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Nonstationary Characteristics of Precipitation and Flood Response Under Changing Environment in Taihu Basin, China

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Abstract. Change of the environment, namely climate change and human activities, is influencing hydrological cycles globally. Nonstationary changes have been widely detected in precipitation series, which has significantly increased the flood risk in various areas. Taking Taihu Basin as the typical study area, the nonstationary characteristics of precipitation are analyzed through the Mann-Kendall trend test, Pettitt abrupt change test, Sen's slope estimator and Seasonality Index in this study. Spatial distributed daily precipitation data during 1979-2017 is used. An 1D-2D coupling hydrodynamic model is built by MIKE Zero to simulate the change of flood risk under the nonstationarity of precipitation. According to the results of statistical analysis, the precipitation of Taihu Basin shows increasing trends in various temporal and spatial scales. Especially, the torrential rain and extreme precipitation, which are the main cause of flood disasters of the basin, are increasing significantly especially in highly urbanized areas such as Shanghai city. According to simulation results, the increase of flood risk shows high correlation with the nonstationary change of precipitation. The results indicate a great impact of climate change and urbanization on the regional flood risk, which must be well solved during social and economic sustainable development.

Keywords. Climate change, precipitation, Taihu Basin, flood risk, nonstationarity

1. Introduction

Under the influence of climate change and human activities, the hydrologic cycle is undergoing continuous changes globally and the frequency of extreme weather events is increasing as a result [1, 2]. As the main cause of flood disasters, precipitation has been widely detected to be nonstationary [3, 4]. Such nonstationarity impacts the flood risk of basins, thus making a great influence on flood management planning and construction. Therefore, it is of great necessity for basins and regions to explore the nonstationary characteristics of precipitation process and its influence on flood risk.

Taihu Basin is located in the middle and lower reaches of Yangtze River Basin with an area of 36900 km^2, which is one of the most developed and populated regions in China.

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With dense river networks and a large number of lakes, the water surface ratio is up to 16.6%, with half area of both rivers and lakes. According to the distribution of hydraulic boundaries such as rivers and mountains, the basin is divided into eight hydraulic regions: ZX, HX, WCXY, TH, YCDM, HJH, PX and PD region. The upper reaches of the basin are mountains and hills, which are mostly in the area of ZX region, accounting for 1/5 of the total land area. The rest of the land is totally plain river network areas. Figure 1 presents the location and topography of the basin, as well as the boundaries of the eight hydraulic regions. Taihu Basin features a subtropical monsoon climate with distinct flood and dry seasons. The long-term average annual precipitation is up to above 1100 mm, with 60% happening from May to September. The precipitation distributes unequally within the year. Flood disasters in Taihu Basin, which often occur in the wet season, are mainly caused by two types of precipitation: plum rain with long duration and large magnitude, and typhoon rainstorm with short duration and high intensity. With global climate change and developing urbanization, the basin suffers more from flood disasters in recent years.

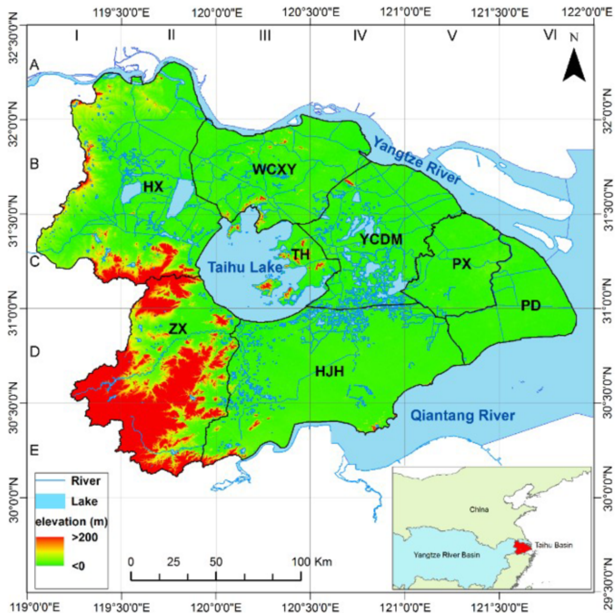

Figure 1. Topographical map and hydraulic regions of Taihu Basin.

There have already been some studies on nonstationary changes of hydrologic processes of Taihu Basin. Yang et al. [5] declared that accumulative precipitation and extreme precipitation in Taihu Basin increases with urbanization rate rising. Zeng et al. [6] studied the temporal change of annual total precipitation during 1960-2015 of Taihu Basin and a slight upward trend of about 18.8 mm per year was found, but not significant. Liu and Xu [7] took the annual total precipitation series of 1954-2006 of six stations in Taihu Basin in their study and found a wetter tendency in precipitation while it is not significant. Yu et al. [8] studied the spatiotemporal characteristics of the torrential rain of 18 stations in Taihu Basin over 1955-2010. They found more torrential rain in the northeast and less in the southwest. A general increasing trend was found in the whole basin, though the slope varies. Moreover, they found daily maximum precipitation decreased at first and then increased.

The methods used in most of the former related researches are single. There is also lack of combination of statistical analysis and numerical modelling to figure out the impact of precipitation nonstationarity on flood risk of the basin. Therefore, combining multiple statistical methods and hydrodynamic modelling, the present study aims at a comprehensive analysis of the characteristics of nonstationary change of precipitation process and the flood response to such changes.

2. Methodology and Dataset

2.1. Methodology

The methods used in this study can be divided into two types. The one is statistical methods, including modified Mann-Kendall (MMK) trend test [9], Pettitt abrupt change test [10], Sen's slope estimator [11] and the Seasonality Index (SI) [12]. The other is numerical modelling methods, for which MIKE ZERO model is used for hydrodynamic modelling of the flood process of typical area.

In detail, MMK trend test and Sen's slope estimator are applied for trend detection and estimation. Pettitt abrupt change test is used to identify the abrupt change points during the time series. SI is applied to evaluate the strength of the seasonality of precipitation process. MIKE 11 and MIKE 21 are separately used to build 1D and 2D hydrodynamic models of typical area in Taihu Basin, and MIKE Flood is used for the coupling of the two models.

2.2. Dataset for Statistical Analysis

The raw data used in this study is spatial-distributed daily precipitation provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at https://www.esrl.noaa.gov/psd/. The data covers N latitudes 30.0° to 32.5° and E longitudes 119.0° to 122.0° with grids of 0.5-degree latitude×0.5-degree longitude. The 23 subareas of Taihu Basin divided according to data grids are shown in Figure 1. The data covers the time period during 1979-2017. Based on the raw daily data, some characteristic time series were obtained. To avoid confusion, it is stated that the word "total" is used in contrast to "graded", stating whether the precipitation is the accumulation of all rainfall in the duration or with a certain intensity grade. The total and graded precipitation are jointly named accumulative precipitation herein to be distinguished from the sampled annual maximum precipitation. The characteristic time series are described as follows:

- Total precipitation on various temporal scales, including annual, seasonal and monthly.
- Total rain days on various temporal scales, mainly including annual and seasonal.
- Graded precipitation with the intensity grades of light, moderate, heavy and torrential and the temporal scales of annual and seasonal. The daily precipitation in the range of 1-10 mm, 10-25 mm, 25-50 mm and more than 50 mm are classified into light, moderate, heavy and torrential grades respectively.

- Graded rain days of different grades on various scales.
- Annual maximum n-day precipitation (PXnD) with representing extreme precipitation events with various durations.
- Annual seasonality index (ASI), representing the uniformity of the intra-annual distribution.

2.3. Setup of Hydrodynamic Model

2.3.1. Model Setup

As the region is of dense river network and numerous lakes, the model must be generalized considering the stability and speed of the model. One of the principles of generalization is keeping the capacity of water transport and storage of the water surface in the model the same as reality. Following the principle, some of the small rivers distributed densely were generalized into a wider one, and some additional storage areas were added to keep the water storage capacity.

Moreover, there is a kind of unique area called polder area in the region, which is built with a round of dike and some gates and pumps to protect the area from flood and waterlogging in low-lying areas. So, another principle of generalization is reserving the rivers connected with gates or pumps around polder areas in order to ensure the normal drainage of the polder. As the result of generalization, there are totally 740 rivers in the model.

2.3.2. Calibration and Validation

The main parameters that need to be calibrated are the bed resistance coefficients of the rivers in the 1D model. The calibration was done using the water level process of four stations in the study area during the period of June 14th to 30th, 2011. After the calibration, most of the Manning Coefficients n were valued between 0.02-0.025 and the calculated water level process fits the measured one well.

The Typhoon Haikui in 2012 and Fitow in 2013 were used for the validation of the coupling model. Table 1 shows the error of flood peak and the Nash Coefficients of each station. The largest error of water level is 13 cm, which occurs at Luoshe Station on August 9th, 2012. The Nash Coefficients of all stations are no less than 0.89, showing the high accuracy of the model.

Table 1. Error analysis of validation.

Station	Flood	Error of peak level	Nash Coefficient
Changzhou	Haikui	2	0.99
	Fitow	11	0.93
Qingyang	Haikui	12	0.92
	Fitow	7	0.95
Wuxi	Haikui	12	0.91
	Fitow	4	0.97
Luoshe	Haikui	13	0.89
	Fitow	8	0.93

2.3.3. Design Conditions

Based on the study of extreme precipitation in Taihu Basin, the key consideration of numerical modelling is the increase of precipitation magnitude of the same return period caused by nonstationarity. The return period is set to be 50a. Moreover, precipitations of both long and short duration are considered, taking 7-day and 24-hour as examples. The combination of boundary conditions of the 4 cases are listed in Table 2.

Table 2. Boundaries combination list of design conditions.

Case	Return period	Stationarity	Duration	Rainfall pattern
A	50	Stationary	7 days	1991 measured
B	50	Nonstationary	7 days	1991 measured
D	50	Stationary	24 hours	84 flood map
E	50	Nonstationary	24 hours	84 flood map

3. Results and Discussion

3.1. Nonstationary Characteristics of Total Precipitation

The mean annual precipitation of the basin is 1173.3 mm with a maximum of 1879.8 mm in 2016 and a minimum of 689.6 mm in 1994. Summer precipitation accounts for the highest proportion of the annual total, followed by spring and fall, and only 12.8% in winter. Through the Sen's slope estimation, a decreasing trend of 0.29 mm/a was detected in spring precipitation, while various uptrends were detected in annual precipitation and the other three seasonal series. However, the slopes of total precipitation on the annual and seasonal scales are all judged to be insignificant by the MMK test.

With a general understanding of precipitation characteristics on the basin scale, further discussion was made on the subarea scale to explore the spatial distribution of the temporal change mode of total precipitation. Except HX region in the northwest with a slight uptrend, positive trends beyond the 0.1 significant level were detected in all the other regions. Trends of ZX region in the southwest and YCDM region in the east are further beyond the 0.05 significance level. According to Figure 2, spring precipitation presents slight increasing trends in ZX region and the southwest part of HJH region, while slight decreasing trends were detected in HX region, WCXY region, YCDM region, and TH region. PD & PX region shows a lack of tendency. Summer precipitation shows insignificant upward trends across the basin, with ZX region of the highest significance and HX region of the lowest. Total precipitation in fall presents increasing trends in the whole basin as well. With YCDM region and PD & PX region as two growth centers, significant trends were detected in the east part of the basin, while the trend of the west part is not significant. Although winter accounts for the lowest proportion of the annual precipitation, the total precipitation presents the most widely increasing tendency among the seasons. Increasing trends beyond 0.1 significance level were detected in the whole basin except a small area in the southern ZX region and HJH region. Moreover, the significance of the trends of PD & PX region and the southwest part of HX region are further beyond 0.05.

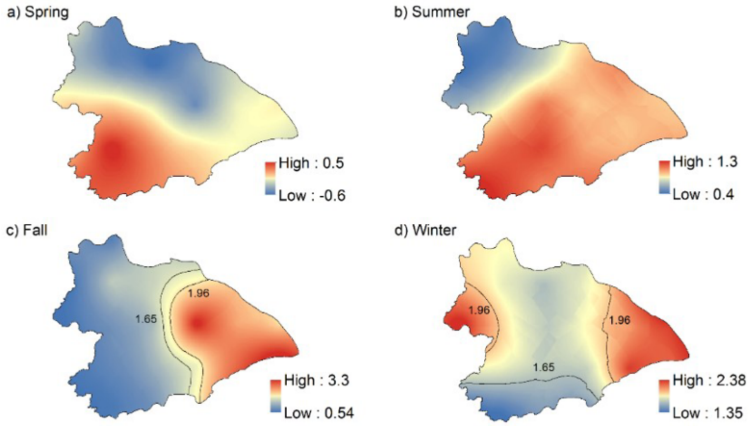

Figure 2. Spatial distribution of the MMK results on seasonal total precipitation on the subarea scale.

Besides the discussion of interannual change, the intra-annual distribution of total precipitation and its spatiotemporal characteristics were also discussed. SI of the 23 subareas indicates some level of seasonality of the precipitation, but not strong. The north part is generally classified into "Equable but with a definite wetter season" while the more seasonal south part belongs to "Rather seasonal with a short drier season". It was found by applying the MMK test on the ASI time series of all the subareas that the ASI shows an insignificant decreasing trend across the whole basin. It indicates a weakening trend of precipitation seasonality in Taihu Basin. This may be caused by the increase of precipitation in the dry seasons, namely fall and winter, while precipitation in summer has no significant trend. However, such a weakening trend of seasonality does not mean a reduction of flood risk in the wet season, but a slight growth in dry seasons.

3.2. Nonstationary characteristics of graded precipitation

In Taihu Basin, days of light rain account for nearly 80% of total rain days, while total precipitation of light rain accounts for less than 30%. Days of moderate rain account for 23.9%, only less than that of light rain, while it accounts for the highest proportion of multi-year average precipitation, up to 38.5%. The proportion of precipitation and rain days of heavy and torrential rain decreases successively. There are only 1.7 days of torrential rain annually on average, but it accounts for more than 10% of annual total precipitation due to its high precipitation intensity. With the SI of 1.070, belonging to "Most rain in 3 months or less", torrential rain shows the strongest seasonality among all grades with nearly 75% distributes in summer and hardly happens in winter and spring. It indicates that the real flood risk in the wet season may be much more than that seen from the SI of multi-year average total precipitation.

On the basin scale, various uptrends were detected in total precipitation and rain days of all the intensity grades, while only torrential rain presents a significant increasing trend with slopes of 2.253 mm/a in precipitation and 0.033 d/a in rain days. Besides, though the total rainfall and rain days of moderate rain both present large apparent slope by Sen's estimator, the null hypothesis of stationarity in the MMK test still cannot be rejected due to their strong positive long-term persistence.

Moreover, the MMK test was further applied to annual torrential rain on the subarea scale (results in Figure 3). Significant uptrends appear in most of the basin except HX region, with two increasing centers in WCXY and ZX region. On the seasonal scale, the increase of torrential rain mostly took place in summer, with an apparent slope of 1.338 mm/a beyond 0.05 significance level, while no significant trend was detected in other seasons.

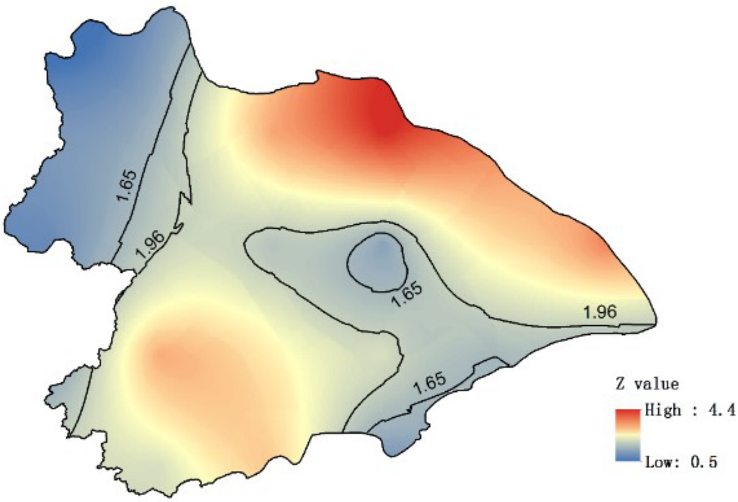

Figure 3. Spatial distribution of Z values of annual torrential rain on the basin scale through the MMK test.

3.3. Nonstationary Characteristics of Extreme Precipitation

According to the results of statistical tests, PXnD with different durations present similar interannual variation and spatial variation, while both of them decreases slightly with the duration increasing. The reason of such a decrease may be the reducing uncertainty of the variable caused by the increasing duration. Moreover, all the PXnD series present significant upward trends according to the MMK test, also with lower significance of longer durations. The increase of PXnD results in nonstationarity, which has a further impact on frequency analysis of extreme precipitation, thus affecting flood management planning and design standard of flood control structures. For instance, if the trend component is assumed to be a linear trend of the mean and remains unchanged for 50 years from 1979, the design rainstorm of the return period of 50 a and 100 a with different duration were obtained under both stationarity and nonstationarity assumptions (Table 3). With the consideration of nonstationarity, the design value of a rainstorm of the same duration increases obviously. The longer the duration and the larger the return period, the larger the increase of design rainstorm. In the case of Table 3, the design rainstorm of once in 50 a under nonstationarity nearly equals to the design value of once in a century under stationarity, suggesting a significant change of extreme precipitation process in Taihu Basin along with climate change and urbanization. As a result, the flood prevention standards of existing structures are actually falling, which should be considered in planning and design in the future.

Table 3. Design values of annual maximum precipitation (mm) of Taihu Basin under both the stationarity and nonstationarity assumptions.

	PX1D		**PX3D**		**PX7D**		**PX15D**	
	50 a	100 a	50 a	100 a	50 a	100 a	50 a	100 a
Stationarity	106.12	116.02	163.53	177.33	217.25	235.15	314.03	337.29
Nonstationarity	117.06	143.06	175.54	211.64	246.13	295.53	331.69	388.99

Moreover, there is an obvious characteristic of the intra-annual distribution of extreme precipitation in Taihu Basin. Each point in Figure 4 represents an extreme precipitation event in one of the 23 subareas during the study period (date of the medium day is used as the X coordinate, e.g. date of the 4th day for PX7D). Points with lighter colors represent precipitation events with longer duration. It is illustrated that annual maximum precipitation in Taihu Basin mostly occurs from early Jun to early Oct and points are especially dense in summer. There are also a few points in spring, while PXnD hardly occurs in winter. For PX1D, PX3D, and PX7D, there is no significant correlation between the occurring date and its precipitation amount. Meanwhile, the precipitation amount of PX15D presents strong seasonality: nearly all of the PX15D events with more than 400 mm precipitation occurs during late Jun. to early Jul., while PX15D in other months shows lower precipitation amount. The period basically coincides with the plum rain period of Taihu Basin which features precipitation with large areas and long durations. It can be preliminarily inferred that the plum rain is the main cause of the long-duration extreme precipitation in the basin.

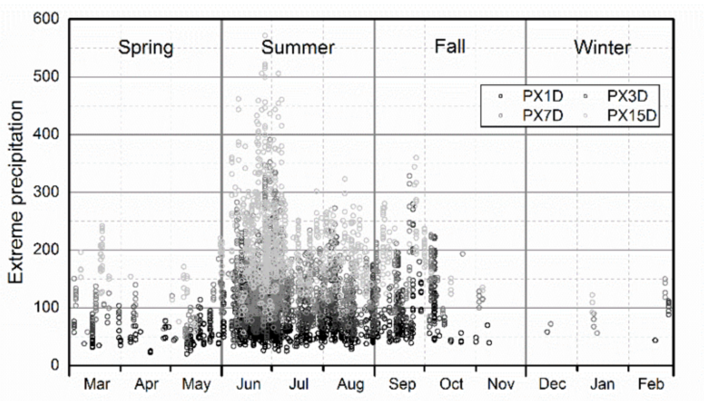

Figure 4. Intra-annual distribution of annual maximum precipitation events in the 23 subareas of Taihu Basin.

MMK test was further applied to the PXnD series on the subarea scale. The result indicates a general increasing trend across the basin. There are two increasing centers of extreme precipitation, ZX region and the east part of the basin including PD & PX region and YCDM region. Significant uptrends were detected in PX1D and PX3D in ZX region, while PX1D, PX3D, and PX7D in the east area present significant increasing trends. The northwest and the middle parts of the basin show no significant change of extreme precipitation. Annual maximum precipitation of longer than a week present slight upward trends, but not significant across the basin.

3.4. Flood Response of Nonstationary Change of Precipitation Process

In this section, simulated process of flood level of Luoshe and Chenshu stations are taken as representatives of rivers outside polders of pump-drainage area and rivers in self-drainage area separately. Figures 5 and 6 respectively shows the comparison of water level of two stations between Cases 1, 2 and Cases 3, 4, reflecting the influence of precipitation nonstationarity on the river flood process under the return period of 50 a.

Considering the increase of design precipitation magnitude caused by the nonstationarity, the flood peak of Luoshe and Chenshu in long-duration cases increases by 0.137 m and 0.143 m, while that of short-duration cases increases by 0.066 m and 0.085 m respectively. Obviously, no matter the duration, the increase of precipitation magnitude leads to the increase of flood peak level, as well as the increase of ground waterlogging. Moreover, the flood peak level of long-duration precipitation is higher than that of the short-duration cases with the same return periods.

The difference between the two types of flood processes is due to the difference in precipitation characteristics. That is, the long-duration precipitation usually shows long duration and large precipitation magnitude, which can raise the water level of the river network in a large region or even in the whole basin, making it difficult for the region to drain normally and leads to the occurrence of waterlogging in a large area. One of the common flood-causing precipitation in Taihu Basin, plum rain, is of this type. The precipitation magnitude of short-duration precipitation is lower than that of the former, but it performs high precipitation intensity in a short time and the discharge of production and confluence is much higher than the drainage capacity of polders or the speed of self-drainage, thus leading to small-scale waterlogging in the low-lying areas or the polders with insufficient drainage capacity. The other common flood-causing precipitation in the basin, typhoon rainstorm, is of this type.

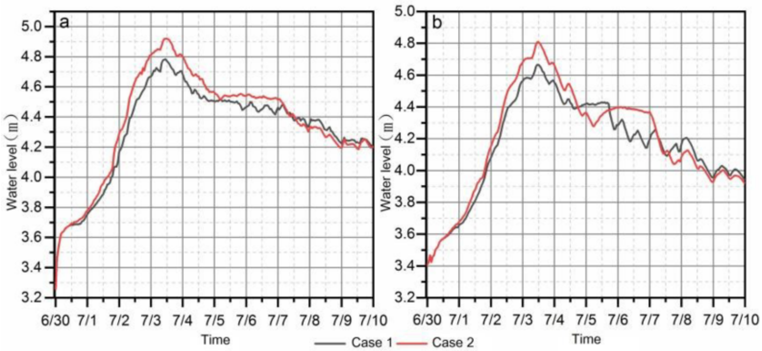

Figure 5. Influence of precipitation nonstationarity on flood level during 7-day precipitation. (a): Luoshe; (b): Chenshu.

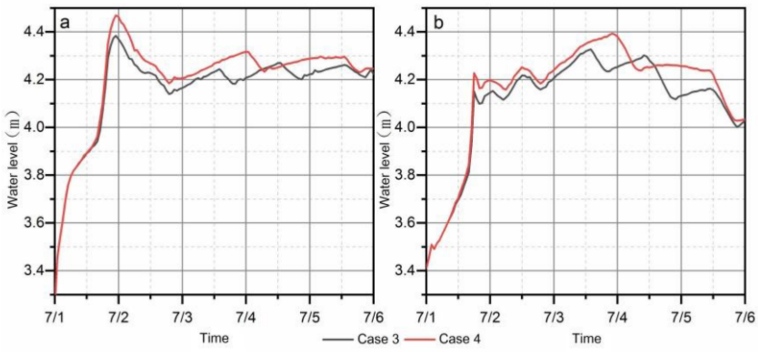

Figure 6. Influence of precipitation nonstationarity on flood level during 24-hour precipitation. (a): Luoshe; (b): Chenshu.

In addition, the maximum water level of Luoshe station is higher than that of Chenshu in the same case, and the arrival time of flood peak of Luoshe is earlier than that of Chenshu in the short-duration cases. The reason is that there are numerous polders on both sides of Beijing-Hangzhou Grand Canal where Luoshe station is located. At the time of precipitation, the intensive drainage of polders leads to the rise and advance of flood peak in the channels outside the polders, especially in cases with short-duration heavy rainfall. However, the area where Chenshu station is located is self-drainage area, artificial drainage has little influence on the flood process, and the flood process is closer to natural state. It indicates that with the construction of flood control projects, although the flood risk in polders has reduced in some level, the risk has been transferred to outer channels of the polders, especially the main flood-passing channels. The contradiction needs more attention to avoid a series of disasters, such as overflow and dambreak disaster.

4. Conclusion

In this study, the methods of statistical analysis and numerical modelling are used to study the nonstationarity characteristics of precipitation and its influence on flood process. The main conclusions are drawn as follows.

- Total precipitation is not much seasonal in Taihu Basin, which is actually influenced by the precipitation of low intensity grades which distributes uniformly during the year. The torrential rain, which poses the greatest risk to flood safety, presents as “Most rain in 3 months or less”. As the wet season of Taihu Basin, summer concentrates about 75% torrential rain and most of the extreme precipitation events. Moreover, though the uptrend of total precipitation in summer is not significant, the torrential rain and annual maximum precipitation both increased significantly in summer, indicating a change of precipitation intensity structure along with urbanization development. Increasingly serious flood risk in Taihu Basin is implied.
- PD & PX region centered on Shanghai city is with large short-duration extreme precipitation as well as significant interannual increasing trends in both the torrential rain and extreme precipitation. With a high urbanization level, the

region depends heavily on the drainage network to drain the flood as a result of the high impervious rate of the underlying surface in urban areas. The increase of short-duration rainstorm decreases the flood prevention standard of the existing drainage network, thus enlarging the risk of waterlogging disasters.

- The nonstationary change of precipitation significantly enlarges the flood risk of Taihu Basin. The construction of drainage capability of polders reduces flood risk inside the polders indeed, while the risk is actually transferred to outer flood-passing channels. The contradiction between flood control in the polder and region needs to be fully noticed and solved.

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