Postprint: Analysis of Flood Evolution Patterns and Causes of the "Four Sources" of the Tarim River

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Abstract

Based on daily runoff data from five hydrological stations in the "four source tributaries" of the Tarim River Basin from 1981-2020, together with gridded temperature, precipitation, and snow depth data, this study employs maximum value and POT (Peaks Over Threshold) sampling methods to analyze characteristics of flood magnitude, frequency, and peak occurrence timing. Simultaneously, correlation analysis is utilized to reveal relationships between different flood indices and influencing factors and to identify key influencing factors. The results indicate: (1) During 1981-2020, the ranking of peak discharge magnitudes at the stations in the "four source tributaries" of the Tarim River is as follows: Kaqun > Xiehela > Tongguziluoke > Shaliguilank > Dashankou. Peak discharge at both annual and seasonal scales generally exhibits an increasing trend, while the timing of winter flood peaks shows an advancing trend. Among these stations, Shaliguilank exhibits the largest average annual advance of 2.61 days, whereas Kaqun Station shows an advance of only 0.67 days. (2) Within the study period, the Tarim River Basin experienced two high-incidence flood periods, namely 1994-2002 and 2006-2011, with large-magnitude floods in the basin concentrated after 1990. (3) At various times preceding flood occurrence, minimum temperature, precipitation, and snow depth are predominantly characterized by increasing trends, while maximum temperature is predominantly characterized by a decreasing trend. Spring flood indices demonstrate the highest correlation with maximum 3-day precipitation, whereas autumn flood indices show the highest correlation with maximum 7-day precipitation. Compared to single-day precipitation, multi-day precipitation exhibits higher correlations with flood indices. Among snow depth-related factors, maximum 15-day snow depth shows the highest correlation with spring flood indices at each station. The research findings provide a theoretical basis for regional water resources management and flood disaster prediction.

Evolution Patterns and Causes of Floods in the "Four Sources" of the Tarim River

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Abstract

Based on daily runoff data from five hydrological stations in the "four sources" of the Tarim River Basin from 1981 to 2020, together with gridded temperature, precipitation, and snow depth data, this study employs maximum value and peak-over-threshold (POT) sampling methods to analyze flood magnitude, frequency, and peak occurrence timing. Correlation analysis is used to reveal relationships between different flood indicators and influencing factors and to identify key influencing factors. The results show: (1) From 1981 to 2020, the peak discharge at each hydrological station in the "four sources" of the Tarim River Basin ranked as follows: Kaqun > Tongguzluok > Sharikilank > Dashankou. Annual and seasonal peak discharge generally showed an increasing trend, while winter flood peak occurrence time showed an advancing trend, with Sharikilank showing the largest average annual advance of 2.61 days and Kaqun station advancing by only 0.67 days. (2) During the study period, there were two high-incidence flood periods in the Tarim River Basin: 1994–2002 and 2006–2011, with large-scale floods concentrated after 1990. (3) Minimum temperature, precipitation, and snow depth at different times before flood occurrence mainly showed increasing trends, while maximum temperature mainly showed decreasing trends. Spring flood indicators had the highest correlation with maximum 3-day precipitation, while autumn flood indicators had the highest correlation with maximum 7-day precipitation. Multi-day precipitation showed higher correlation with flood indicators than single-day precipitation. Among snow depth-related factors, maximum 15-day snow depth had the highest correlation with spring flood indicators at each station. These findings provide a theoretical basis for regional water resource management and flood disaster prediction.

Keywords: flood; recurrence period; POT sampling; four sources streams of Tarim River

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report indicates that climate warming has accelerated global and regional water cycles, with the frequency and intensity of extreme climate events continuing to increase [?]. Climate change-induced flood disasters pose a serious threat to regional economies and people' s lives and property [?]. According to statistics, in 2021 alone, global flood disasters caused losses as high as 6510$×$10^8 USD [?]. Previous studies have found that increased autumn and winter precipitation has led to more floods in northwestern Europe, while factors such as rising temperatures, increased evaporation, and reduced snow cover have decreased floods in eastern Europe [?]. When investigating global flood causes, researchers discovered that flood timing advances in North America and Europe are related to earlier snowmelt, while soil moisture excess and extreme precipitation jointly cause flood timing delays in the Amazon, South Africa, India, and Japan [?]. The severity, duration, and frequency of floods have all increased [?]. Extreme precipitation and accelerated melting of glaciers and snow caused by temperature rise undoubtedly affect land hydrological processes, alter river runoff recharge structures and flood peak characteristics, and increase uncertainty in flood risk, seriously threatening human life and property safety. Therefore, research on flood evolution patterns and key influencing factors under climate change has become extremely urgent.

Current domestic research mainly focuses on the Yellow River [?], Huai River [?], and Yangtze River [?], with less attention paid to flood issues in rivers of northwest arid regions. Xinjiang is located in the hinterland of the Eurasian continent at mid-latitudes and is a sensitive region for global climate change [?]. River runoff in Xinjiang mainly originates from mountain precipitation and glacier/snow meltwater, with more complex meteorological causes for extreme hydrological events and obvious vertical zonation patterns in flood formation and distribution [?]. The Tarim River is China' s longest inland river. Affected by long-term flow interruption and ecological water transfer, 321 km of its downstream channel has dried up. With oasis agricultural development, the Tarim River Basin has undergone tremendous changes, with various water systems gradually losing connection with the main stream. Currently, the water systems still connected to the main stream are the Aksu River, Hotan River, and Yarkant River, known as the three upstream sources [?]; while the Kaidu River supplies water to the downstream Tarim River, together forming the “four sources” that constitute the main flood sources for the Tarim River.

Flood types in the “four sources” of the Tarim River mainly include ice-snow melt floods, glacial outburst floods, and rainstorm floods, mostly occurring from June to September each year. Overall runoff has increased over the past 60 years [?]. Based on generalized extreme value distribution, previous research analyzed flood frequency characteristics at various stations in the “four sources” of the Tarim River over 50 years [?]. Huang et al. [?] studied flood frequency characteristics of the Kaidu River, finding that extreme runoff approximately follows a Frechet distribution and flood frequency showed significant increase. Gu [?] found that increased flood intensity and frequency in the Tarim River Basin since the 1980s were mainly caused by increased precipitation and temperature. However, existing research mostly focuses on single flood indicators, and there remains a lack of quantitative analysis of spatiotemporal variation characteristics of floods in the Tarim River Basin and in-depth study of their influencing factors. Therefore, this study takes the period 1981-2020, when climate change is most significant, as the research period. By analyzing the spatiotemporal evolution characteristics of floods in the "four sources" of the Tarim River and their main influencing factors, this study proposes adaptive countermeasures and suggestions for flood risk under climate change. This research helps reveal the response patterns and processes of flood risk in alpine basins recharged by ice and snow meltwater to extreme climate change, holding important scientific significance and practical application value.

1.1 Study Area Overview The Tarim River Basin is located in southern Xinjiang Uygur Autonomous Region, bordered by the Tianshan Mountains to the north, the Pamir Plateau to the west, and the Kunlun and Altun Mountains to the south, with a total basin area of approximately 1.02$×$10^6 km^2. It is China’ s largest inland river basin. The Tarim River consists of nine major water systems with 144 rivers [?] [Figure 1: see original paper]. The total glacier area is 19,877.7 km^2, making it an important component of the Asian Water Tower and one of its most vulnerable units [?]. Ice and snow meltwater from the "four sources" of the Tarim River is one of the main recharge sources for runoff, making it more susceptible to climate change and prone to flood events [?].

This study selected five hydrological stations in the "four sources" of the Tarim River: Sharikilank Station (basin area 18,400 km^2, glacier coverage 742.7 km^2) and Xehera Station (basin area 12,820 km^2, glacier coverage 947.01 km^2) on the Aksu River; Tongguzluok Station (basin area 14,575 km^2, glacier coverage 2,958.31 km^2) on the Hotan River; Kaqun Station (basin area approximately 50,248 km^2, glacier coverage approximately 4,964.63 km^2) on the Yarkant River; and Dashankou Station (jurisdiction basin area 19,022 km^2, glacier coverage approximately 444.53 km^2) on the Kaidu River, as shown in [Figure 2: see original paper]. The Tarim River Basin has scarce rainfall, strong evaporation, and a dry climate [?], with large diurnal temperature differences, representing a typical continental warm temperate extremely arid climate. The annual average temperature ranges from 10.6-11.5°C, and annual average precipitation shows significant spatiotemporal distribution differences, with less than 100 mm in plain areas and over 1,000 mm in mountainous areas.

1.2 Data Sources and Processing Daily runoff data from the five hydrological stations in the "four sources" of the Tarim River were obtained from the Xinjiang Tarim River Basin Administration. Except for Xehera and Sharikilank stations on the Aksu River (runoff data range 1981-2020), data from other stations range from 1986–2020. Flood indicators selected continuous 1-day, 3-day, and 7-day maximum temperature, minimum temperature, precipitation, and 15-day snow depth data before flood occurrence. Precipitation and temperature data were obtained from the National Oceanic and Atmospheric Administration Climate Prediction Center (NOAA CPC) global daily gridded dataset with 0.5° spatial resolution. Snow depth data were obtained from the National Snow and Ice Data Center (NSIDC) with 25 km spatial resolution. To verify gridded data accuracy, data from 23 meteorological stations and 5 measured snow depth sampling points in the study area were selected for comparative analysis (FIGURE:2). Results showed that gridded maximum and minimum temperatures had high correlation with most stations and passed significance tests. Precipitation correlation was slightly lower but still greater than 0.5. Correlation between measured snow depth data and gridded snow depth data reached 0.65.

1.3 Methods

1.3.1 Flood Index Extraction This study selected nine flood indicators (TABLE 1) and used maximum value (AM) and peak-over-threshold (POT) sampling methods to describe flood magnitude, frequency, and peak timing characteristics [?]. The AM method selects only the annual maximum flow, but in dry years without floods, using the annual maximum would affect research representativeness. The POT method overcomes this defect by calculating all floods exceeding the threshold regardless of occurrence time, maximizing sample representativeness. Therefore, this study simultaneously used both methods to supplement and increase flood sample representativeness. This method has been widely applied in the Tarim River Basin [?, ?]. The threshold was selected using the discriminant standard proposed by the U.S. Water Resources Association (USWRC) to determine flood peak independence [?]:

$$D > 5 + \log10(A)$$

where D is the interval time between two consecutive flood peaks (days), and A is the watershed area (km^2). The minimum flood magnitude Qmin was set as the 95th percentile of daily runoff.

1.3.2 Recurrence Period Estimation Recurrence period is the average interval time during a certain period of record when a hydrological element of a certain magnitude or greater occurs once [?], essentially a small probability problem on the right side of a probability distribution. This study used the extreme value Type I distribution method to calculate recurrence period. The extreme value Type I distribution function is:

$$F(x) = \exp\{-\exp[-a(x-u)]\}$$

where F(x) is the distribution function of maximum values; x is the hydrological element maximum; a and u are extreme value distribution parameters calculated by:

$a = \pi/(\sqrt{6}\sigma\_x)$ $u = \bar{x} - 0.5772/a$

where $\bar{x}$ is the sample mean and σ_x is the sample standard deviation.

In extreme value recurrence period calculation, p is probability (the reciprocal of recurrence period), and Xp is the hydrological element value corresponding to probability p, calculated by:

$Xp = u - (1/a)\ln[-\ln(1-p)]$

1.3.3 Trend Analysis Linear trend method was used to calculate trends in flood indicators [?]:

$\text{Slope} = [n\ (i \cdot Ti) -\ i \cdot\ Ti] / [n\ i\hat{}2 - (\ i)\hat{}2]$

where Slope is the linear regression equation slope; n is the time series length; i is the year number (1,2,⋯,n); Ti is the extreme flood value in year i. A positive slope indicates an increasing trend, while a negative slope indicates a decreasing trend.

1.3.4 Pearson Correlation Analysis Pearson correlation analysis is commonly used to reveal the closeness of relationships between geographical elements [?]. The correlation coefficient is calculated as:

$r = [\ (xi - \bar{x})(yi - \bar{y})] / \sqrt{}[\ (xi - \bar{x})\hat{}2 \cdot\ (yi - \bar{y})\hat{}2]$

where r is the correlation coefficient between x and y; n is the sample size; xi and yi are flood indicator values or climate element values in year i; $\bar{x}$ and $\bar{y}$ are the means of x and y. The r value ranges from [-1, 1], with larger absolute values indicating stronger correlation.

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2. Results and Analysis

2.1 Flood Spatial-Temporal Distribution Characteristics All stations in the "four sources" of the Tarim River showed highest flood peak discharge in summer, consistent with annual maximum flood peak discharge, and lowest in winter. Summer Kaqun Station had the highest flood peak discharge at 1,423.10 $m^{3 \cdot s}$-1, followed by Xehera Station (1,326.45 $m^{3 \cdot s}$-1). Winter Dashankou Station had the highest flood peak discharge at 89.79 $m^{3 \cdot s}$-1, with Xehera and Kaqun stations next at 77.87 $m^{3 \cdot s}$-1 and 70.46 $m^{3 \cdot s}$-1, respectively. Except for Sharikilank and Dashankou stations, other stations had greater autumn flood peak discharge than spring. For annual maximum flood occurrence date, Sharikilank Station was 188.25 days, Tongguzluok Station 180.48 days, Xehera Station 214.00 days, Dashankou Station 214.18 days, and Kaqun Station 217.08 days, with Kaqun having the latest flood occurrence period. In average flood occurrence dates, Sharikilank Station was 180.24 days, slightly lower than its annual maximum flood date. Xehera and Dashankou stations were 212.91 and 215.20 days, respectively, significantly lower than their annual maximum flood dates.

Tongguzluok Station was 195.70 days, while Kaqun Station was 211.31 days. Except for Dashankou Station, other stations' POT3M flood peak discharge was higher than annual maximum flood peak discharge. Dashankou Station had the highest sample count, averaging 1.14 floods per year, followed by Kaqun Station (1.02 floods/year). Except for Xehera Station, other stations showed increasing POT3F trends, indicating POT method may overestimate flood frequency at these stations. Comparing threshold-exceeding flood peak discharge with annual maximum flood peak discharge revealed that Kaqun and Tongguzluok stations had more floods exceeding the 20-year return period, indicating Yarkant River has the highest flood peak discharge among the four sources, while Kaidu River has the lowest.

2.2 Flood Recurrence Period and Frequency FIGURE 3 shows the temporal distribution of floods at different recurrence periods for each station. Results indicate that floods exceeding the 20-year return period were most concentrated in 1994–2002, with 11 floods occurring at five hydrological stations. Another high-incidence period was 2006–2011, with 10 floods. Different stations showed higher frequencies for 10-year return period floods (FIGURE 3). Notably, based on the AM method, different stations extracted flood event distributions across seasons. It is evident that the high-incidence period was also between 1994–2002. From different basins, the Aksu River had the most floods during this period (Sharikilank Station 4 times, Xehera Station 3 times) and Hotan River (Tongguzluok Station 2 times). Except for Tongguzluok Station, other stations' 20-year return period flood occurrence times were relatively concentrated. The Kaidu River Dashankou Station had 3 floods exceeding the 20-year return period, concentrated in 1999 and 2005. The Yarkant River Kaqun Station had 3 floods in 1999, 2005, and 2010. Among them, 1999 was the most concentrated flood year. Except for Tongguzluok Station, other stations' 20-year return period flood events in other seasons were more dispersed. Winter and spring floods exceeding the 20-year return period occurred least frequently, with only 2 spring floods at Kaqun Station and 1 or none at other stations. Winter floods mainly occurred after 1990.

FIGURE 4 shows peak discharge at different return periods. Summer Kaqun Station had the highest peak discharge, reaching 3,500 m$^{3 \cdot s}$-1 at the 100-year return period, followed by Xehera Station at 2,500 m$^{3 \cdot s}$-1. Dashankou Station had the lowest peak discharge at all return periods. Except for Xehera Station, other stations showed increasing trends in 10-year return period floods, with Sharikilank, Dashankou, and Tongguzluok stations showing significant increases ($P < 0.05$). In terms of occurrence time, Kaqun and Tongguzluok stations showed advancing trends in autumn flood timing, while other stations showed delaying trends. Due to complex geographical conditions, the Tarim River is prone to glacier-induced floods in winter. Except for Xehera Station, other stations'20-year return period flood events showed insignificant increasing trends, with Sharikilank, Xehera, and Tongguzluok stations showing average advances of 2.61, 1.57, and 1.31 days, respectively. Autumn is the season with the most flood occurrences, with Dashankou Station having 3 floods exceeding the 20-year return period, while other stations had 2 or none. All hydrological stations showed temporal clustering of floods in certain periods, such as 1994–2002 and 2006–2011, with multiple stations experiencing simultaneous floods in certain years, indicating floods may occur in clustered patterns both temporally and spatially.

2.3 Flood Index Variation Characteristics FIGURE 5 shows temporal variation trends of flood indicators at each station. Different stations' AMFWi showed insignificant trends. Xehera Station had the largest AMFWi but a decreasing trend at -4.25 m$^{3\cdot s}$-1 • a^-1. Sharikilank, Dashankou, and Tongguzluok stations showed increasing AMFWi trends at 6.95, 2.98, and 2.54 m$^{3\cdot s}$-1 • a^-1, respectively. In terms of timing, Xehera Station showed a significant advancing trend at -2.38 days • a^-1, while Sharikilank, Tongguzluok, Dashankou, and Kaqun stations showed insignificant advancing trends at 1.57, 1.31, 1.20, and 0.67 days • a^-1, respectively. Winter flood occurrence times all showed advancing trends, with Sharikilank, Tongguzluok, Xehera, Dashankou, and Kaqun stations advancing by 2.61, 1.57, 1.31, 1.20, and 0.67 days per year, respectively. Due to warming temperatures accelerating melting of alpine snow, winter flood magnitude has increased. Except for Xehera Station, other stations showed insignificant increasing trends in POT3M-detected flood magnitude, with Tongguzluok and Kaqun stations increasing at 1.14 and 1.02 m$^{3\cdot s}$-1 • a^-1, respectively, while Dashankou Station decreased at -1.14 m$^{3\cdot s}$-1 • a^-1. This indicates that except for the Kaidu River basin, flood magnitude in other source streams of the Tarim River has increased. In terms of occurrence frequency, Sharikilank, Xehera, and Tongguzluok stations showed insignificant increasing trends in POT3F at 0.60, 0.48, and 0.51 floods • a^-1, respectively, while Dashankou and Kaqun stations showed decreasing trends. Rising spring temperatures increase glacier and snow melt, significantly altering spring flood magnitude and timing. In the Aksu River basin, Sharikilank and Xehera stations' AMFSp showed increasing trends, but flood timing showed advancing and delaying trends, respectively. Other stations showed decreasing spring flood peaks, with only Kaqun Station delaying flood timing. The Tarim River has high summer temperatures and heavy precipitation, with AMFSu and AMFAu showing insignificant trends at all stations. Xehera Station showed advancing flood timing, while Sharikilank, Kaqun, and Tongguzluok stations showed delaying trends. Dashankou Station' s POT3F showed an advancing trend.

2.4 Trends of Factors Influencing Flood Occurrence FIGURE 6 shows trends of maximum temperature, minimum temperature, snow depth, and precipitation at different times before flood occurrence. In the Aksu River basin, Sharikilank Station showed decreasing trends in both maximum and minimum temperatures before floods, while Xehera Station showed increasing trends. Dashankou Station showed decreasing maximum and minimum temperatures in spring and AMFAu, but increasing trends in other seasons. For AMFWi floods, only flood occurrence showed increasing trends. Kaqun Station showed mainly increasing minimum temperatures before floods, while maximum temperature before spring and AMFAu floods showed decreasing trends. Tongguzluok Station showed increasing maximum temperature and decreasing minimum temperature trends before winter floods. In summary, minimum temperature, precipitation, and snow depth before floods in the Tarim River basin mainly showed increasing trends, while maximum temperature mainly showed decreasing trends.

In the Aksu River basin, snow depth before floods showed increasing trends, except for decreasing snow depth before autumn floods. Snow depth before winter floods at Sharikilank and Xehera stations showed the highest change rates. Dashankou Station showed significant increasing snow depth trends before AMFWi floods. Kaqun Station showed increasing snow depth trends before different floods. Precipitation showed increasing trends in the Aksu and Yarkant Rivers, with maximum increase rates of 7.61 cm · a^-1, while the Hotan River showed decreasing trends, with maximum decrease rates of -5.44 mm · a^-1. Overall, snow depth before floods in the Tarim River basin showed increasing trends, with Xehera Station having the highest increase rate at 7.61 cm · a^-1.

2.5 Relationship Between Flood Indicators and Influencing Factors

FIGURE 7 shows correlations between flood indicators and influencing factors at different hydrological stations in the Tarim River Basin. Annual and summer flood indicators at all stations showed consistent correlations with precipitation, maximum temperature, minimum temperature, and snow depth. Tongguzluok Station flood indicators showed negative correlations with precipitation, while other stations showed positive correlations, with Dashankou Station having the highest correlation with precipitation at over 0.5, indicating precipitation increases directly affect annual and summer maximum flood peaks. In the Aksu River basin, Sharikilank Station’ s annual and summer flood indicators showed negative correlations with maximum and minimum temperatures, with the highest correlation with maximum 7-day temperature at -0.42. Xehera Station flood indicators showed negative correlations with maximum temperature and positive correlations with minimum temperature. Kaqun Station’ s annual and summer flood indicators showed the strongest negative correlations with snow depth, reaching -0.45 with Prep7.

Spring flood indicators at Sharikilank Station showed negative correlations with precipitation and minimum temperature, with the strongest correlation with maximum 3-day precipitation (-0.41), while maximum temperature and snow depth showed positive correlations. At Xehera Station, spring flood indicators showed negative correlations with maximum and minimum temperatures, but positive correlations with precipitation and snow depth. The other three stations (Dashankou, Tongguzluok, Kaqun) showed positive correlations between spring flood indicators and precipitation, maximum temperature, minimum temperature, and snow depth, with relatively high correlations with snow depth.

Autumn and winter flood indicators showed similar precipitation correlations across stations, with all except Sharikilank showing negative correlations. For autumn flood indicators, Sharikilank Station showed negative correlations with both maximum and minimum temperatures, while Kaqun Station showed positive correlations. Minimum temperature and snow depth were important factors affecting Tongguzluok Station' s autumn flood indicators, with single-day minimum temperature (Tmin1) showing the highest correlations at 0.41 and 0.42. Tongguzluok and Kaqun stations' winter flood indicators showed high correlations with maximum and minimum temperatures, with Tongguzluok showing negative correlations and Kaqun showing positive correlations; other stations showed weaker correlations.

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3. Discussion

Temperature and precipitation in the Tarim River Basin of Xinjiang have both increased in recent decades [?], with climate shifting from "warm-dry" to "warm-wet" [?]. Flood occurrence is mainly affected by temperature, precipitation, and mountain glacier/snow melt. Rising temperatures promote glacier and snow melt, while increased precipitation further leads to increasing river flow and flood peaks [?]. Among the "four sources" of the Tarim River, the Aksu River originates from the southern slope of the western Tianshan Mountains. Since 1960, the Aksu River basin has warmed at 0.38°C · a^-1, significantly higher than northwest China and Central Asia [?]. The Kaidu River is located on the southern side of the Tianshan Mountains, with maximum snow depth reaching 30 cm [?]. Dashankou Station' s summer flood peak discharge shows an increasing trend, mainly determined by precipitation, positively correlated with precipitation but negatively correlated with maximum temperature, possibly because precipitation events in large mountainous areas are often accompanied by cooling processes [?]. Spring flood peaks in the Aksu and Kaidu Rivers show positive correlations with snow depth at different times. Spring flood peaks in the Aksu River increase due to accelerated snow melt from rising temperatures. Meanwhile, the Hotan and Yarkant Rivers flow into the Tarim River from the northern slope of the Kunlun Mountains, with snow depth generally below 10 cm but rich glacier resources [?]. As temperatures rise, glacial meltwater becomes the main factor triggering floods. In recent years, spring and summer maximum temperatures in the Yarkant River basin have continuously decreased while winter precipitation has continuously increased [?]. Kaqun Station's spring and summer flood peaks show decreasing trends, while autumn and winter flood peaks show increasing and advancing trends. Winter and spring flood peaks show positive correlations with temperature and snow depth before flood occurrence, indicating large winter snowpack and temperature recovery can easily trigger floods in winter and spring. Autumn maximum rainfall is often stored, and as soil moisture and groundwater levels continuously increase to maximum values in winter, increased winter precipitation leads to earlier winter flood occurrence. For the Hotan River, floods are mainly formed by glacial meltwater and seasonal snow melt. Tongguzluok Station' s annual, summer, autumn, and winter floods show increasing trends, with increasing snow depth before floods in different periods over the past 20 years positively correlated with autumn and winter floods, indicating the significant increase in autumn and winter flood peaks is closely related to snow melt caused by temperature rise.

Annual and summer flood peak occurrence times in the "four sources" of the Tarim River show delaying trends, with only Xehera Station showing decreasing annual maximum flow and advancing occurrence time. Zhou et al. [?] also found that with increasing precipitation and temperature, river runoff in the southern Tianshan Mountains increased, and annual maximum runoff appeared earlier, related to accelerated glacier melt and shortened water storage period of the Merzbacher glacial lake basin [?]. All stations' winter flood peak occurrence times show advancing trends. In the Hotan and Aksu River basins, POT3M flood occurrence frequency shows increasing trends. Zhang et al. [?] found consistent results. Except for Dashankou Station on the Kaidu River, other stations' POT3F timing trends were consistent with AM: Xehera Station advanced, while Sharikilank, Kaqun, and Tongguzluok stations delayed; Dashankou Station' s POT3F showed advancing trends, consistent with Gu [?].

Before flood occurrence, minimum temperature, precipitation, and snow depth in the "four sources"of the Tarim River mainly show increasing trends, while maximum temperature mainly shows decreasing trends. Temperature has greater impact on floods in the Yarkant River basin, while precipitation is the main influence in the Aksu River basin. Compared with single-day precipitation before floods, maximum 3-day precipitation shows higher correlation with flood indicators. Snow depth at different times before floods has greater impact on winter and spring floods, while summer and autumn flood indicators are more affected by minimum temperature.

From a spatiotemporal perspective, floods in the Tarim River basin may occur in clustered patterns. After 1990, floods became more frequent in the Tarim River basin. The study found that in 1999, all stations in the basin experienced large-scale floods, covering both northern and southern Tianshan slopes, southern Xinjiang western mountainous areas, and the northern Kunlun slope. These floods were mainly mixed-type floods formed by snow melt and rainstorm superposition, with wide range, long duration, and large magnitude. In 1999, 33 rivers in Xinjiang reached dangerous flow levels, including the Aksu and Kaidu Rivers, with 18 rivers setting historical highest water levels [?]. He [?] found that in the summer of 1999, extensive snow cover and sudden cooling of upper air temperatures, combined with westward extension of the Western Pacific subtropical high causing re-warming, plus long-duration and heavy mountain precipitation, jointly triggered concentrated floods in this region. Additionally, in arid and semi-arid alpine regions, floods are influenced by multiple factors such as upper atmospheric temperature, potential flood risk from glacial lakes, and human activities. These factors vary according to geographical and climatic conditions, adding complexity to flood prediction. Therefore, future research should focus on flood formation mechanisms and use future scenario data to predict flood changes.

4. Conclusions

1) Flood indicators at different stations and seasons showed highest summer flood peak discharge, consistent with annual maximum flood peak discharge. Based on POT sampling results, station peak discharge ranked as: Kaqun > Tongguzluok > Sharikilank > Dashankou. Kaqun Station had the latest flood occurrence date, followed by Dashankou Station.

2) During the study period, there were two high-incidence flood periods: 1994-2002 and 2006-2011. The Aksu River basin had the highest flood frequency during these periods. The summer flood high-incidence period was between 1994-2002, with 11 floods exceeding the 20-year return period occurring at five hydrological stations.

3) Before flood occurrence, minimum temperature, precipitation, and snow depth in the "four sources" of the Tarim River mainly showed increasing trends, while maximum temperature mainly showed decreasing trends. Temperature had greater impact on floods in the Yarkant River basin, while precipitation was the main influence in the Aksu River basin. Compared with single-day precipitation before floods, maximum 3-day precipitation showed higher correlation with flood indicators. Snow depth at different times before floods had greater impact on winter and spring floods, while summer and autumn flood indicators were more affected by minimum temperature.

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Note: Figure translations are in progress. See original paper for figures.