Response of spring flood to snow cover in Kaidu River Basin, China

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ABSTRACT

Global climate change is projected to transform hydrologic processes, prompting more severe flood risks. Snowpack in mountainous areas is sensitive to climate change, impacting the flood volume. Snowmelt water is an important trigger of spring flood in the Kaidu River Basin (KRB) in the Tianshan Mountains of China. However, research in terms of spring flood (from March to May) response to snow is limited in KRB. Considering the observed snow data are scarce in KRB, the remote sensing snow cover data after cloud removal are used to investigate the response of spring flood to snow variation. Due to the complex topography in KRB, the impact of snow cover in different elevation zones on spring floods is also explored. The results showed that the snow cover area does show an obvious change trend over time and has a significant positive correlation with precipitation and a negative correlation with temperature in winter. The spring flood generally happens in April and May in KRB, and its peak is generally smaller than that in summer. Spring flood in April or May depends on the snow cover area within the elevation of 2000-3000m in April: Flood in April is sensitive to the average snow cover area of 2000-2500m elevation zone in April, while flood in May is sensitive to the maximum snow cover area in April for the whole basin, particularly that in the 2000-3000m elevation zone. These findings can support water resources management and disaster prevention in KRB.

KEYWORDS: Kaidu River Basin, spring flood, snow cover, response mechanism, climate change

1 INTRODUCTION

The world is facing a global changing climate which is projected to transform water cycles and availability, resulting in more severe flooding and water shortage events (Blöschl et al. 2019). The changing climatic conditions alter the hydrological regimes on a local and global scale, impacting the recurrence of flood period (Zafar and Zaidi 2019), especially in the cold and mountainous watersheds where the snowmelt is an important water source (Li and Simonovic, 2001). As an important inland river flowing to the Taklamakan desert in the south of the Tianshan Mountains (TMs), the Kaidu River Basin (KRB) often faces spring floods, which are directly related to downstream water resources management and disaster prevention. Snow situation in spring is one of the key driving factors for the formation of floods. Existing studies have shown that the spatiotemporal changes in snow cover in the TMs directly affect the scale and timing of meltwater runoff (Wu et al., 2023) , while the snow melting rate under the background of warming climate may exacerbate flood risks (Zheng et al., 2024). There is still a lack of systematic and in-depth exploration on how snow dynamics specifically affect the formation process, peak flow, and temporal characteristics of spring floods in the KRB, as well as their quantitative relationships. Understanding the response of spring floods to snow cover has an urgent practical need for predicting the change of flood regimes, optimizing reservoir operation, reducing losses from flood disasters, and ensuring regional ecological security (Zhang et al., 2025).

Existing studies on snow hydrology mainly focus on monitoring snow distribution or simulating snowmelt runoff, but the direct relationship between snow melting processes and flood events lacks (Ni et al., 2023). In the KRB, there have been studies using models such as DHSVM and SDHydro to simulate hydrological processes (Zhang et al., 2016; 2025) or explore the impact of climate change on runoff (Zheng et al., 2024). However, focusing on the response relationship between spring floods and snow cover change, especially in the vertical distribution of snow cover along the elevation in the basin still lacks. Regional studies have shown that vertical changes in snow cover in the Taolai River Basin in the Qilian Mountains (Wu et al., 2023) and other watersheds in the TMs (Ni et al., 2023) have an impact on runoff, providing references for the study. The present study aims to analyze the spatiotemporal variation patterns of snow cover in the KRB and empirically demonstrate its relationship with spring flood processes. The objectives of the study are: (1) to analyze the response of spring floods to snow cover changes in the KRB by integrating remote sensing data and hydro-meteorological observation data, and (2) to explore the impact of climate change. The findings are expected to provide a scientific basis for flood forecasting and early warning, water resource management, and climate change mitigation in the KRB.

2 STUDY AREA AND METHODS

2.1 Study Area

The KRB is located on the south slope of the central TMs in Xinjiang, China. It spans geographic coordinates 82°58′– 85°55′E and 42°19′ –43°21′N, and stretches 525 km with an area of 1,9022 km^2 (Figure 1). With a typical temperate continental climate, the annual average precipitation and temperature are 270 mm and -4.29 °C, respectively. With a range from about 1400 m to 4700 m above sea level, the Kadu River flows from west to east and finally flows into Bosten Lake. The overall terrain of the basin presents the characteristics of high in the west, low in the east, high in the north, and low in the south. This complex terrain pattern profoundly affects the water and heat distribution and snowmelting process within the basin, providing the basic terrain conditions for the formation of spring floods. The snowpack begins to accumulate in November and starts to melt in the next March, leading to flooding in April and May with increasing temperature (Shang et al., 2013). The average annual runoff is 34.21 x 10^8 km^3, in which snowmelt in spring contributes 23.2%. The maximum runoff month is in July, and the minimum runoff month is in February. The runoff from May to August accounts for 56.3% of the annual runoff.

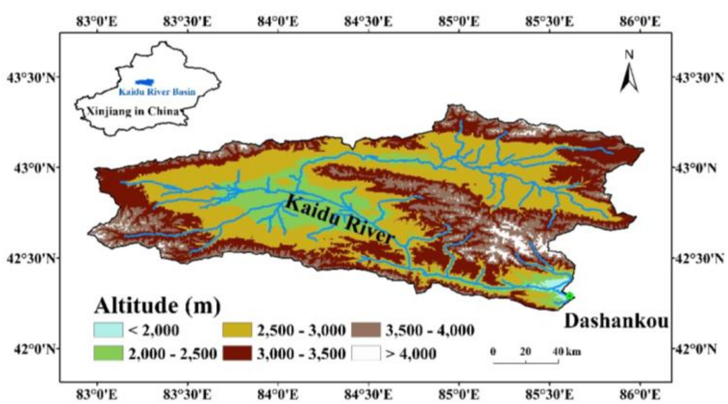

Figure 1 Location of the Kaidu River Basin

2.2 Datasets

(1) Meteorological and hydrological observation data

One meteorological and hydrological observation station with daily recording data is located in Dashankou. Due to the noncontinuous observed data and a dam constructed which inferences the flow, the time scale from 2001 to 2011 was used. Spring peaks occur in April or May from snowmelt contribution, while the annual peak flow generally appears in August, contributing from rainfall mixing with snowmelt in high elevation. The monthly meteorological data, i.e. precipitation and temperature, and streamflow are used in this study to investigate the response of spring flood to snow cover in KRB.

(2) Remote sensing snow cover data

Daily snow cover data during 2001-2011 with a spatial resolution of 500m are from China MODIS Daily Cloudless 500m Snow Area Product Dataset (https://www.ncdc.ac.cn/portal/metadata/be3a4134-2e5c-467f-8a5e-b1c0ed6cc341). This dataset utilizes high-resolution Landsat TM data as ground truth, combined with the MODIS land cover classification product, to train the threshold indicators for snow discrimination in forested and non-forested areas. It employs the MODIS snow retrieval algorithm to obtain the initial product. Invalid values and cloud cover are then removed using a Hidden Markov Model-based cloud removal and snow depth data interpolation method. Finally, a daily cloud-free snow cover area product for the study region is generated (Gao et al., 2019). According to this dataset, snow cover mainly concentrates in the mountainous area during the early snow melt period (Figure 2).

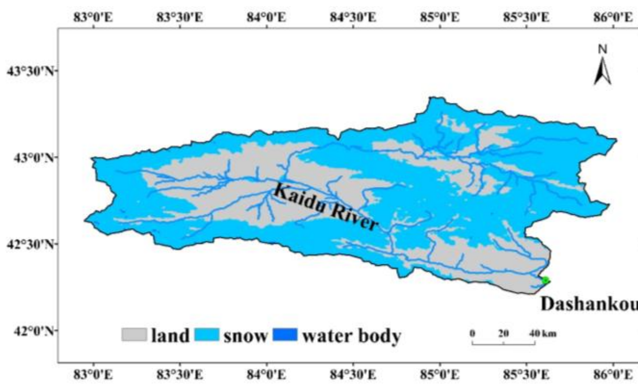

Figure 2 Snow cover on April 1st in 2004

2.3 Method

In order to investigate the spatial heterogeneity of flood sensitivity to snowpack, the study area is divided into six elevation zones, i.e. < 2000m, 2000m-2500m, 2500m-3000m, 3000m-3500m, 3500m-4000m, and >4000m (Figure 1) with one elevation zone of 500m. This study utilizes the correlation coefficient between monthly flood and monthly snow cover area to explore the flood sensitivity to snow cover. Specifically, the maximum daily snow cover area is taken as the monthly snow cover area for the study area in different elevation zones, and the maximum daily streamflow in April and May is taken as the flood volume in the corresponding month, respectively.

3 RESULTS AND DISCUSSION

3.1 Spatiotemporal change of snow cover

3.1.1 Change of snow cover over time

Figure 3a exhibits clear interannual fluctuations cycles of snow cover without obvious change trend over time. This fluctuation is closely related to the winter snowfall and early spring temperature. Snow cover exhibits a typical unimodal variation: snow accumulates from late September, reaches its peak in January and February (with an average snow coverage rate of over 60%), enters a stable melting period in March, and is mostly melted from late April to early May. Average monthly snow cover in Figure 3b further highlights that the growth period of snow cover in the basin starts in September to February of the following year. The snow cover is relatively stable from mid-December to early March of the following year, with the maximum value of 14180 km^2 in January and a minimum snow coverage of about 1000 km^2 in August. This seasonal pattern directly determines the occurrence time and potential scale of spring snowmelt runoff, and is a key background for understanding the formation of spring floods.

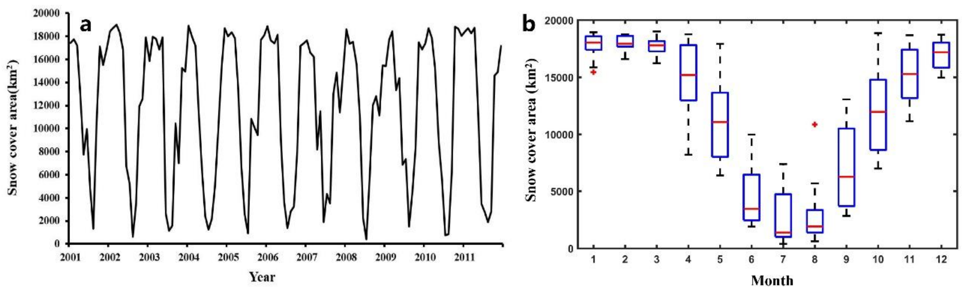

Figure 3 Interannual and monthly variation of snow cover area from 2001-2011. (a) Interannual Snow cover variation. (b) Average monthly snow cover variation

3.1.2 Change of snow cover along different elevation zones

The change pattern of total snow cover area at different elevation zones is shown in Figure 4. The snow cover area is relatively large between elevations of 2000m and 4000m without obvious change trend over time, while relatively small in elevations below 2000m with a slight decreasing trend. The elevation below 2000m shows seasonal snow accumulation, mainly from middle February to middle April with less percentage of cover areas and large fluctuations. The elevation between 2000-3000m is a seasonal snow accumulation zone with a large area and significant fluctuations from February to middle April within a year. The elevation between 3000-4000m is a transitional zone of perennial snow accumulation, with a stable area. The elevation above 4000m is a high-elevation permanent/semi-permanent snow accumulation zone with a high proportion of area and continuous stability.

3.2 Impact of temperature and precipitation on snow cover

Temperature (T) and precipitation (P) presented in Figures 5 and 6 are two important factors affecting snow cover. In order to clarify the impact of changes in T and P on snow cover area, correlation analysis was conducted between T and P data and snow cover data from 2001 to 2011. The results indicate in Table 1 that there is a negative correlation between T and snow cover area in Spring (March-May), summer (June-August), autumn (September-November), and winter (December-February of the following year) at the 1% significance level, indicating that T changes have a significant impact on snow cover. P has the greatest impact on snow cover in winter, showing a significant positive correlation, indicating that winter snowfall is an important accumulation stage of snow; P shows a highly significant negative correlation with snow cover in spring in which T begin to rise and P gradually falls in the form of rain, promoting the melting of snow cover; In summer, there is a positive correlation between P and snow cover, but not at a significant level because the snow cover area mainly exists as permanent snow at high elevation in summer, which is relatively stable. P as the form of rainfall in high-elevation areas replenishes this scattered permanent snow cover; In autumn, there is a low negative correlation between P and snow cover, because P falls mostly as rainfall, while snow accumulation begins because snowfall starts and T decreases.

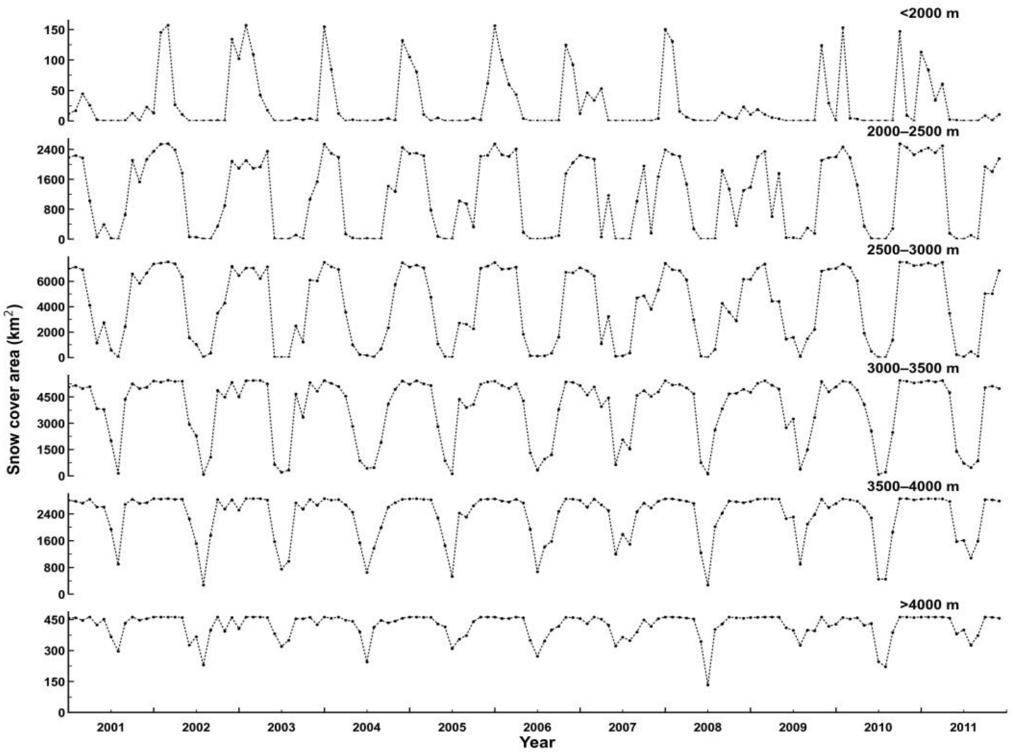

Figure 4 Distribution and variation of Snow cover along the elevation

Table 1. Correlation between snow cover area and precipitation & temperature

	Spring	**Summer**	**Autumn**	**winter**
Precipitation	-0.522**	0.312	-0.230	0.540*
Temperature	-0.807**	-0.480*	-0.806**	-0.831**

** Significant at 0.01, *Significant at 0.05

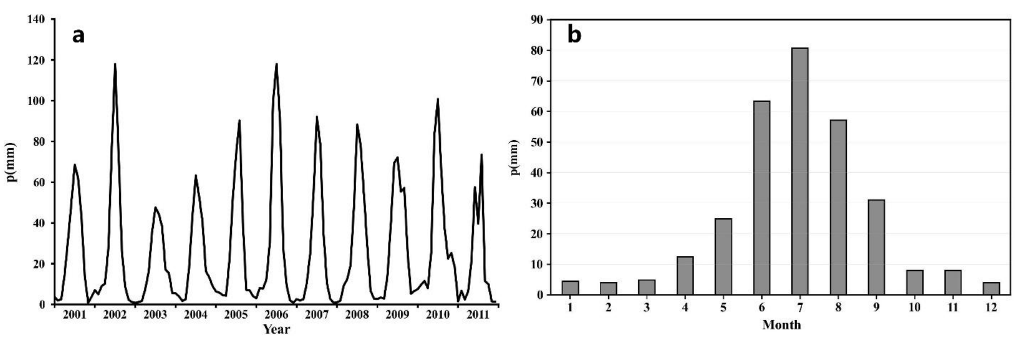

Figure 5 Interannual and monthly precipitation variation from 2001-2011. (a) Interannual precipitation variation. (b) Average monthly precipitation variation

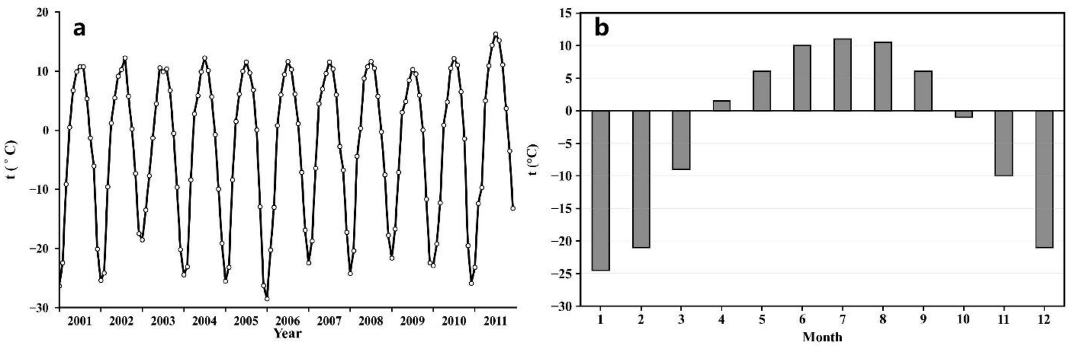

Figure 6 Interannual and monthly temperature variation from 2001-2011. (a) Interannual temperature variation. (b) Average monthly temperature variation

3.3 Streamflow chareateristics

The annual streamflow of the river exhibits certain interannual fluctuations (Figure 7), showing a bimodal characteristic: the first peak occurs in spring (April or May), mainly depending on the melting of seasonal snow in the middle to high mountain range, while the main peak appears in summer (June or August), mainly contributed by the summer P and glacier/snow-melting in high mountains. Streamflow from snowmelt increases in spring, which is closely related to the amount of snowfall in the winter and spring seasons, as well as the rate of T rise in spring (Zhang et al., 2014), but its increase in summer is caused by the amount of rainfall and snow/glacier-melt. The overall streamflow in the KRB showed an increase trend from 2001 to 2011, with a seasonal pattern of "spring increase, summer stability, autumn increase, and winter decrease". Snowmelt runoff accounts for about 30-40%, rainfall runoff accounts for about 45-55% (mainly in summer), and groundwater recharge accounts for about 15% (stable recharge) .

The flood driven by snowmelt generally occurs in April and May, which is generally lower than that in summer, depending on the melting timing and area variation of snow cover at different elevations. The overall trend of spring flood shows a pattern of "early start, stable peak, and prolonged duration" with large interannual fluctuations. The annual snowmelt flood volume in spring increased with a rate of about 16 million m³/a (P<0.05).

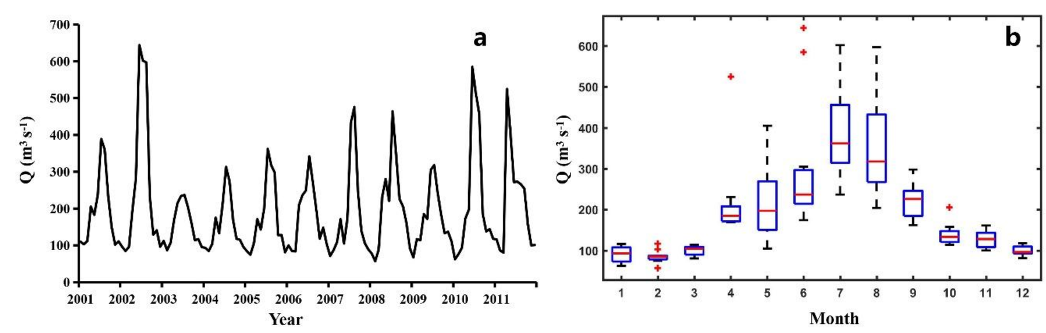

Figure 7 Interannual and monthly streamflow variation from 2001-2011. (a) Interannual streamflow variation. (b) Average monthly streamflow variation

3.4 Response of spring flood to snow cover

Snow cover plays a key role in the spring flood. The peak flow of spring flood has a correlation coefficient of r=0.78 with the spring snow cover area. Spring flood regime depends on snow cover area and melting at different elevations in spring. Figure 8 shows that flood in April is sensitive to the average snow cover area of 2000-2500m elevation zone in April (R^2 =0.7897), while flood in May is sensitive to the maximum snow cover area in April within the whole basin (Figure 9), particularly that in the 2000-3000m elevation zone (R^2 >0.67). Low elevation snow cover determines the occurrence time and initial intensity of floods, while middle to high elevation snow cover dominates the peak scale and duration of floods. Snowmelt in low elevation below 2000m above sea level starts in March as the T rises rapidly, forming initial runoff and initiating the pre-flood process. With T rise from late March to April, the maximum amount of snowmelting occurs within middle elevations between 2000-3000m above sea level, which significantly increases the streamflow and is the main incremental area of spring floods. A large snowmelt overlapping sudden rainfall in April can easily lead to small-scale excessive floods. After the T rises to the threshold from late April to May, the concentrated snow melting at middle to high elevations (2000-4000m) directly triggers the peak of spring floods. The duration of melting can reach 1.5-2 months, transforming the flood process from a "short-term" to a "gradual and persistent" one.

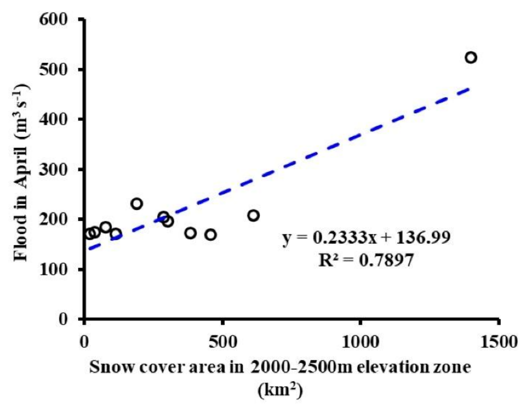

Figure 8 Relation between flood flow in April and snow cover area in the elevation between 2000-2500m

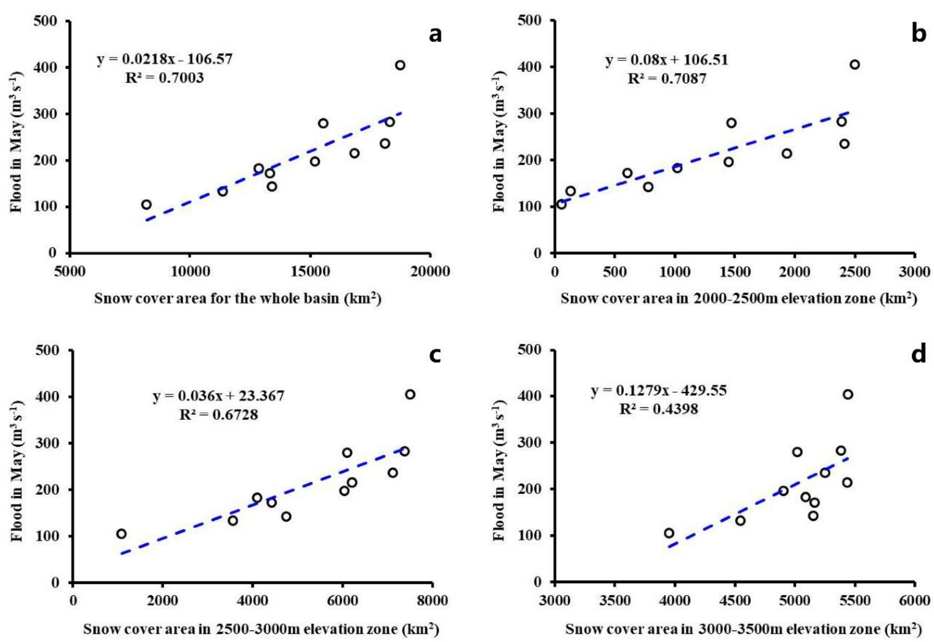

Figure 9 Relation between flood flow in May and snow cover area with different elevations

4 CONCLUSIONS

This study analyzes the spatiotemporal changes of snow cover and its relation with spring floods in the Kaidu River Basin. The results highlight that the snow cover starts accumulation from September, then reaches the maximum in January or February. Snow cover does not show an obvious change trend over 2001-2011. The spring flood generally happens in April and May in the basin, and its volume is generally smaller than that in summer driven by rainfall. Spring flood in April or May depends on the snow cover area in April. Flood in April is sensitive to the average snow cover area of 2000-2500m elevation zone in April, while flood in May is sensitive to the maximum snow cover area in April within the whole basin, particularly that in the 2000-3000m elevation zone. These findings can support water resources management and spring flood disaster prevention in the Kaidu River Basin.

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