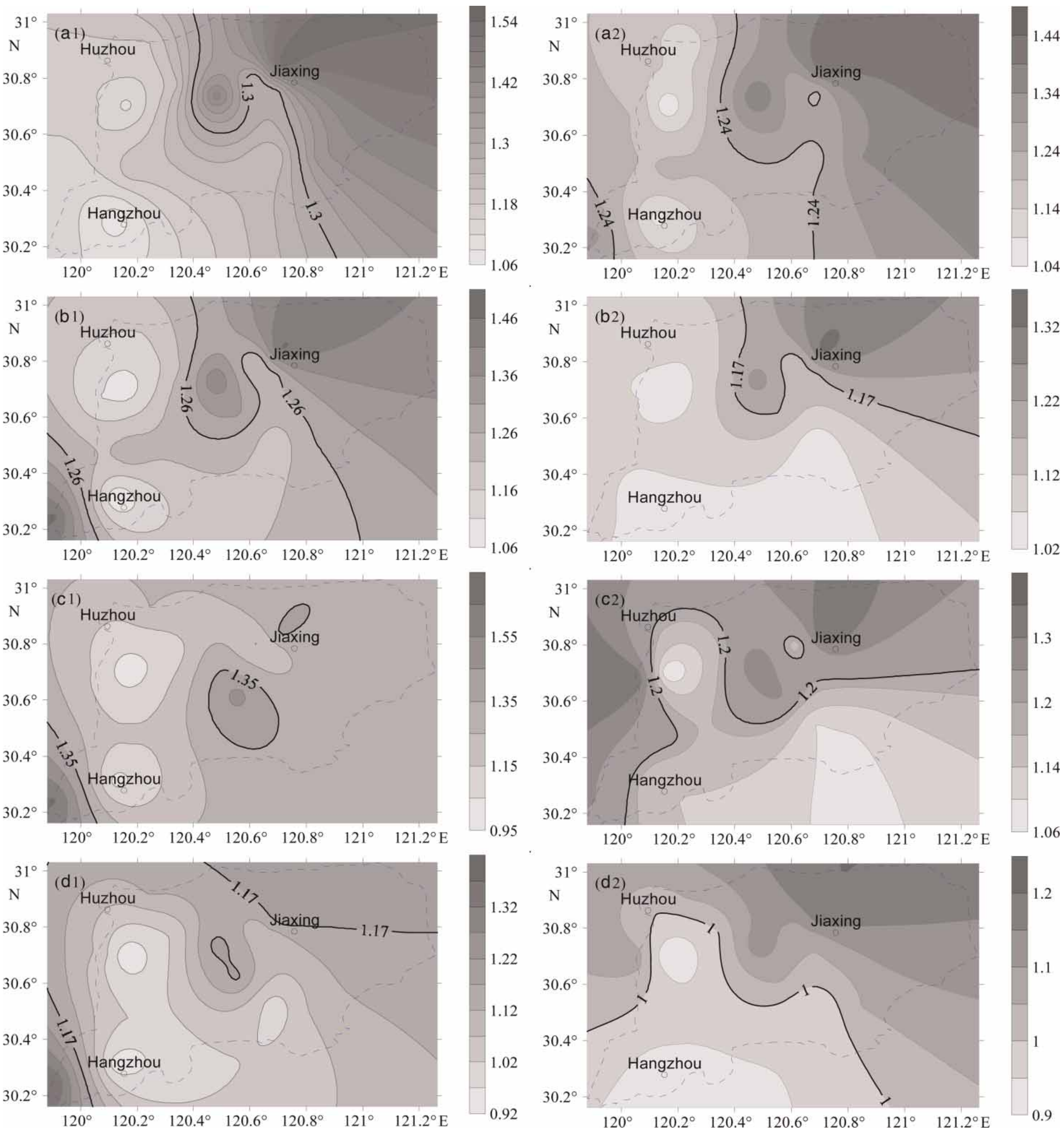

Figure 4 | The ratio of water levels before and after 1982: (a1), (a2) minimum and maximum in January; (b1), (b2) minimum and maximum in April; (c1), (c2) minimum and maximum in July; (d1), (d2) minimum and maximum in October.

Water level after/before urbanization

The ratio of monthly minimum and maximum water level after/before urbanization

The ratio indicates that 321 values are greater than 1 in all 384 ratios (accounting for 90.4%). And more ratios >1 can be observed in terms of monthly minimum water level when compared with monthly maximum water level (94.8 and 85.9% respectively).

In terms of the ratio of C_v after/before urbanization, there are 83 values >1 (accounting for 21.6%). And more values >1 can be observed in terms of monthly maximum water level when compared with monthly minimum water level (66.3 and 33.7% respectively).

Spatial distribution of the ratio of monthly minimum and maximum water level and C_v after/before urbanization

It can be observed in Figure 4 that the majority of the region is characterized by increased water level. And smaller increases are detected near Hangzhou City, Jiaxing City and Huzhou City. The peri-urban region of the three cities is characterized by highly increased monthly minimum and maximum water levels.

In terms of the C_v, most of the region is characterized by reduced C_v of monthly minimum water levels especially in July, while a major part of the region is characterized by increased C_v of monthly maximum water levels. And reduced C_v can be observed mainly near Hangzhou, Jiaxing, and Huzhou while increased C_v is mainly distributed in peri-urban regions.

Hydrologic alteration at urban and peri-urban station

To compare the IHA of the urban and peri-urban stations, Gongchengqiao station and WangJiangJing station are selected as the representative station of urban and peri-urban regions, respectively. The slopes of monthly water level of the two stations are the most and the least significantly changed.

Figure 5 shows the degrees of hydrological alteration. The solid line represents the ±67% degree of alteration, and the dashed line represents that the ±33% degree of alteration. For the urban regions, most of the degrees of hydrological alteration are located in the low and medium class. There are only two high classes of hydrological alteration (12 medium classes and 17 low classes) in all 31 indicators. And there are 20 positive values shown in the figure, which indicated that about two-thirds of hydrological indicators are more concentrated at the RVA target after urbanization. (The RVA target range for each parameter is bracketed by the 25th and 75th percentile values before urbanization.)

As for the peri-urban station, most of the degrees of hydrological alteration are medium and high class. There are 14 high classes of hydrological alteration, 10 medium classes and seven low classes in all 31 indicators. There are only two positive values and 29 negative values, which indicated that more than 90% of the hydrological indicators performed more discrete to the RVA target after urbanization.

The alterations in water levels within the PRNR region are not driven by a single factor. All the factors influencing the changes in water levels interact with each other. Previous studies showed that there are no significant trends in precipitation during the past several decades in the study area (Xu et al. 2012). The increases in impervious areas, and straightening and simplification of natural water

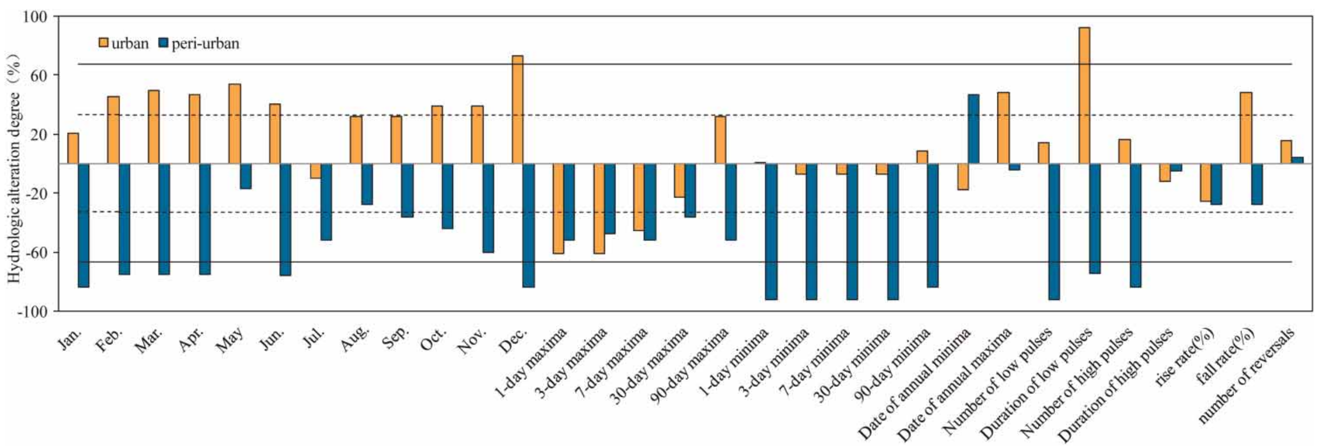

Figure 5 | Hydrologic alteration degree at urban and peri-urban station: solid line – high alteration; dashed line – medium alteration.

courses in urbanized regions may be the main factors on water level increase due to the shortening of convergence time. Meanwhile, in comparing the urban and peri-urban areas, there are a larger number of dikes and dams in the periphery of urban regions for flood control than in peri-urban regions (Lin 2002). It is the possible underlying cause of the smaller increase of water level in urban than in peri-urban areas, as well as the difference of C_v and IHA. Furthermore, because the regulation of dikes and dams to control water level in urban regions is selective due to the requirement of flood control and water transmission, some index changes in urban and peri-urban are also similar (for example, monthly maximum water level in flood season).

CONCLUSION

In this study, we employed trend analysis and the Mann–Kendall test to detect the water level changes of five decades and then analyzed the mean and C_v of water level before and after urbanization. Then, the kriging interpolation method was used to evaluate the spatial patterns of the changes. Finally, the hydrological alterations of urban and peri-urban stations were assessed comparably.

With respect to the slope of water level changes, 83.6% of series are positive slopes, and about 38.5% of changes are significant under the significance level 0.05. Bigger slope and higher significance level can be observed in monthly minimum water level than in monthly maximum water level, in peri-urban regions than in urban regions, and in December–April and October than in the other months.

With respect to the monthly minimum and maximum water level after/before urbanization, 94% of the mean water levels are increased and 78.4% of the C_v are decreased. The urban region is dominated by increased mean but decreased C_v in monthly minimum and maximum water level, while the peri-urban region is mainly dominated by increased mean and increased C_v in monthly minimum and maximum water level. And the percentages of mean increased in the peri-urban region compared to urban regions.

With respect to the hydrologic alteration of urban stations, 29 IHA of all 31 are in low and medium class, and 20 IHA (more than two-thirds of all). And about 2/3 of hydrological indicators are more concentrated at the RVA target than before urbanization. As for peri-urban station, 24 IHA are high and medium class, and 29 IHA (more than 90% of all) are more discrete to RVA target than before urbanization. Combined with the hydrological time series analysis, the rate and the pattern of water level increase are different between urban and peri-urban regions. The increasing rates are bigger in peri-urban stations than in urban stations. The increasing water level is accompanied by decreased C_v and the concentration of most indicators around the RVA target in urbanization, while the increasing water level is accompanied by increased C_v and most indicators of hydrological alteration being discrete in peri-urbanization.

ACKNOWLEDGEMENTS

This research work is financially supported by the key program of National Natural Science Foundation of China (Grant No. 41301029, 41371046, 40730635 and 41301011), and the Commonwealth and Specialized Program for Scientific Research, Ministry of Water Resources of China (Grant No. 200901042 and 201301075).

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First received 25 November 2013; accepted in revised form 27 February 2014. Available online 15 March 2014