Evolution characteristics and variability analysis of rainfall and runoff based on time scale

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Abstract. With the rapid development of economy, the hardening area of city is increasing, which leads to the change of the runoff production law in the city. In order to understand the change of urban rainfall and runoff in the changing environment, the control basin of the Dahongmen hydrological station of Liangshui river in Beijing was selected as the research object. Mann-Kendall nonparametric rank correlation test, Non-parametric Pettitt test and qualitative and quantitative models of the Variable fuzzy set were used to study the evolution characteristics and variability of rainfall and runoff based on the measured data from 1980 to 2015. The results show that the flood peak and flood amount in the 1990s were smaller than those in 1980s, and the flood peak and flood amount were significantly greater than those in the 1980s and 1990s after 2000. The actual maximum flood peak and flood amount had significantly rising trend. For variability analysis, the mutation point of annual rainfall and runoff occurred in 1996 and 1993 respectively. They did not change qualitatively on the time scale, but only showed the quantitative variation. This study results can provide a basis for rational decision of flood prevention departments.

1. Introduction
The rapid development of economy promotes the acceleration of urban construction, which leads to the great changes of the underlying surface of the city. The increase of the surface hardening area and impermeability leads to the obvious change of hydrological characteristics in urban areas. It is mainly manifested in the increase of urban runoff generated by heavy rainfall in flood season, the increase of flood peak, the early occurrence of flood peak, and the change of peak type from the original squat type to the lean and tall type [1]. In addition, due to the obvious urban heat island effect in recent years, the local rainstorm and extreme weather are frequent [2], resulting in severe water accumulation in low-lying areas such as some sections of roads and overpasses. In recent years, the flooding caused by heavy rainfall in Beijing has occurred from time to time, which has brought great threat to social economy and people's lives. The Liangshui River, as an important flood control channel in Beijing city, plays an extremely important role in regulating waterlogging for Beijing city. Therefore, it is necessary to understand the evolution characteristics of rainfall and runoff in the Dahongmen basin of Liangshui River on the time scale.

Urban flood control and waterlogging control are a hot issue. In recent years, the research of the rainfall and runoff is not uncommon [3], especially in the series diagnosis of hydrology factor. For example Guo Ai-jun [8] analyzed the variation of the rainfall and runoff for 50 years by sliding partial correlation coefficient method and the characteristics of the rainfall and runoff by the introduction of Cupola function, proposing the contribution rate and incidence of the change of both human activities and climate condition on the rainfall and runoff; Zhu Yingjie [9] studied the spatial and temporal
variation law of rainfall in Wuzhou City, Guangxi Province, China for 30 years, and applied Kriging, IDW, Spline and Trend methods to make the difference of rainfall in Wuzhou region, and proposed the suitable method for rainfall calculation in Wuzhou City. Yufeng Cao et al. [10] analyzed the variation of rainfall trend in the Huaihe River basin over the past 58 years, and used M-K test to test the rainfall data and found the mutational site. Binyan Wang et al. [11] studied the extremes and extreme return periods of 10 short-term rainfall in Beijing by using the fuzzy identification method and statistical analysis method. Jiakai Liu et al. [12] analyzed the response characteristics of runoff to the rainfall in the Chaobai River basin on multi-scale. Based on these researches, we conclude that the study of rainfall and runoff is very important for urban flood control and waterlogging control. However there are few studies about the Liangshui River on the spatial-temporal evolution characteristics and the diagnosis of the hydrological elements in the long series.

In order to illustrate the distribution and variation characteristics of rainfall and runoff in the Liangshui River basin and evolution laws of hydrological elements in the Dahongmen control basin of Liangshui River on the time scale, the observed data from 1980 to 2015 was selected and analyzed by the methods of Mathematical statistical analysis and numerical simulation in this study.

2. Basin Overview
The Liangshui River originates from Houniwa village in Fengtai district, Beijing, China. It flows through Fengtai, Daxing and Tongzhou, and enters into the North Canal at the upstream of Yulinzhuang Gate. It is a main tributary of the North Canal. The river basin above Dahongmen Gate is the main catchment area of the Liangshui River, including Caoqiao River, Machao River and Xinfeng machao River, with a basin area of 127km². The runoff in the study area is mainly the surface runoff generated by rainfall, the industrial, agricultural and domestic sewage in this area, and the amount of rain discharged from the Youanmen Spillway. The Liangshui river, as a representative river of the North Canal system in the Haihe river basin, is an important channel for "north - south flood diversion" in Beijing. This basin is the continental monsoon climate, with an average annual rainfall of 528.4mm (1980-2015). The rainfall is mainly concentrated in the flood season from June to September, accounting for more than 85% of the annual rainfall. The annual variation of rainfall is significantly different. The average annual runoff in the drainage basin is 118 million m³ (1980-2015).

3. Methods
The linear regression analysis and Mann - Kendall nonparametric rank correlation test were used to study the change trend of the hydrological factor time series. The fuzzy mathematical model was used to diagnose the time series of hydrological factor. The diagnosis results were inspected and reviewed by the nonparametric Pettitt test.

3.1 Mann - Kendall nonparametric rank correlation test
The mann-kendall method is a non-parametric test method proposed by Mann and perfected by Kendall [13,14]. With the condition of stable hydrological and climatic series, a sequence of order

$$d_k = \sum_{i=1}^{k} r_i (2 \leq k \leq n)$$

is constructed for time series x with n sample sizes, $$r_i$$ is the accumulated value when the $$i^{th}$$ sample ($$X_i$$) is greater than $$j^{th}$$ sample ($$X_j$$) with $$1 \leq j \leq i$$.

$$E[d_i] = \frac{k(k-1)}{4}$$

$$Var[d_i] = \frac{k(k-1)(2k+5)}{72} (2 \leq k \leq n)$$

With the assumption of random independence of time series, the statistical variable is defined as:
\[ U_{F,k} = \frac{d_k - E(d_i)}{\sqrt{\text{Var}[d_i]}} (k = 1, 2 \ldots n) \]  

If the significance level \( \alpha = 0.05 \), then \( U_{\alpha,1.96} \), there is the increase trend or decrease trend, and All \( U_{F,k} \) will form a curve UF. This method was applied to the reverse sequence, then another curve UB can be got. The curves of UF and UB and \( \pm 1.96 \) were draw in a piece of paper. If the UF is greater than 0, it shows the data sequence increase, or decrease. If the UF and UB exceed the critical line, it shows that the increase or decrease trend was significant, and the exceeded range can be defined as the time range of mutational current. If the UF and UB curves intersected between the critical line, the time at which the UF and UB curves intersected would be the mutation began time.

### 3.2 Non-parametric Pettitt test

This method was first proposed by A. N. Pettitt [15], who regarded the continuous sequence as consisting of two samples \( x_1, \ldots, x_T \) and \( x_{b+1}, \ldots, x_T, \) where \( T \) is the sample size. \( U_{i,T} \) are defined as statistical variables, whose expression is:

\[ U_{i,T} = U_{i-1,T} + V_{i,T} \]  

\[ V_{i,T} = \sum_{j=1}^{T-i} \text{sgn}(x_i - x_j), t=2, \ldots, T \]  

\[ \text{sgn}(x) = \begin{cases} 
1, & x > 0 \\
0, & x = 0 \\
-1, & x < 0 
\end{cases} \]

Where, when the \( [U_{i,T}] \) reaches the maximum, that is the mutational site. Its probability can be expressed as:

\[ p(t) = 1 - \exp \left( \frac{-6U_{i,T}^2}{T^3 + T^2} \right) \]  

From equation (6), it can be concluded that the phenomenon of mutation point is more obvious when \( P(t) \) value is closer to 1. If the \( \alpha \) is the trust level and \( p(t) > (1 - \alpha) \), the trend of existed mutation point is obvious. If there are multiple points of \( p(t) > (1 - \alpha) \), the point corresponding to the maximum value of \( P(t) \) is considered as the mutation point.

### 3.3 Qualitative and quantitative models of the Variable fuzzy set

The concept of fuzzy set was proposed by Zadeh in 1965 [16]. Supposing A represents the fuzzy concept of rainfall or runoff, and u is the research object, representing the annual rainfall series or annual runoff series of the basin. Applying the qualitative and quantitative variation theorems based on the variable fuzzy set theory, the specific steps of analyzing variation points of rainfall series and runoff series are as follows:

The continuous sequence of the rainfall or runoff are regarded as the consisting of two samples \( x_1, \ldots, x_b \) and \( x_{b+1}, \ldots, x_T, \) where \( T \) is the sample size.

1. Establishing the evaluation index i of u with respect to A. For other time series variation test methods, such as Mann-Kendall non-parametric rank correlation test and Non-parametric Pettitt test, the mean value of sequences is usually used to test whether sequence is mutational or not. In this study, the mean value (i) of the sequence was selected as an indicator to test whether the sequence is stable. The evaluation index of the basin rainfall series is: \( P \rightarrow \) average rainfall (mm), and the evaluation index of the runoff series is: \( W \rightarrow \) average runoff (100 million m3).
2. Determining the supremum ($\bar{i}$) and infimum ($\underline{i}$) of the index $i$. For the determination of the supremum and infimum of each evaluation index, 95% confidence was referred to. The 95% quantile and 5% quantile of the rainfall and runoff series were used as the supremum and infimum of evaluation indexes respectively.

3. The reference period. If the first 10 years of the series was selected and the hydrological time series of this period was considered as a stationary series, the mean value ($\bar{x}_b$) of this period was calculated. As the length of the hydrological time series increases by one year every year, the mean value of the new hydrological time series was calculated $\bar{x}_{b+1}$, $\ldots$, $\bar{x}_T$.

4. To determine the relative membership degree of the mean sequence to $A$, we assumed that the size of each mean was proportional to $A$. that is, the larger, the better.

$$
\mu_j(u_i) = \frac{x_j - \bar{x}_i}{i - \bar{x}_i}, \quad j = b + 1, \ldots, T 
$$

(7)

$$
\mu_j(u_i) = \frac{x_j - \bar{x}_i}{i - \bar{x}_i} 
$$

(8)

5. The relative difference degree of the mean sequence to $A$ was determined by the formula (9) and (10). The qualitative change of the hydrological time series was analyzed according to the qualitative change and quantitative change theorem.

$$
D(u_i) = 2\mu_j(u_i) - 1, \quad j = b + 1, \ldots, T 
$$

(9)

$$
D(u_b) = 2\mu_j(u_b) - 1 
$$

(10)

If $D(u_i) \ast D(u_b) > 0$, it indicates that the rainfall series or runoff series ($u$) changes quantitatively at this point, and the rainfall series or runoff series changes to some extent. If $D(u_i) \ast D(u_b) < 0$, the $u$ is a gradual qualitative change, indicating that the change of rainfall series or runoff series has passed the critical value of qualitative change, namely the threshold value. This illustrates the rainfall series or runoff series have obvious changes. If $D(u_i) \ast D(u_b) = D(u_i) \ast D(u_b) = 0$, it indicates that the abrupt qualitative change occurs in rainfall series or runoff series $u$, and significant changes occur in rainfall series or runoff series.

6. the hydrological time series mutation site will be pointed based on the application of qualitative change and quantitative change theorem.

4 Results and Discussion

4.1 Rainfall analysis
The interval between two rainfalls is defined as non-rain or the rainfall less than a given value in this interval. By this way, a series of continuous rainfall data were divided into several independent rainfalls. In this study, the rainfall interval was set as 120 minutes. if the interval is greater than or equal to 120 minutes and the rainfall is less than 0.1mm, the continuous rainfall process is divided into two sessions, as shown in Fig. 1. Based on the above division criteria, the rainfall evens from 1980 to 2015 were 2,158.
Figure 1. The standard for the classification of rainfalls

(a) 

(b) 

(c) 

(d) 

Rainfall

Previous rainfall

Next rainfall

≥ 120 mins

0

0.5

1

1.5

2

2.5

3

3.5

0

0.5

1

1.5

2

2.5

3

3.5

Annual rainfall (mm) 

Year

Annual runoff (×10^8 m³) 

Year

Rainfall each (mm) 

Year

Flood amount (×10^4 m³) 

Year

Previous rainfall

Next rainfall

 ≥ 120 mins
According to the measured rainstorm and flood data at the Dahongmen hydrological station from 1980 to 2015, the annual rainfall change, the runoff changes, the number of rainfall, the flood peak and the flood amount changes in the Liangshui River basin were analyzed. The results are shown in Fig. 2. The annual rainfall and annual runoff showed a downward trend in Fig. 2 (a) and (b). It can be seen in Fig. 2 (c) that the sub-rainstorm volume presented a downward trend, and its correlation coefficient was 0.042. It can be seen from Fig. 2 (d) and (e) that both the sub-rainstorm flood volume and the maximum flood peak showed an upward trend, and their correlation coefficients were 0.217 and 0.312 respectively.

The annual rainfall, the annual runoff, the sub-rainstorm volume, the maximum flood peak and flood changes in the Liangshui River Dahongmen basin were analyzed by using the Mann- Kendall non-parametric rank test analysis. The results are list in Table 1. The annual runoff and annual rainfall time rainstorm presented the downward trend was not significant, the actual maximum flood peak and flood had significantly rising trend.

| Typical Basin | Test Results | Annual Rainfall | Annual Runoff | Sub-rainfall | Flood Peak | Sub-flood amount |
|---------------|--------------|-----------------|---------------|--------------|------------|-----------------|
| e Dahongmen control basin of the Liaoshui River | Statistical magnitude | -0.14 | -0.52 | -0.96 | 2.36 | 3.11 |
| | Trend | Down | Down | Down | Up | Up |
| Significance | Non-Significance | Non-Significance | Non-Significance | Significance | Significance |

Table 2 The similar groups were compared in different time periods in the study watershed

| Rain-fall | Rain-fall | Rain-fall | Rainfall | Flood | Change Rate | Flood | Change Rate |
|-----------|-----------|-----------|----------|-------|-------------|-------|-------------|
| Order     | (mm)      | Duration (h) | Intensity (mm/h) | Number | Amount (×10^4 m^3) | Peak (m^3/s) | Peak (%)     |
| 1         | 129.5     | 12        | 10.8     | 19830804 | 131       | -9.1   | 72.8        | -35.99      |
|           | 131.9     | 12        | 11       | 19980723 | 119.13    | 46.6   |             |             |
| 2         | 93.3      | 18        | 5.2      | 19810703 | 159.45    | -5.46  | 59.2        | -28.72      |
|           | 96.6      | 18        | 5.4      | 19980629 | 150.75    | 229.7  | 42.2        | 710.4       |
4.2 Analysis of flood evolution characteristics
Based on the measured rainfall data, it is divided into three time periods from 1980 to 1990, 1991 to 2000 and 2001 to 2015 by taking the time scale as the node. Similar rainfall events at different time scales are selected to analyze the flood evolution characteristics of the basin based on the time scale. The analysis results are showed in Table 2.

By comparing the similar rainfall in three periods from 1980 to 1990, 1991 to 2000, and 2001 to 2015, it can be known that the annual flood volume and peak from 1991 to 2000 were smaller than those before 1990, but the flood volume and peak increased significantly after 2000. According to the data analysis of 2 and 3 groups in Table 2, the maximum flood peak in this basin after 2000 was 7 times higher than that in 1990s, and the flood volume was 2 times and 13 times higher respectively. According to the data analysis of groups 1 and 3, the flood volume and maximum flood peak in the 1980s were larger than those in the 1990s, but the difference was not significant. The main reason was that when the underlying surface changed smoothly, the groundwater level in the basin decreased, leading to the surface runoff infiltration increased and the rainfall yield decreased. Although the rainfall duration of group 3 was about 5 hours shorter than that of group 2, the flood peak and flood volume were significantly increased.

4.3 Mutation point analysis
Based on the variable fuzzy set qualitative change and quantitative change models, the variation of the rainfall and runoff series D(uj)*D(ub) over time in the Dahongmen control basin of the Liangshuihe River from 1980 to 2015 was analyzed. Results are showed in Fig. 3. The annual runoff sequence D(uj)*D(ub) in this basin was all greater than 0, indicating that the annual runoff in the basin only changed quantitatively, without obvious variation points. The annual rainfall series D(uj)*D(ub) was greater than 0 in all years except 1996 and 1998. Since the values of D(uj)*D(ub) in 1996 and 1998 were very close to 0, we considered that the variation points of annual rainfall obtained in 1996 and 1998 were caused by random fluctuations and were not the real variation points.

The sequences D(uj)*D(ub) of the rainfall, flood peak and flood volume in the Dahongmen control basin of the Liangshuihe River were all greater than 0, indicating that only rainfall, flood peak and flood volume changed quantitatively in this basin, without obvious variation point. The fluctuations in the curve were caused only by changes in rainfall.

4.4 Mutation point test
The non-parametric Pettitt test method was used to test the mutation point of the annual rainfall and runoff time series in typical basins. The rainfall and runoff data in the basins were divided into two samples, and the 5% significance level was used to test. The test results are showed in the Table 3.

According to the analysis, the mutation points of the annual rainfall and annual runoff in the Dahongmen control basin of the Liangshuihe river occurred in 1996 and 1993, respectively, with the probability of 0.772 and 0.14 being less than 1-a, suggesting that the mutation points were not significant. The mutation points of the sub-rainfall, flood peak and flood volume all occurred in 1986, and the probability of occurrence was 0.87, 0.35 and 0.42, respectively, which were all less than 1-a, suggesting that the mutation points were not significant. The results were consistent with those obtained by variable fuzzy set qualitative and quantitative models for analyzing the variation points of hydrological series.
Figure 3. Analyzed the catastrophe point of rainfall and runoff in past year
(a) Analyzed the mutation point of annual runoff in the past; (b) Analyzed the mutation point of annual rainfall in the past; (c) Analyzed the mutation point of session rainfall in the past; (d) Analyzed the mutation point of flood peak in past year; (e) Analyzed the mutation point of flood amount in past year.

Table 3. The Pettitt non-parametric test results of rainfall and runoff in the study watershed

| Mutation point | P>0.95 | Mutation point | P>0.95 | Mutation point | P>0.95 | Mutation point | P>0.95 | Mutation point | P>0.95 |
|----------------|--------|----------------|--------|----------------|--------|----------------|--------|----------------|--------|
| of annual      | a=5%   | of annual      | a=5%   | of the sub-     | a=5%   | of the flood   | a=5%   | of the flood   | a=5%   |
| rainfall       |        | runoff         |        | rainfall       |        | peak           |        | amount         |        |
| 1996           | 0.77   | 1993           | 0.14   | 1986           | 0.87   | 1986           | 0.35   | 1986           | 0.42   |
5. Discussion

It is necessary to understand the law of rainfall yield and confluence under the condition of change of the underlying surface of city. In this paper, the evolution characteristics and hydrologic time series diagnosis and analysis of typical flood control river channels in Beijing were studied to find out the evolution characteristics and variability of hydrologic elements in typical river basins, so as to provide some basis for urban flood control.

The results show that the annual rainfall and annual runoff in the Dahongmen control basin of the Liangshui river showed a gentle downward trend. The sub-rainstorm volume showed a decreasing trend, and its correlation coefficient was 0.042. The sub-rainstorm flood volume and maximum flood peak showed the upward trend, and their correlation coefficients were 0.217 and 0.312 respectively. The analysis by the Mann-kendall non-parametric rank correlation test shows that the annual rainfall, annual runoff and sub-rainstorm showed an insignificant downward trend, while the maximum flood peak and flood volume showed a significant upward trend. By comparing the similar rainfall in three periods from 1980 to 1990, 1991 to 2000, and 2001 to 2015, it can be known that the annual flood volume and peak from 1980 to 1990 were smaller than those before 1990, but the flood volume and peak increased significantly after 2000. The maximum flood peak in this basin after 2000 was 7 times higher than that in 1990s, and the flood amount was 2 times and 13 times higher respectively. The flood volume and maximum flood peak in the 1980s were larger than those in the 1990s, but the difference was not significant. The main reason was that when the underlying surface changed smoothly, the groundwater level in the basin decreased, so the surface runoff infiltration increased and the rainfall yield decreased.

According to the analysis data of the underlying surface of the urban planning area, the impermeable area reached 31% after the 1980s. and the urbanization development was not obvious. After the 1990s, the impermeable area reached 61%; From the late 1990s to 2005, the impermeable area accounted for 62% of the total area in the Fengtai district. Based on the above analysis, it can be seen that the underlying surface changes mainly influence on the flood peak and flood amount of the rainfall, but does not influence on rainfall and annual runoff. This is mainly due to the decrease of infiltration amount causing by the increase of surface hardening area, and the sink flow increase and the confluence time decrease. As a result, the maximum flood peak and flood amount of each rainfall showed a significant upward trend. Wei zhaozhen [17] studied the changes of underlying surface in different periods in the Haihe river basin. She found that the changes of underlying surface were in a stable state before 2000, and the hardening area of underlying surface increased continuously after 2000, especially the rapid increase of urban surface hardening area in 2006. It shows that the increase of hardening area of underlying surface is the main factor of rainfall runoff, and the influence of local extreme weather is the secondary factor. This conclusion is consistent with that by Guo.

Based on the analysis of the variable fuzzy set qualitative change and quantitative change, the annual rainfall only changed quantitatively in the Dahongmen control basin of the Liangshuihe River without obvious variation points. The annual rainfall series D(uj)*D(ub) was greater than 0 in all years except 1996 and 1998. Since the values of D(uj)*D(ub) in 1996 and 1998 were very close to 0, we considered that the variation points of the annual rainfall obtained in 1996 and 1998 were caused by random fluctuations and were not the real variation points. The results of the variation points test by variable fuzzy set qualitative and quantitative models are consistent with those obtained the non-parametric Pettitt test method, so we concluded that the variable fuzzy set qualitative change and quantitative change model can be applied to analysis the variation points of the hydrologic element series.

6. Conclusion

In this paper, the Liangshui River Dahongmen control basin was taken as the research object, the measured data of rainfall and runoff from 1980 to 2015 in the Dahongmen was taken as the research basis, and the mathematical theoretical analysis and numerical simulation were combined as the
research means to study the evolution characteristics and variability of rainfall and runoff based on the time scale in the Lianshui River Dahongmen control basin. We concluded:

The significant change trends of five actual hydrological elements in the Dahongmen control basin of the Lianshui River, the annual rainfall, the annual runoff, sub-rainstorm, the flood peak and the flood amount, were analyzed by using the Mann - Kendall nonparametric rank correlation test. The results show that the annual rainfall, the annual runoff and the sub-rainstorm non-significantly presented the downward trend. The actual maximum flood peak and flood amount had significantly rising trend.

The mutatopm point of the hydrological elements in the Dahongmen control basin of the Lianshui River was analyzed by using the variable fuzzy set qualitative change and quantitative change model. The results show that the annual rainfall, the annual runoff, the sub-rainstorm, flood peak and flood amount did not change qualitatively based on the time scale, but only showed the quantitative variation of random fluctuation.

The nonparametric Pettitt test method was used to test the mutation points obtained from the qualitative and quantitative analysis of the hydrological series by the variable fuzzy set model, and the test results were consistent with that analyzed by the variable fuzzy set qualitative change and quantitative change model. It shows that it is reasonable and feasible to use the variable fuzzy set qualitative and quantitative model to analyze the hydrological series, and it provides some technical support for the related research work in the future.

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