

◆ Research Paper

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Analysis of Hydrological Characteristics of the Haihe River Basin from 2012 to 2023

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Abstract: Based on remote sensing observation data from 2012 to 2023, this study systematically analyzed the effects of rainfall and the moisture content of the 0-10 cm surface soil on the variability of evaporation in bare soil. The Mann-Kendall (M-K) mutation test method was adopted in the study to conduct an in-depth discussion on the annual average distribution of rainfall, surface soil moisture content and bare soil evaporation, as well as the monthly mutation characteristics. The results show that the precipitation and bare soil evaporation in the Haihe River Basin reach their maximum values in July and June respectively, and the surface soil moisture content reaches its maximum value in August. However, the influence of rainfall shows obvious lag and seasonal dependence, and it is found that there are significant differences in the three variables on both sides of the Yanshan Mountains. The M-K mutation test further revealed that the mutation points of the three in the annual distribution were mainly concentrated in late spring and early summer and autumn. The rainfall increased sharply in June, the surface soil moisture content increased sharply in May, and the evaporation of bare soil generally decreased sharply in November, suggesting that the climate seasonal transition and precipitation events play a key regulatory role in the evaporation process. This study provides data support and theoretical basis for understanding the surface water heat exchange mechanism in arid and

semi-arid regions and improving the parameterization scheme of bare soil evaporation in land surface process models.

Keywords: Remote sensing; Spatio-temporal variability; Mann-Kendall test; The Hai River Basin

1 Introduction

Bare soil evaporation, as a key component of the terrestrial water cycle and energy balance, directly affects soil moisture dynamics, surface energy distribution, and regional climate feedback processes [1,4]. Especially in areas lacking vegetation coverage, bare soil evaporation often constitutes the main path of surface water loss, and its spatiotemporal variability is jointly regulated by multiple environmental factors. Among them, rainfall input and surface soil moisture content are regarded as the two most direct and crucial driving factors. In recent years, with the development of remote sensing technology, surface parameter products with high spatiotemporal resolution have made it possible to study the evaporation process on a large scale and for a long time series [5]. However, there is still a lack of systematic analysis on how rainfall and surface soil moisture synergistically affect the long-term variation characteristics of bare soil evaporation, especially the abrupt changes on the interannual and monthly scales. For this purpose, based on the rainfall, surface soil moisture content of 0-10 cm and bare soil evaporation data obtained by remote sensing inversion from 2012 to 2023, combined with the Mann-Kendall (M-K) mutation test method, this paper quantitatively analyzes the variation patterns and interrelationships of the three in terms of annual mean, monthly mean and monthly mutation. The aim is to reveal the temporal characteristics of the response of bare soil evaporation to hydro-meteorological factors, providing scientific support for regional water resources management and drought monitoring [2].

2. Overview of the research area

This study area is located in the Haihe River Basin of China, which is one of the seven major river basins in our country. It is situated between 111° and 121° east longitude and 34° and 44° north latitude. The Hai River Basin is conventionally composed of three major water systems: the Hai River, the Luan River and the Tuhai Majia River. The total area of the basin is approximately 318,000 square kilometers, accounting for 3.3% of the country's total area. To the north of the basin lies the Yanshan Mountains, and to the west is the Taihang Mountains. The two

mountains are connected and distributed in an arc from northeast to southwest. To the west and north of the mountains lies the Loess Plateau, while to the east and south of the mountains is the vast North China Plain.

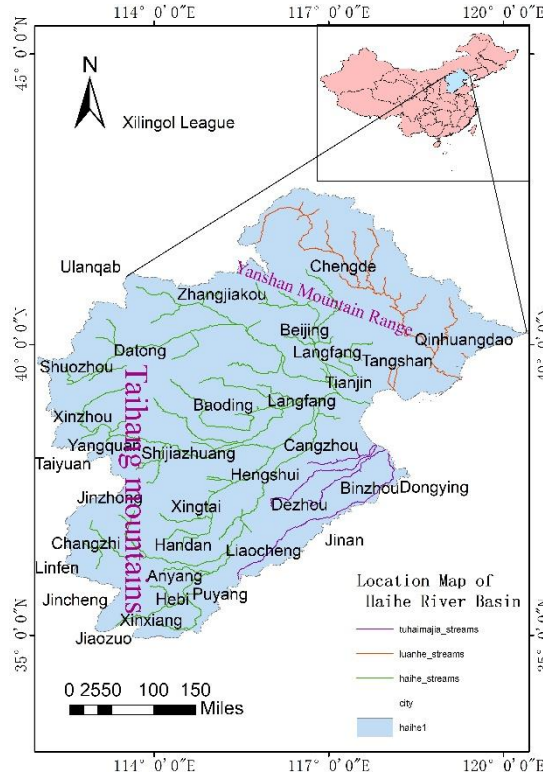


Figure 1 Haihe River Basin and its three major water systems

The Haihe River Basin, as an important water system in northern China, has had a profound impact on the regional economy, society, and ecological environment due to its frequent flood disasters. Influenced by complex meteorological conditions such as terrain uplift, convergence of subtropical high pressure and cold air, the Haihe River Basin experiences frequent and intense rainstorms. Coupled with steep mountainous slopes and short transitional plains, this leads to rapid rises and falls of floods, high peak values, and short durations, making it highly prone to extremely severe floods. In recent years, the three extremely severe rainstorm events in Beijing, namely "7·21" (2012), "7·20" (2016), and "23·7" (2023), have all posed significant threats to the Haihe River Basin. Their impact scope, disaster intensity, and challenges faced are all typical. In the "7·21" rainstorm in 2012, parts of the Beijing Metro Airport Line were suspended, the 6th Line construction site collapsed, and flights were severely delayed; after the "7·20" rainstorm in

2016, the Beijing Miyun Reservoir increased its water storage by 21 million cubic meters, but it also led to local water quality deterioration; the "23·7" rainstorm in 2023 triggered a major flood in the Haihe River Basin, affecting over 5 million people, with 22 rivers exceeding the warning level and 8 rivers experiencing their largest historical floods. The Yongding River and the Daqing River experienced extremely severe floods, and the Zhaowei River had a major flood. The Ministry of Water Resources initiated the highest-level emergency response and activated 8 flood storage and retention areas, presenting unprecedented challenges in engineering scheduling.

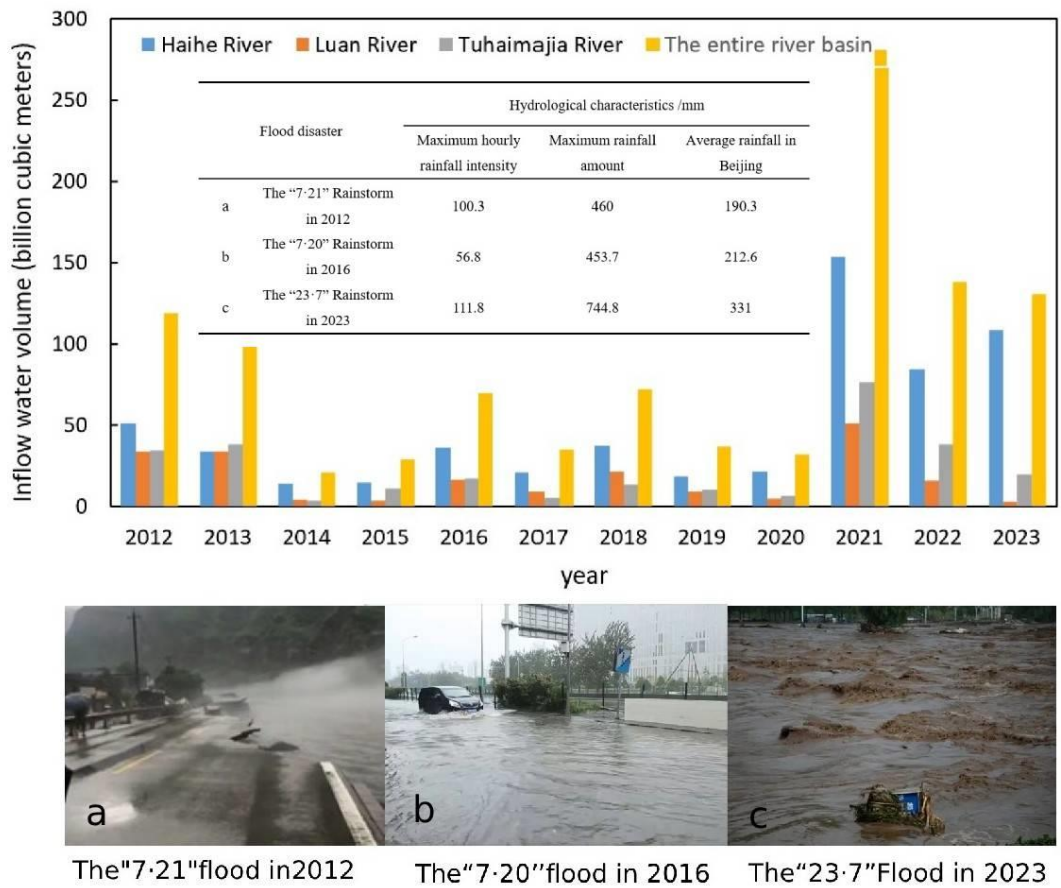


Figure 2 Inflow volume and flood disasters of the Haihe River Basin from 2012 to 2023

(a) A road in Chenjiatai Village, Fuzijiu Township, Fangshan District, Beijing; (b) Guang'an Road in Fengtai District, Beijing; (c) Yongding River Estuary Village

3. Data Sources and Research Methods

3.1. Data Sources

All the data used in this article are from remote sensing satellites. This includes the monthly precipitation data of the Haihe River Basin region from January 2012 to December 2023 in the

1km resolution monthly precipitation dataset of China, and GLDAS 2.1 Noah's 0.25° resolution monthly scale data of surface soil moisture content at 0-10cm from January 2012 to December 2023 and the monthly scale data of bare soil evapotranspiration in GLEAM dataset v3.7b version from January 2012 to December 2023 The GLEAM dataset v3.7b is a global dataset spanning 20 years from 2003 to 2022. This dataset is mainly driven by satellite data. GLEAM provides data on different components of land evaporation (or "evapotranspiration"): Transpiration, exposed soil evaporation, retention loss, open water evaporation and sublimation, as well as other related variables such as surface and root zone soil moisture, sensible heat flux, potential evaporation and evaporation stress conditions, this paper will use the data of exposed soil evaporation.

3.2. Research Methods

The Mann-Kendall trend test (M-K) is a widely used statistical test method, and the M-K mutation test is a non-parametric statistical method [8]. Non-parametric test methods, also known as non-distribution tests, do not necessarily have the characteristics of a normal distribution for the changing elements and are not affected by a few outliers. They have a high degree of quantification, a wide detection range, low interference, and simple calculation. They are mainly used to identify trend changes and sudden change points in time series data. It does not rely on the distribution of data, and thus is suitable for various types of data, especially for data analysis in fields such as environment, meteorology and economy. This method was initially proposed by H.B. Mann and M.G. Kendall and is now widely applied in the trend analysis of factors such as climate change, precipitation, temperature, and runoff. Let A_1, A_2, \dots, A_n is a time series variable and n is the number of samples, then the statistic S can be defined as:

$$S = \sum_{i=2}^n \sum_{j=2}^{i-1} \text{sgn}(A_i - A_j) \quad (1)$$

In the formula: sgn represents the symbolic function;

S represents the normal distribution, with a mean equal to 0. Its variance is calculated as shown in Equation (2).

$$\text{Var}(S) = n(n - 1)(2n + 5)/18 \quad (2)$$

$$\text{sgn}(A_i - A_j) = \begin{cases} 1 & A_i - A_j > 0 \\ 0 & A_i - A_j = 0 \\ -1 & A_i - A_j < 0 \end{cases} \quad (3)$$

The Z values corresponding to different S intervals in the Mann-Kendall statistical formula

are:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & S < 0 \end{cases} \quad (4)$$

Then, the M-K test was used for mutation analysis.

In conclusion, in the M-K trend test, when substituting the specific confidence level a value, if $Z \geq Z_{1-\alpha}/2$, the assumption does not hold. When $Z > 0$, it indicates an increase in amplitude; when $Z < 0$, it indicates a decrease in amplitude. When $Z \geq 1.28$, it indicates that the significance test is greater than 90%; when $Z \geq 1.64$, it indicates that the significance test is greater than 95%; when $Z \geq 2.32$, it indicates that the significance test is greater than 99%.

Then, the M-K test method was used for time series mutation analysis, and the structure is shown in Equation (5):

$$S_k = \sum_{i=2}^{i=n} \sum_{j=2}^{j=n-1} a_{ij} \quad (5)$$

$$k = 2, 3, 4, \dots, n$$

In the formula: $a_{ij} = \begin{cases} 1 & A_i > A_j \\ 0 & A_i < A_j \end{cases} \quad 1 < j < i$

The calculation formula of the statistic:

$$UF = \frac{S_k - E(S_k)}{\sqrt{Var(S)}} \quad (6)$$

$$k = 1, 2, 3, 4, \dots, n$$

In the formula: $E(S_k)$ represents the mean, and $Var(S_k)$ represents the variance. Calculate according to formula (7):

$$E(S_k) = \frac{k(k+1)}{4} \quad Var(S_k) = \frac{k(k-1)(2k+5)}{72} \quad (7)$$

The time series follows A_n, A_{n-1}, \dots , Arrange A_1 in sequence, and according to the above method, make $\begin{cases} UB_k \\ k = m + 1 - k \end{cases} \quad k = 1, 2, 3, 4, \dots, n$ to UB_k and UF_k the curve is plotted. In the confidence interval $U \leq 1.96$, if the UB_k and UF_k curves intersect, then the intersection point is the sudden change point of this time series, and the input confidence level is 0.95.

4. Spatio-temporal variation characteristics of precipitation, surface soil moisture content and bare soil evaporation

4.1. Interannual spatiotemporal distribution of precipitation, moisture content of surface soil and evaporation of bare soil

The three most important factors influencing the soil moisture content in the study area are precipitation, soil moisture content and bare soil evaporation. Among these three factors, the one that has the most direct impact on bare soil evaporation is the surface soil moisture content, that is, the soil moisture content within 0-10cm. In this article, the units of precipitation and bare soil evaporation are both mm. The soil moisture content used is soil volumetric moisture content, that is, the percentage of water volume in a unit volume of soil to the total volume. The temporal and spatial variation patterns of precipitation, 1-10cm surface soil moisture content and bare soil evaporation in the Haihe River Basin from 2012 to 2023 within the study area are shown in Figure 3 and Table 1. The spatial distribution pattern of the multi-year average precipitation over the past 10 years is high in the southeast and low in the northwest, and it transitions from the humid area to the arid area within the study area. The multi-year average precipitation in the study area mainly ranges from 843.2mm to 331.8mm, and the average multi-year average precipitation in the Haihe River Basin during the study period is 526.58mm. The Hai River Basin belongs to the semi-humid and semi-arid continental monsoon climate zone. The average annual precipitation in Datong, Shanxi Province in the northwest and most areas of Inner Mongolia within the basin is less than 400mm, and the area of this part accounts for 5.95% of the total area of the study area. It can be seen from Figure 3(a) that there is a significant difference in the average annual precipitation with the Yanshan Mountains as the boundary. This might be because the mountains prevent the flow of water vapor in the air, which in turn leads to a significant difference in rainfall on both sides of the Yanshan Mountains.

The spatial scale variation pattern of the average annual soil moisture content of 0-10cm in the Haihe River Basin over 12 years is that the difference is smaller in the south and larger in the north. As can be seen from Figure 3(b), the average annual soil moisture content of 0-10cm in the study area ranges from 32.62% to 15.74%. Among them, the maximum and minimum soil moisture content of 0-10cm in the study area both occurred in the northern region. The maximum value was in the southeast of Tianjin and the southeast of Beijing, and the minimum value occurred in Xilingol League, Inner Mongolia City, in the northwest corner of the basin. The reason for this is that the southeastern part of Xilingol League has less precipitation and a large

evaporation rate, so the soil moisture content is low.

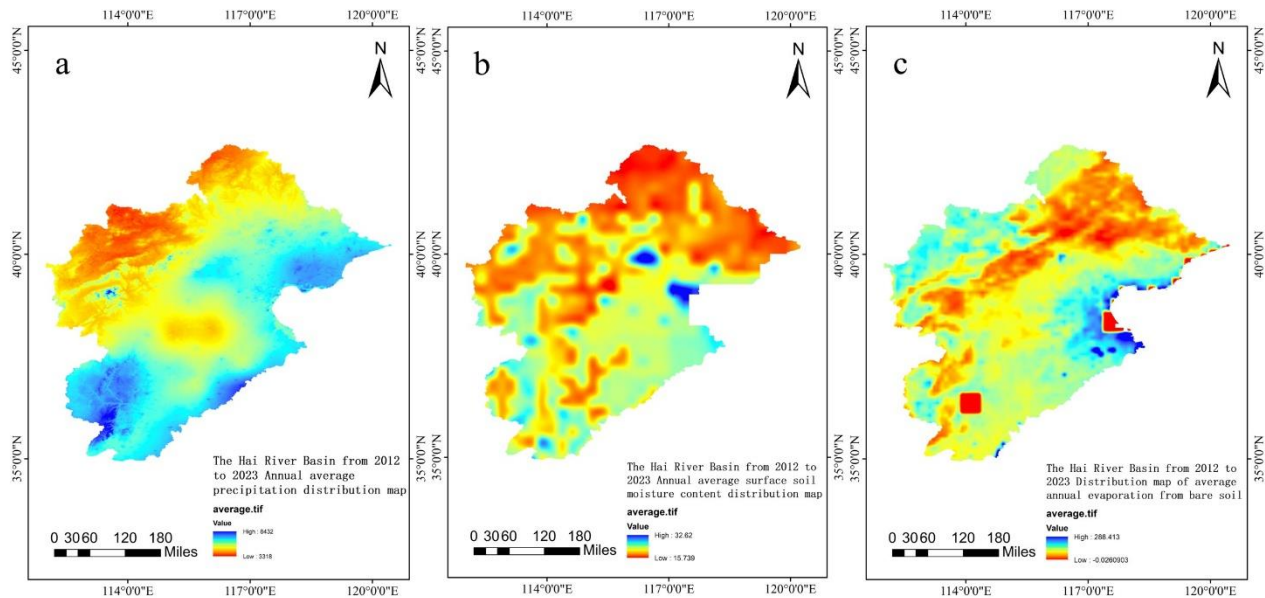


Figure 3 Multi-year average data of the Haihe River Basin from 2012 to 2023

The variation pattern of bare soil evaporation in the study area (excluding plant interception evaporation, plant transpiration, snow sublimation and open water evaporation) in spatial scale is that the bare soil evaporation in the eastern part close to the ocean and the western part far from the ocean is higher, while the bare soil evaporation in the middle area is relatively lower. As shown in Figure 3(c), the evaporation of bare soil first decreases and then increases from the east to the west. Generally, the evaporation of bare soil is relatively low in the Yanshan Mountains and Taihang Mountains. The overall 12-year multi-year average bare soil evaporation in the Haihe River Basin ranged from 288.41mm to -0.03mm, and the average value of the entire study area was 100.76mm. Negative values in evaporation data indicate negative latent heat flux, which is due to the period of net condensation of water vapor to the land surface (negative latent heat flux). This is a standard feature of the dataset and usually occurs when the net radiation on the surface is negative. The areas with bare soil evaporation greater than 200mm in the Haihe River Basin account for 4.39% of the entire basin area, mainly located in Binzhou City, Shandong Province. In addition, there are also small areas with bare soil evaporation greater than 200mm in the southwestern part of Dezhou City, Shandong Province and the coastal areas of Tianjin City. The areas with bare soil evaporation of less than 100mm in the Hai River Basin are distributed near the Yanshan Mountains and the Taihang Mountains, accounting for 45.99% of the entire basin area.

4.2. Monthly scale variation Analysis of precipitation, surface soil moisture content and bare soil evaporation

The variation relationships of monthly precipitation, surface soil moisture content and bare soil evaporation in the study area in different months are shown in Figure 4. The total annual precipitation in the Haihe River Basin is 526.07mm and the total annual bare soil evaporation is 100.44mm. The precipitation and bare soil evaporation in the Haihe River Basin reach their maximum values in July and June respectively, among which the precipitation is 163.17mm. The evaporation of bare soil was 15.85mm, and the moisture content of the surface soil reached its maximum in August, which was 26.19%. The precipitation and bare soil evaporation in the study area reached their minimum values in January, which were 3.18mm and 2.61mm respectively, and the surface soil moisture content reached its minimum value in February, which was 16.97%. To sum up, the changing trends of the three variables are relatively consistent, reaching their maximum values in June, July and August during summer, and their minimum values in January and February during winter. In June, July and August, the total precipitation in the study area was 354.19mm, accounting for 67.3% of the annual precipitation. The total evaporation of bare soil was 36.4mm, accounting for 36.24% of the annual evaporation of bare soil. The average moisture content of the 0-10cm surface soil in June, July and August was 21.72%, and the annual average in the study area was 20.65%. During the two months of January and February in winter, the total precipitation in the study area was 9.16mm, accounting for 1.74% of the annual total. The total evaporation of bare soil was 7.05mm, accounting for 7.02% of the annual total. The average soil moisture content of 0-10cm was 17.25%.

In order to further determine the monthly variation trends of the average precipitation, the average 0-10 soil moisture content and the average bare soil evaporation in the Haihe River Basin, and to identify their mutation points, the MK test was conducted to verify the three variables. The MK mutation test, usually referred to as the Mann-Kendall (MK) mutation test, is a non-parametric statistical test method used to detect whether there are mutation points or trend changes in time series data. This method was independently proposed by Henry B. Mann and Maurice G. Kendall respectively, and thus got its name. The precipitation in spring and winter accounts for too small a proportion of the annual precipitation and can almost be ignored. Therefore, the MK test for precipitation this time only includes the precipitation in summer and

autumn, that is, from May to October. The MK test trend chart of precipitation in summer and autumn is shown in Figure 5. The detailed data of the average monthly precipitation in each month of the study area from summer to autumn in 2012 to 2023 are shown in Table 1.

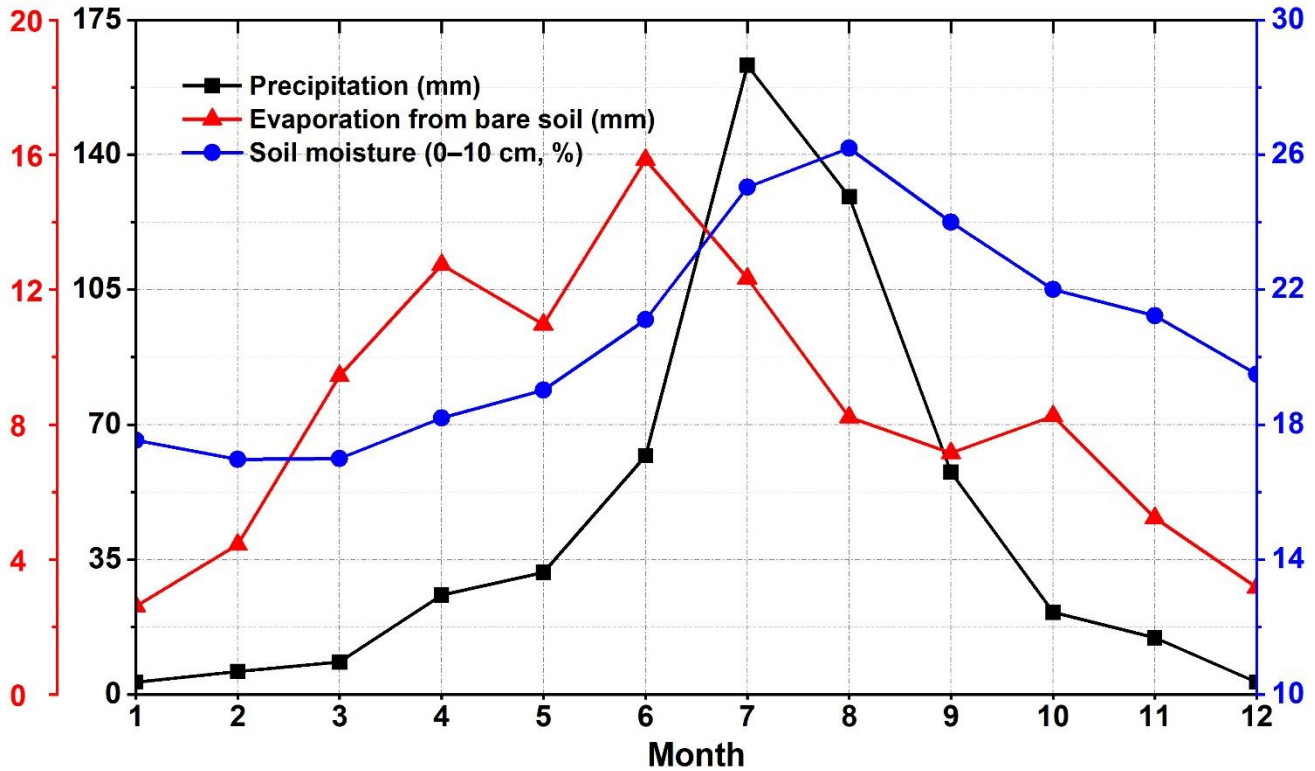


Figure 4 Monthly scale variations of precipitation, soil moisture content from 0 to 10cm, and evaporation from bare soil

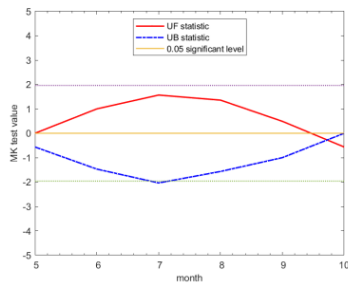
Table 1 Detailed data of MK test for summer and autumn precipitation from 2012 to 2023

| mon th | year | | | | | | | | | | | |
|-----------|------|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
| 5 | 20.6 | 23.5 | 42.8 | 36.2 | 37.8 | 30.59 | 35.14 | 34.42 | 43.26 | 24.02 | 18.81 | 33.10 |
| 6 | 77.4 | 87.1 | 73.7 | 55.1 | 80.9 | 67.67 | 55.72 | 38.07 | 50.60 | 45.48 | 76.05 | 35.21 |
| 7 | 196 | 204 | 110.3 | 104.1 | 227 | 127.4 | 186.9 | 104.1 | 130.5 | 188 | 204.9 | 176.9 |
| 8 | 97.9 | 101 | 83.1 | 122.1 | 143.5 | 171.1 | 13.90 | 151.7 | 184.3 | 124.5 | 113.1 | 120.0 |
| 9 | 69.1 | 56.7 | 87.4 | 64 | 44 | 22.67 | 42.11 | 57.22 | 61.52 | 113.9 | 20.29 | 52.87 |
| 10 | 16.3 | 15.4 | 15.6 | 19 | 47.7 | 25.65 | 8.24 | 26.38 | 10.15 | 30.44 | 21.09 | 20.50 |

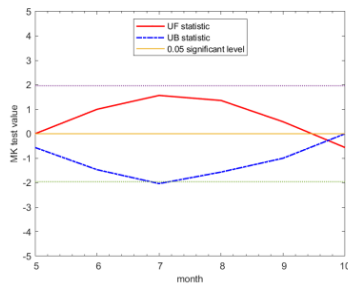
Note: The data in the table are the detailed precipitation data used for the MK test, with the unit being mm.

According to the results of the M-K trend analysis of precipitation in summer and autumn (from May to October) from 2012 to 2023, in 2012, 2013, 2014, 2016 and 2018, the UF and UB curves of precipitation M-K in the study area did not exceed the critical line. It indicates that the precipitation variation trends in summer and autumn of these years are generally stable, while there are significant variation trends in the remaining years. As shown in Figure 13, there are significant changing trends in August 2015, 2017, 2019, 2020, October 2022 and 2023, and July 2021. It can be seen that the months with a significant increase in precipitation within the research time period are mainly concentrated in July and August.

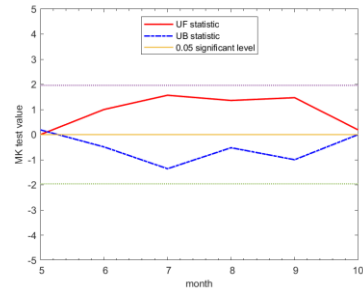
The UF curves in October 2012, 2013, 2018 and 2023 were negative, indicating a decreasing trend in precipitation. The UF curve value in September 2018 was 0, suggesting that the changing trend could be disregarded. The UF values in all other months were positive, indicating an increasing trend in precipitation in that month. Among them, The UF curve values greater than 1.96 in August 2015, 2017, 2019 and 2020 indicate that the precipitation significantly increased at the 0.05 confidence level. The UF curve value less than -1.96 in July 2021 indicates that the precipitation significantly decreased at the 0.05 confidence level in that month. Mutations occurred in June 2014, 2015, 2019, 2020 and 2021, and the intersection points of the UF and UB curves were all positive, indicating the existence of mutant growth. In September 2017 and 2022, the UF and UB curves intersected and were positive, indicating significant growth. In October 2012, 2013 and 2018, there were intersections of the UF and UB curves. The intersections in all years were negative, indicating a sudden decline. The intersection points of the UF curve and the UB curve of the M-K test for summer monthly precipitation in the study areas of 10 years were all within the test range, indicating that it passed the 0.05 significance test within the confidence level interval.



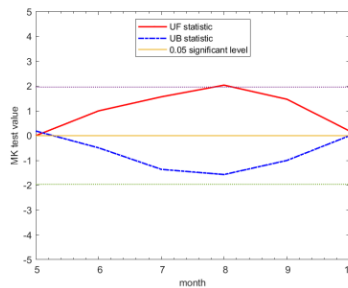
(a) 2012 M-K Test



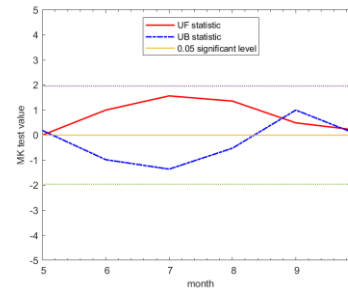
(b) 2013 M-K Test



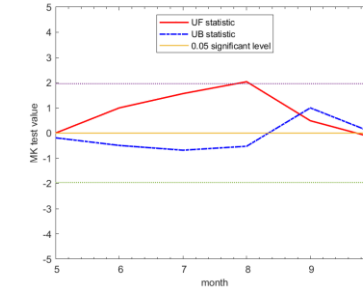
(c) 2014 M-K Test



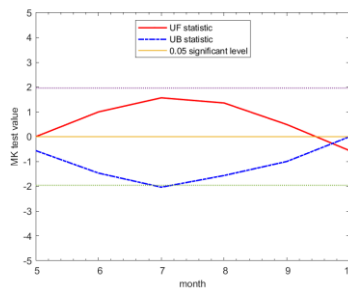
(d) 2015 M-K Test



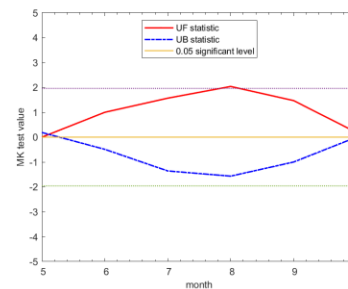
(e) 2016 M-K Test



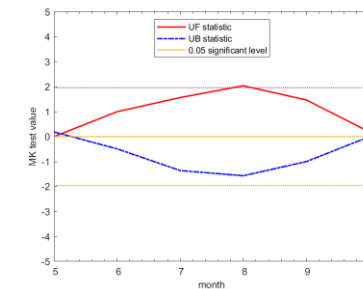
(f) 2017 M-K Test



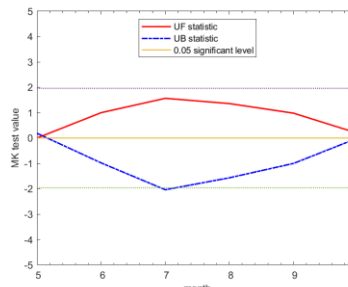
(g) 2018 M-K Test



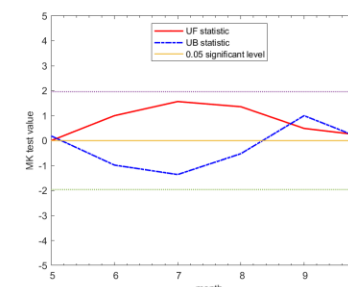
(h) 2019 M-K Test



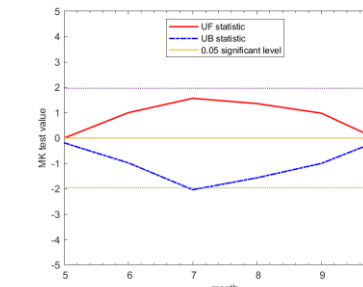
(i) 2020 M-K Test



(j) 2021 M-K Test



(k) 2022 M-K Test



(l) 2023 M-K Test

Figure 5 The M-K test trend chart of precipitation in summer and autumn from 2012 to 2023

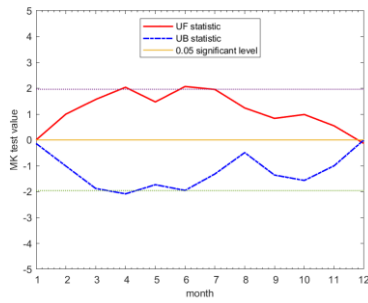
For the data of bare soil evaporation, as its variation range is relatively small, the data from January to December throughout the year are used for MK testing. The trend chart of the monthly bare soil evaporation MK test in the study area is shown in Figure 6. Detailed data on the average monthly bare soil evaporation in each month of the study area from 2012 to 2023 are shown in Table 2.

According to the results of the M-K trend analysis of bare soil evaporation from 2012 to 2023, the curves of the UF statistic and UB statistic in the M-K test graph from 2012 to 2023 all have intersection points after November, indicating that since November, the average bare soil evaporation in the study area has begun to decrease sharply. Moreover, all the intersection points are within the confidence level range, indicating that the mutation is relatively significant and has passed the 0.05 significance test. From 2012 to 2023, the general trend of the UF curve was to first increase and then decline. Moreover, except for 2018 and 2021, the average UF values in June and July of the remaining years were all greater than or equal to 1.96, indicating a significant increase. Additionally, except for 2018 when the UF value was less than 0 and began to decline in October, the UF value was less than 0 in November of the other years. The evaporation of bare soil has begun to show a decreasing trend.

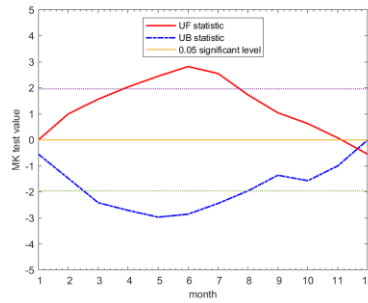
Table 2 Detailed data of bare soil evaporation MK test from 2012 to 2023

| month | year | | | | | | | | | | | |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
| 1 | 2.39 | 2.73 | 2.52 | 3.34 | 3.28 | 2.69 | 2.61 | 1.86 | 2.68 | 2.04 | 2.34 | 2.83 |
| 2 | 3.42 | 4.68 | 3.50 | 4.62 | 6.27 | 3.23 | 2.86 | 3.10 | 7.00 | 5.92 | 4.57 | 4.14 |
| 3 | 10.03 | 10.31 | 6.14 | 6.17 | 6.70 | 6.61 | 10.98 | 7.72 | 12.40 | 17.42 | 11.69 | 7.20 |
| 4 | 13.84 | 11.69 | 9.11 | 14.93 | 12.95 | 9.45 | 16.75 | 13.64 | 11.41 | 12.14 | 12.22 | 14.74 |
| 5 | 9.41 | 11.99 | 14.49 | 10.48 | 13.85 | 9.19 | 10.60 | 10.82 | 11.80 | 10.29 | 7.87 | 10.81 |
| 6 | 16.78 | 16.57 | 14.22 | 13.89 | 20.8 | 18.15 | 12.65 | 13.40 | 13.91 | 18.59 | 19.08 | 12.07 |
| 7 | 11.64 | 11.92 | 11.53 | 12.19 | 10.45 | 12.32 | 10.36 | 14.08 | 12.97 | 13.99 | 12.34 | 14.17 |
| 8 | 6.82 | 9.00 | 9.27 | 8.84 | 7.56 | 7.96 | 8.05 | 7.68 | 8.68 | 7.78 | 8.47 | 8.47 |
| 9 | 7.06 | 8.72 | 8.75 | 7.70 | 7.55 | 6.33 | 7.05 | 5.24 | 7.20 | 8.46 | 4.46 | 7.39 |
| 10 | 10.41 | 8.81 | 9.24 | 8.80 | 10.94 | 8.84 | 7.51 | 7.59 | 4.31 | 9.42 | 7.25 | 5.99 |
| 11 | 6.97 | 5.48 | 3.03 | 5.01 | 6.21 | 4.39 | 3.70 | 6.17 | 3.60 | 6.77 | 6.01 | 5.51 |
| 12 | 2.81 | 2.97 | 3.77 | 4.12 | 3.01 | 2.24 | 3.24 | 3.43 | 2.56 | 3.95 | 2.92 | 3.05 |

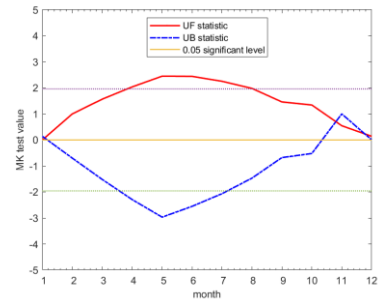
Note: The data in the table are the detailed data of bare soil evaporation for the MK test, with the unit being mm.



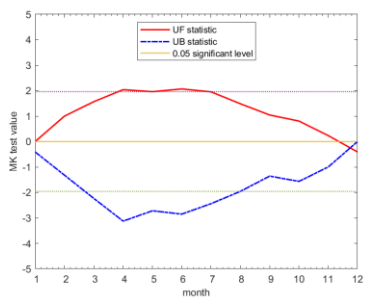
(a) 2012 M-K Test



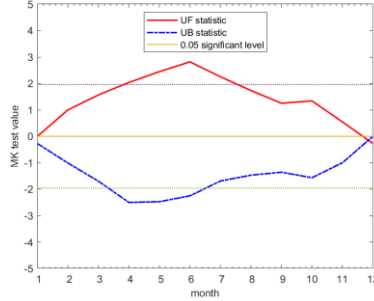
(b) 2013 M-K Test



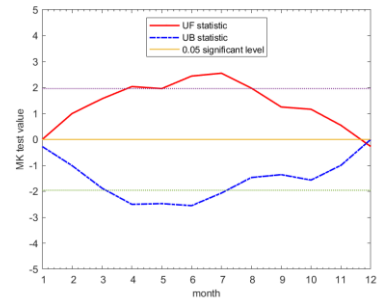
(c) 2014 M-K Test



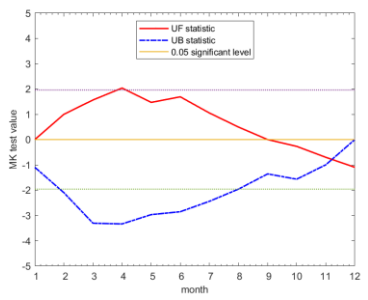
(d) 2015 M-K Test



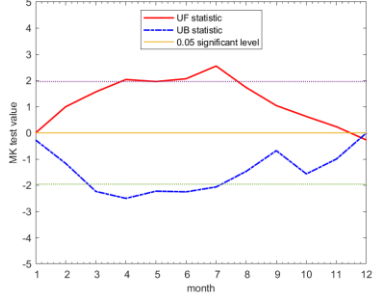
(e) 2016 M-K Test



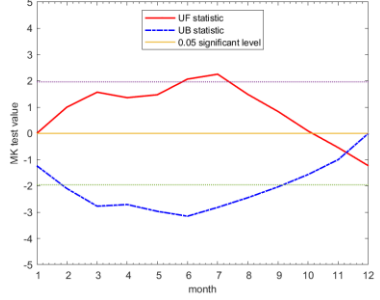
(f) 2017 M-K Test



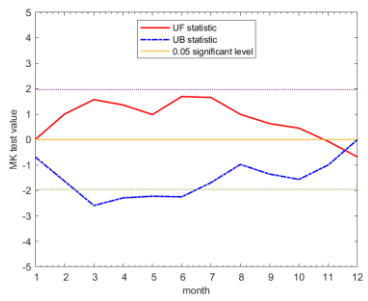
(g) 2018 M-K Test



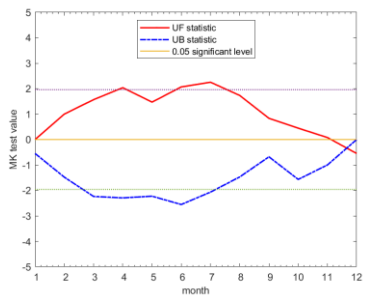
(h) 2019 M-K Test



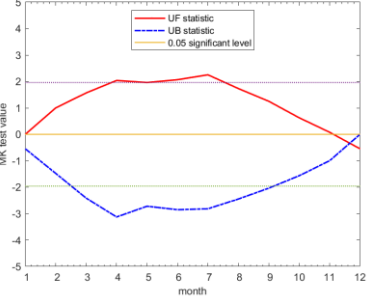
(i) 2020 M-K Test



(j) 2021 M-K Test

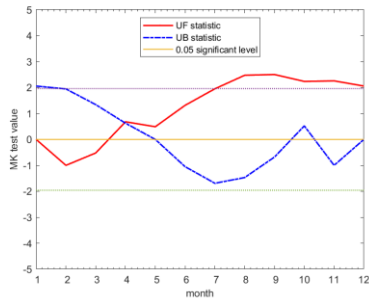


(k) 2022 M-K Test

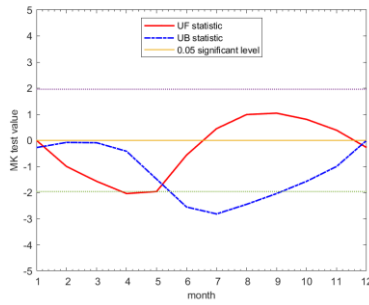


(l) 2023 M-K Test

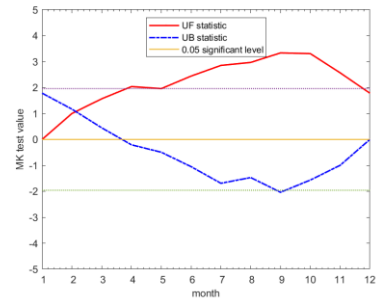
Figure 6 M-K test trend chart of bare soil evaporation from 2012 to 2023



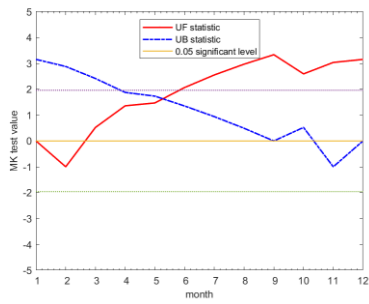
(a) 2012 M-K Test



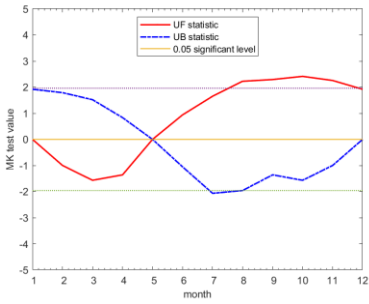
(b) 2013 M-K Test



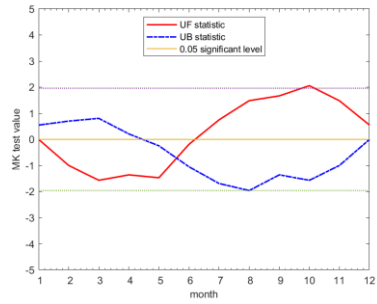
(c) 2014 M-K Test



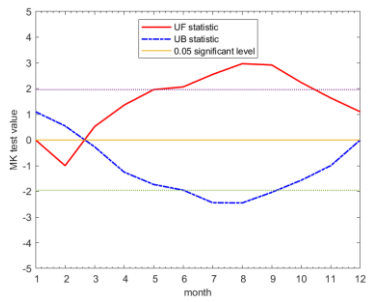
(d) 2015 M-K Test



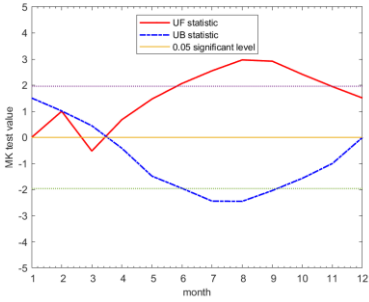
(e) 2016 M-K Test



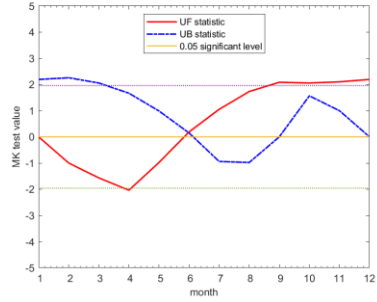
(f) 2017 M-K Test



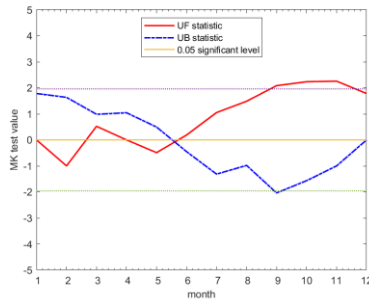
(g) 2018 M-K Test



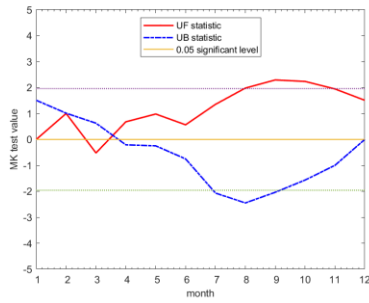
(h) 2019 M-K Test



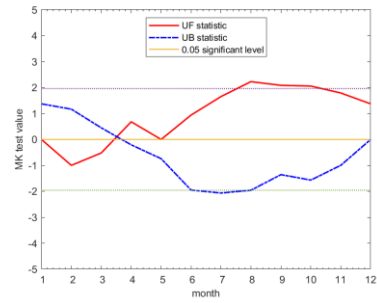
(i) 2020 M-K Test



(j) 2021 M-K Test



(k) 2022 M-K Test



(l) 2023 M-K Test

Figure 7 Trend Chart of Soil moisture content M-K test from 2012 to 2023

For the 0-10cm soil moisture content in the study area, the variation range is also relatively small. Data from January to December throughout the year can also be used for MK testing. The MK testing trend chart of the 0-10cm soil moisture content on a monthly scale from 2012 to 2023 is shown in Figure 7. Detailed data on the average monthly soil moisture content of 0-10cm in the study area from 2012 to 2023 are shown in Table 3.

Table 3 Detailed data of surface soil moisture content MK test from 2012 to 2023

| month | year | | | | | | | | | | | |
|-------|-------|-------|-------|-------|-------|-------|-------|--------|-------|-------|-------|-------|
| | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
| 1 | 18.46 | 20.55 | 14.2 | 13.98 | 17.96 | 18.78 | 14.62 | 15.16 | 21.43 | 19.55 | 19.64 | 16.03 |
| 2 | 15.26 | 19.74 | 15.48 | 13.96 | 17.12 | 18.55 | 14.33 | 15.22 | 20.25 | 17.96 | 17.24 | 18.50 |
| 3 | 15.87 | 17.18 | 16.13 | 15.57 | 15.09 | 16.39 | 15.19 | 14.21 | 19.29 | 24.58 | 18.65 | 15.78 |
| 4 | 18.9 | 16.02 | 18.8 | 19.69 | 15.99 | 17.79 | 20.08 | 17.21 | 17.99 | 19.47 | 20.57 | 21.75 |
| 5 | 17.92 | 16.51 | 17.69 | 18.83 | 19.65 | 17.29 | 21.09 | 19.54 | 21.17 | 18.73 | 18.56 | 21.31 |
| 6 | 21.1 | 22.67 | 19.61 | 19.79 | 21.58 | 21.27 | 20.74 | 19.65 | 21.91 | 23.77 | 23.30 | 17.93 |
| 7 | 24.63 | 28.07 | 21.73 | 20.52 | 26.13 | 24.25 | 25.93 | 21.833 | 25.59 | 30.41 | 28.48 | 23.20 |
| 8 | 25.61 | 25.85 | 19.65 | 21.47 | 27.25 | 26.03 | 26.98 | 25.91 | 28.51 | 28.71 | 28.95 | 29.35 |
| 9 | 24.03 | 22.33 | 23.35 | 22.91 | 23.4 | 23.24 | 23.03 | 20.69 | 25.86 | 30.89 | 21.97 | 26.29 |
| 10 | 20.59 | 19.88 | 20.89 | 18.67 | 24.5 | 24.59 | 18.79 | 19.45 | 22.34 | 29.87 | 22.46 | 22.06 |
| 11 | 22.6 | 18.71 | 17.66 | 23.98 | 22.27 | 18.15 | 18.32 | 18.68 | 22.43 | 28.99 | 21.64 | 21.33 |
| 12 | 20.84 | 16.43 | 15.7 | 22.63 | 20.21 | 14.72 | 17.25 | 18.6 | 24.25 | 23.66 | 19.85 | 19.70 |

Note: The data in the table are the detailed soil moisture content data used for the MK test, expressed as percentages.

An M-K trend analysis was conducted on the monthly average soil moisture content of 0-10cm in the study area. The intersection points of the UF statistic and the UB statistic were all within the confidence interval from 2012 to 2023, indicating that mutations occurred in all these years. Mutations occurred in May in 2012, 2013, 2015, 2016, 2017, 2020 and 2021. The mutation points in 2012, 2015 and 2020 were positive, indicating an increase in mutations. The mutation points in 2017 and 2021 were negative, indicating a decrease in mutations. The mutation point value in 2016 was 0 and will not be discussed here. Mutations occurred in March in 2014, 2018 and 2019. The mutation point values in 2014 and 2019 were positive, indicating an increase in mutations. The mutation point value in 2018 was 0 and will not be discussed here. The overall trend in 2014, 2019, 2022 and 2023 was an increase. The UF values were positive in most months, and the UF values from June to October in 2014 and 2019 were both greater than 1.96, indicating

significant growth. The trend of change in the remaining years was a decrease followed by an increase. In 2015, the trend shifted from a decrease to an increase in March. In 2012 and 2018, the trend changed from a decrease to an increase in April. In 2016, 2020 and 2021, the trend changed from a decrease to an increase in June. The trend shift from decrease to increase in 2013 and 2017 occurred in July. Moreover, the UF values of each year from August to November were generally above 1.96, showing a significant growth trend.

5. Conclusion

Based on remote sensing data from 2012 to 2023, this study systematically analyzed the spatio-temporal variation characteristics and interrelationships of rainfall, surface soil moisture content from 0 to 10 cm, and bare soil evaporation in the Haihe River Basin. The results show that all three exhibit significant seasonal variations: the peak of bare soil evaporation occurs in June, the peak of precipitation lags behind by one month to occur in July, and the surface soil moisture content further lags behind to reach the maximum value in August, reflecting the time-delay effect and seasonal dependence of rainfall on soil moisture and evaporation processes. Spatially, the Yanshan Mountains have a distinct differentiation effect on water and heat elements. The precipitation, soil moisture content and evaporation on the side close to the ocean are significantly higher than those on the inland side, highlighting the crucial role of Marine water vapor input in regional hydrological processes. The M-K mutation test further revealed that rainfall and surface soil moisture content showed sudden increases in June and May respectively, while bare soil evaporation generally experienced a sudden decrease in November. The mutation points were concentrated in late spring and early summer and autumn, reflecting the dominant regulation of the monsoon transition and key precipitation events on the surface evaporation process. These differences lead to different spatial and temporal responses of the topsoil to precipitation and evaporation. This discovery holds significant implications for water resource planning and agriculture in the Hai River Basin. Emphasis should be placed on leveraging the water storage capacity of the moist soil in the Hai River Basin, combined with engineering measures such as wetlands and reservoirs, to enhance the runoff interception capacity during the flood season and alleviate drought during non-flood seasons [6,7].

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