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Method to identify composition and production phases of spring runoff in high-latitude mid-temperate regions: a case study in the Second Songhua River Basin, China

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ABSTRACT

Simulation and forecasting of runoff play an important role in the early warning and prevention of drought and flood disasters. To improve the accuracy of spring runoff simulations, it is important to identify spring runoff production patterns under the combined effect of snow and frozen soil. Based on the theory of the hydrological cycle, three important parameters, which include surface and subsurface runoff, precipitation and temperature, were selected for this study. The trend analysis, statistical analysis and Eckhardt's recursive numerical filtering method were used to qualitatively identify the production patterns of spring runoff, the start and end dates and stage periods of the production patterns. Based on the qualitative identification results, the contribution of each production runoff to the total annual runoff and the total annual spring runoff is quantitatively assessed. The results of the study show that the spring runoff production patterns in the Second Songhua River Basin can be divided into snowmelt runoff, frozen soil conditions of snowmelt–rainfall runoff and rainfall runoff under frozen soil conditions; the snowmelt production is from 21 March, the frozen soil conditions production is from 21 April and the frozen soil ablation ended on 15 June; the shortest phases of each production pattern last 28, 20 and 18 days and the longest last 31, 26 and 24 days. This research provides the basis for improving the principles of production runoff calculation in spring runoff simulation methods.

Key words: frozen soil runoff, runoff production phase, snowmelt runoff, spring runoff

HIGHLIGHTS

- Determine the main water source of spring runoff in cold regions.
- Classify the runoff generation patterns of spring runoff based on the characteristics of runoff generation mechanism in high-latitude mid-temperate regions.
- Identify the duration of the runoff according to the characteristics of each runoff pattern.

INTRODUCTION

Snowmelt of stable seasonal snow areas is the main source of water for rivers in spring (Hu *et al.* 2015). The snow accumulation in China covers an area of $900 \times 10^4\ \mathrm{km}^2$ and the snow storage in winter amounts to more than $200 \times 10^8\ \mathrm{m}^3$ snow water equivalent (Dibike & Coulibaly 2008). In some mid-latitude arid and semi-arid mountainous areas, snow and ice meltwater have become an important part of surface runoff. The three major sources of spring runoff among the recharge of ice and snow meltwater, precipitation and groundwater, the recharge of ice and snow melt runoff is up to more than 75% (Wang *et al.* 2006). Therefore, the ice and snow meltwater is an important freshwater resource in China, as well as a strategic resource, with an important impact on all aspects of socioeconomic production and life.

In the high latitudes of China's mid-temperate region, winters are cold and long-lasting, lasting around 5 months, with precipitation mainly in the form of snowfall, which are stable seasonal snow areas in China's cold regions. The Second Songhua River is one of the major rivers in the northeast of China. The high-latitude mid-temperate regions of its basin receive little spring precipitation and the main supply of rivers is snowmelt water (Jiao *et al.* 2009). Spring runoff is the second abundant water season of the year in the Second Songhua River Basin, which coincides with the season for agricultural sowing with huge demand for water for irrigation. In addition, this period is also the peak season of shipping water consumption in the lower reaches of the Second Songhua River. The study of spring runoff patterns allows for the scientific and reasonable formulation

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of reservoir scheduling plans, which can ensure agricultural water supply, shipping water demand and meet power supply water requirements, while reserving reservoir capacity for later flood control and achieving efficient development and utilization of water resources. However, the study of spring runoff norms is challenged due to the diversified water sources of spring runoff (Dewalle & Rango 2008), multiple influencing factors and complicated intertwining among other factors (Singh 2010).

Much of the current research on spring runoff has focused on the calculation of snowmelt water volumes, and many studies have used regression analysis and hydrological model simulations. Although the snowmelt process is important in determining spring runoff, for snowmelt runoff studies, such methods ignore the influence of frozen soil conditions on snowmelt runoff. The amount of spring runoff water source depends not only on the snowfall and rainfall (Li *et al.* 2018), but also on the frozen soil thawing process and the way runoff under frozen soil hydrological characteristics condition (Yang *et al.* 2007). With the frozen soil thawing, the spring runoff process is divided into three stages, which are direct runoff at the beginning of the snowmelt when the frozen soil has not melted, the upper layer of the mid-term frozen soil has just thawed and the soil moisture is high resulting in saturation excess runoff, and at the end term, the frozen soil has completely melted, there is enough soil moisture and the rainfall runoff rate is greater than the soil infiltration rate results in infiltration excess runoff (Liao *et al.* 2008; Li *et al.* 2011).

As can be judged from the process of snowmelt water runoff, the snowmelt runoff confluence is enabled in the following three means: ground confluence, soil middle stream and groundwater confluence (Yang *et al.* 2019). The formation of frozen soil causes the infiltration of snowmelt water to form soil subsurface flow on the impermeable surface of the frozen soil, where this soil subsurface flow is attributed to the surface runoff, and the ground confluence must be generated after the maximum water holding capacity of the underlying surface is reached. The infiltration capacity of the surface soil is usually greater than the rate of snowmelt production, and surface confluence can only occur after the maximum water holding capacity of the surface soil has been reached. Therefore, surface confluence mainly occurs above the frozen soil or on the impermeable surface soil (Bengtsson *et al.* 1992); that is, the main means of the confluence of snowmelt runoff is surface runoff. According to the studies of Kendall *et al.* (1999) and Cooley & Palmer (1997), since the upper layer of soil permeability is greater than the lower layer, together with the existence of frozen soil, snow melting water can flow quickly in shallow soil, that is how runoff is formed under frozen soil conditions. In addition, the groundwater level rises as is replenished by a small amount of snowmelt water, thus increasing the hydraulic gradient of the water table, and the groundwater replenishes the river channel runoff. Regarding the convergence speed of the three water sources, the surface runoff converges the fastest with sharply rising river flows, followed by the soil runoff and the underground runoff with slowly rising river flows. To simplify the study, the soil runoff generated under frozen soil conditions is categorized as surface runoff. Therefore, spring runoff can be simplified into two major categories based on the confluence characteristics: surface runoff and underground runoff. Furthermore, a study on the spring runoff water source composition and phase division can be abstracted to analyze the evolution of surface runoff and underground runoff.

The above research studies can tell that seasonal stable snow regions, where spring runoff is influenced by frozen soil and pre-accumulated snowfall, have complex and diverse runoff production patterns. However, studies of spring runoff in the regions have focused on the quantitative analysis of snow resources, snowmelt water volumes and the qualitative understanding of freeze-thaw processes in frozen soils. Few studies have explored the diversity of production runoff patterns under the effects of frozen soils and pre-accumulated snowfall. This problem is also ignored in the simulation and forecasting of spring runoff. As a result, many high-latitude mid-temperate zones of stable seasonal snowpack have low accuracy of spring runoff simulations. This brings challenges to the forecasting of spring runoff and difficulties in the prevention of spring droughts and floods. This study reveals the diversity of spring runoff production patterns and provides a basis for improved simulation and forecasting methods for runoff.

METHODOLOGY

Base flow segmentation

Baseflow process analysis is an important topic in hydrological studies in addition to flow process analysis. Runoff, baseflow and groundwater-level changes are the main manifestations caused by precipitation production and confluence and underlying surface changes. The analysis of its intra-annual changing course allows the identification of runoff production patterns in different water sources and the recognition of the impact of changes in the underlying surface. As the baseflow cannot be directly observed, foreign researchers have proposed various baseflow splitting methods, such as the direct splitting method, water balance method, numerical simulation method and hydrological modeling method, based on the difference in confluence between the steep rise and fall of surface runoff and the slow rise and fall of subsurface runoff. Among them, the direct splitting method is highly subjective and not suitable for long time-scale baseflow splitting; the water balance method has more parameters, complex formulas and is difficult to optimize; the hydrological modeling method has clear physical meaning and high credibility, but requires more parameters and extremely complex operation; and the numerical simulation method is highly efficient, repeatable and widely used in current research (Hao *et al.* 2019), mainly including the digital filtering method (Hamidreza & Keith 2015), the hydrograph separation program (HYSEP) (Gardner *et al.* 2010) and the minimum smoothing method (Bastola *et al.* 2018).

There are significant differences in the applicability of baseflow splitting methods in different study areas due to hydrometeorological conditions. Based on some existing studies on the applicability of baseflow splitting methods, Li *et al.* (2013) studied the Eckhardt recursive numerical filtering method for the Second Songjiang River basin and determined the baseflow index based on the basin characteristics. The Eckhardt recursive numerical filtering method used in this study is based on the results of this study. The digital wave filtering method is the most frequently studied method of runoff segmentation in recent years. Eckhardt (2008) compared the Eckhardt digital wave filtering method with other methods in 65 basins in the United States and discovered that this method is the most reasonable one for segmenting underground runoff. The calculation method adopted in this paper is the Eckhardt (2005) recursive digital filter equation:

$$q_t = \frac{(1 - \mathrm{GFI}_{\max}) * a * q_{t-1} + (1 - a) * \mathrm{GFI}_{\max} * Q_t}{1 - a * \mathrm{GFI}_{\max}} \tag{1}$$

where Q_t is the river runoff at time t; q_t is the subsurface runoff at time t; q_{t-1} is the subsurface runoff at the previous time t; a is the filter parameters; $\mathrm{GFI}_{\max}$: GFI is the groundwater flow index, indicating the proportion of underground runoff in river runoff; $\mathrm{GFI}_{\max}$ is the largest underground runoff index; and t is the time period.

According to the research of Eckhardt: for the constant-flow river dominated by pore aquifers, $\mathrm{GFI}_{\max}$ is 0.80; for the seasonal river dominated by pore aquifers, $\mathrm{GFI}_{\max}$ is 0.50; for the seasonal river dominated by weak aquifers, $\mathrm{GFI}_{\max}$ is 0.25; and the value of a has little effect on the calculation result and is generally set from 0.95 to 0.98.

When segmenting runoff, $\mathrm{GFI}_{\max}$ is simply taken as 0.80, 0.50 and 0.25 just based on the basin's underlying surface conditions and hydrological conditions, which inevitably results in large errors. Therefore, Hongyan Li improved the value-setting of $\mathrm{GFI}_{\max}$, as the runoff is segmented by the sliding minimum method, then the underground runoff index $\mathrm{GFI}_{\max}$ of each hydrological year is calculated, and the largest $\mathrm{GFI}_{\max}$ is eventually set as $\mathrm{GFI}_{\max}$.

Method to classify the spring runoff water sources and runoff production phases

The analysis of the hydrological processes of the Second Songhua River source section of the Baishan and Fengman basins from 1960 to 2017 (due to the large number of samples, showing that the analysis process of all samples would make the volume of the article larger by too many graphs, this paper selects the last 2017 from the long series of data as an example to show the analysis process and finally provides the analysis results of all samples) illustrates the spring runoff in the middle temperate region of China's production and convergence processes, analyzing spring runoff and baseflow processes, using trend analysis and statistical analysis methods to identify spring runoff production phases and classify the stage periods of each runoff production pattern through the following three methods:

1. Based on the characteristics of the runoff production and confluence of each water source in spring runoff, the runoff production pattern of each water source is divided. The commencing and completion dates of the production phases of each water source are assessed according to the spring runoff process.
2. Based on the evolution trend of the baseflow ratio, the commencing and completion dates of the production stages of each water source are quantitatively analyzed.
3. Combined with the groundwater-level monitoring data in the basin, the classification of each water source runoff production phase was checked according to the groundwater recharge from the water sources of each runoff production phase.

Study area and data

Originating from the Tianchi Lake, Baitou Mountain, the highest mountain in northeastern China, the Second Songhua River has a basin covering an area of 7.34×10^4 km^2, with a humid cold and warm climate. Influenced by the Pacific monsoon, summer here is warm, humid and rainy, while winter is mainly controlled by the Siberian high pressure with a cold and dry climate. Upstream of the mainstream, there are controlling step hydrological hub projects, Baishan Reservoir is the first hub of the step hydroelectric power station group, controlling a watershed area of 1.9×10^4 km^2, and Fengman Reservoir is the second large hydrological hub project, with a catchment area of 4.25×10^4 km^2 (Figure 1), located at the high altitude mountains of the head river of the Second Songhua River. The basin is frozen from late October to early November and thawed in early or mid-April in the following year, with an average annual freeze period of up to 135 days. Winter precipitation occurs mainly in the form of snowfall, which snowfall period from early November to mid to late March each year, during which time snowpack and frozen soil form. The maximum snow cover during the year was 93.12%, which occurred in February, and the minimum snow cover was 4.12%, which occurred in April; the average snow depth during the year was 16.33 cm, with a maximum of 30 cm and a minimum of 2.97 cm. Therefore, as temperatures rise in the spring, the snow melts to form snowmelt runoff, and it becomes an important water source for the region in the spring. The region has little spring precipitation, with varying levels of annual droughts in parts of the region, and spring flooding from snowmelt to a lesser extent in parts of the region. Therefore, the simulation and forecasting of spring runoff are very important.

The data used in this study are as follows.

Baishan Reservoir (1960–2017) daily inflow runoff data are sourced from Baishan Hydropower Plant of State Grid Xin Yuan Company Limited, and Fengman Reservoir (1960–2017) daily inflow data are sourced from Fengman Hydropower Plant of State Grid Provided by Xin Yuan Company Limited.

Monitored data 2017 of the two groundwater levels in Huadian and Jiaohe came from the Jilin Hydrology Bureau.

RESULTS AND DISCUSSION

Spring runoff production pattern classification

Analysis of annual runoff processes

Based on the daily runoff data of Fengman and Baishan reservoirs within the Second Songhua River Basin, the 10-day-scale multiyear average flow process curves were drawn (Figure 2) to describe the distribution of annual runoff from Fengman and

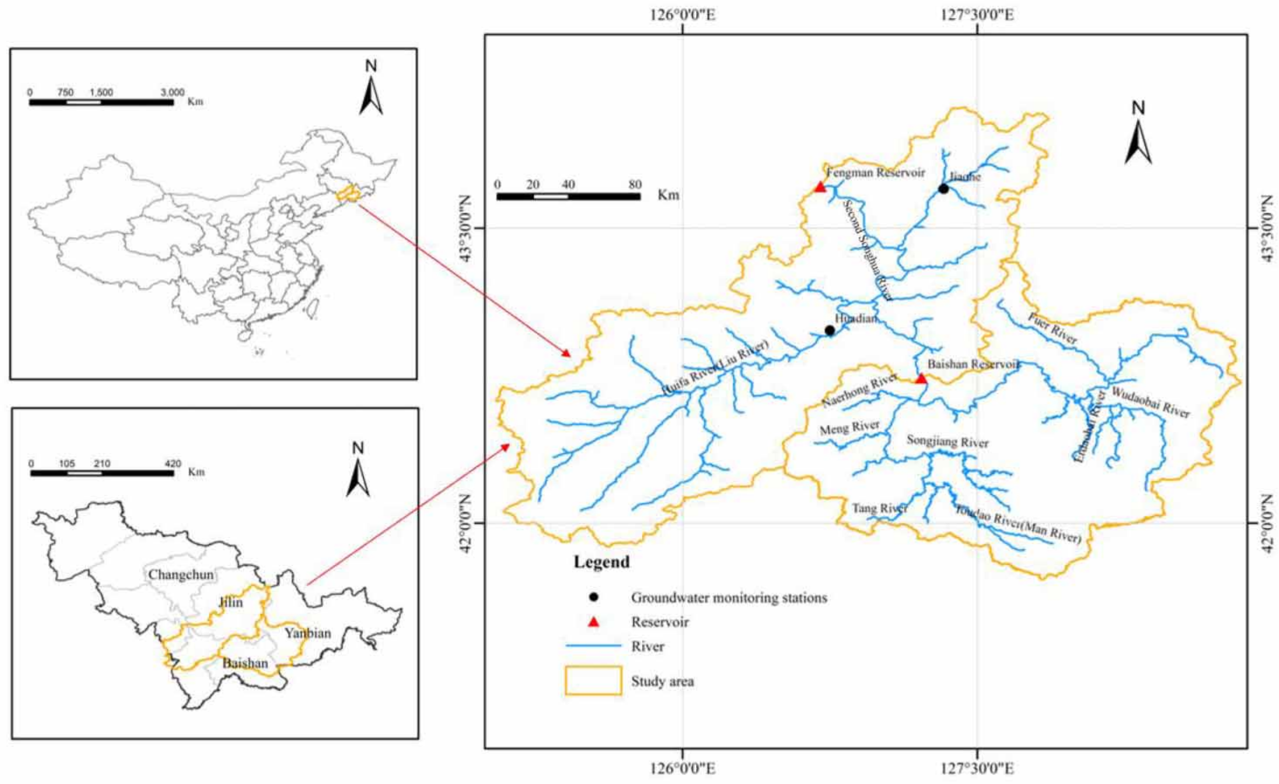

Figure 1 | Location and water system of the study area.

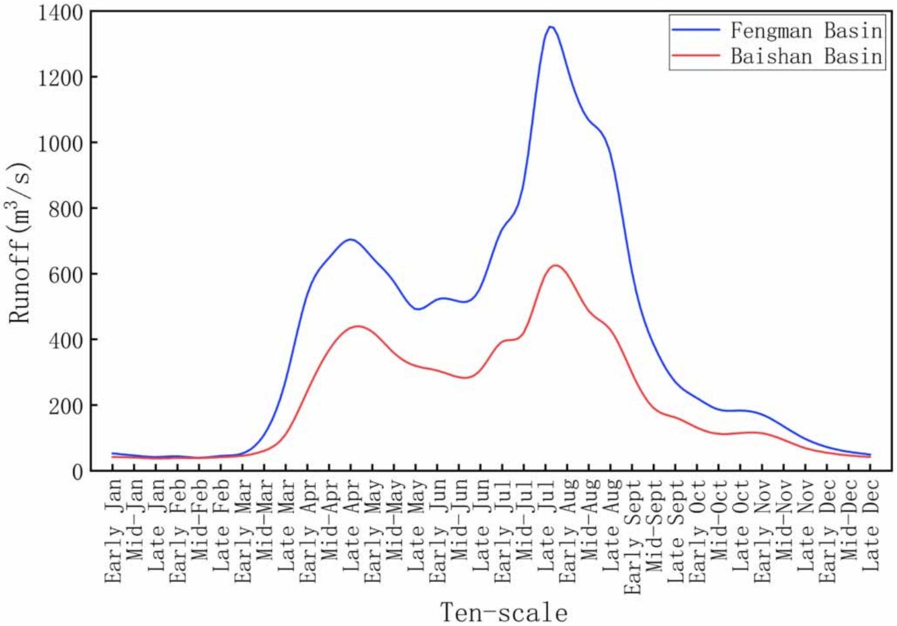

Figure 2 | Multiyear average runoff processes of mainstream in the Second Songhua River Basin.

Baishan reservoirs in multiyear average condition. On the one hand, it is evident that the overall trend of incoming flow from the two reservoirs is similar, indicating the existence of a good hydraulic connection between the two graded reservoirs. It also explains how the spatial and temporal characteristics of the hydrological cycle process are similar. On the other hand, the spring and summer flood processes are evident, although there is little spring precipitation in the basin, and a more pronounced spring flood period exists due to the presence of pre-accumulated snowfall.

Analysis of spring runoff processes

Taking the daily runoff process line of Fengman and Baishan reservoirs in spring 2017 (Figure 3(a) and 3(b)) as a case study, analyzing the slope values of the annual spring runoff trend changes in the basin (Tables 1 and 2), in the Fengman basin, the slope absolute value of trend change in the runoff process is defined as slow fluctuation from 0 to 50, steep fluctuation from 50 to 100 and more than 100 for sharp fluctuations. The area of the Baishan basin is smaller than that of the Fengman basin, so the absolute slope of trend change in the runoff process is defined as slow fluctuation from 0 to 30, steep fluctuation from 30 to 100 and more than 100 for sharp fluctuations. It can be observed that there are three obvious phases of the runoff process in spring (March–May period), which are three phases of steady rise and slow fall, steep rise and slow fall, and sharp rise and slow fall. According to the principles of runoff formation and the climatic characteristics of the study area, the first phase of runoff originates from the snowmelt runoff production, the second phase of runoff originates from the snowmelt and rainfall runoff production process under frozen soil conditions and the third phase of runoff originates from the rainfall runoff production process under frozen soil conditions.

The spring precipitation and average temperature processes in the Fengman and Baishan reservoirs in 2017 (Figure 3(c) and 3(d)) are used as case studies. First of all, observe the precipitation process in both basins, from early March to mid-April there is almost no precipitation in the basin, but there is a very obvious process of change in the runoff process at this stage, while the average temperature keeps rising and starts to be greater than 0 °C by mid-March. The runoff process also starts to rise steadily at this point; this is because the temperature rises and the snow starts to melt to form snowmelt runoff, which is the snowmelt production process described earlier. Precipitation is produced in the basin from mid to late April, with average temperatures greater than 0 °C and increased volatility, and the significant change in runoff during this period is the precipitation and continued melting of undissolved snow to form runoff, a snowmelt and rainfall production process under frozen soil conditions. Precipitation increases from the beginning of May, the average temperature continues to rise, the snow is completely dissolved at this point and the significant change in runoff is the formation of runoff from the rainfall, i.e. the process of rainfall production under frozen soil conditions.

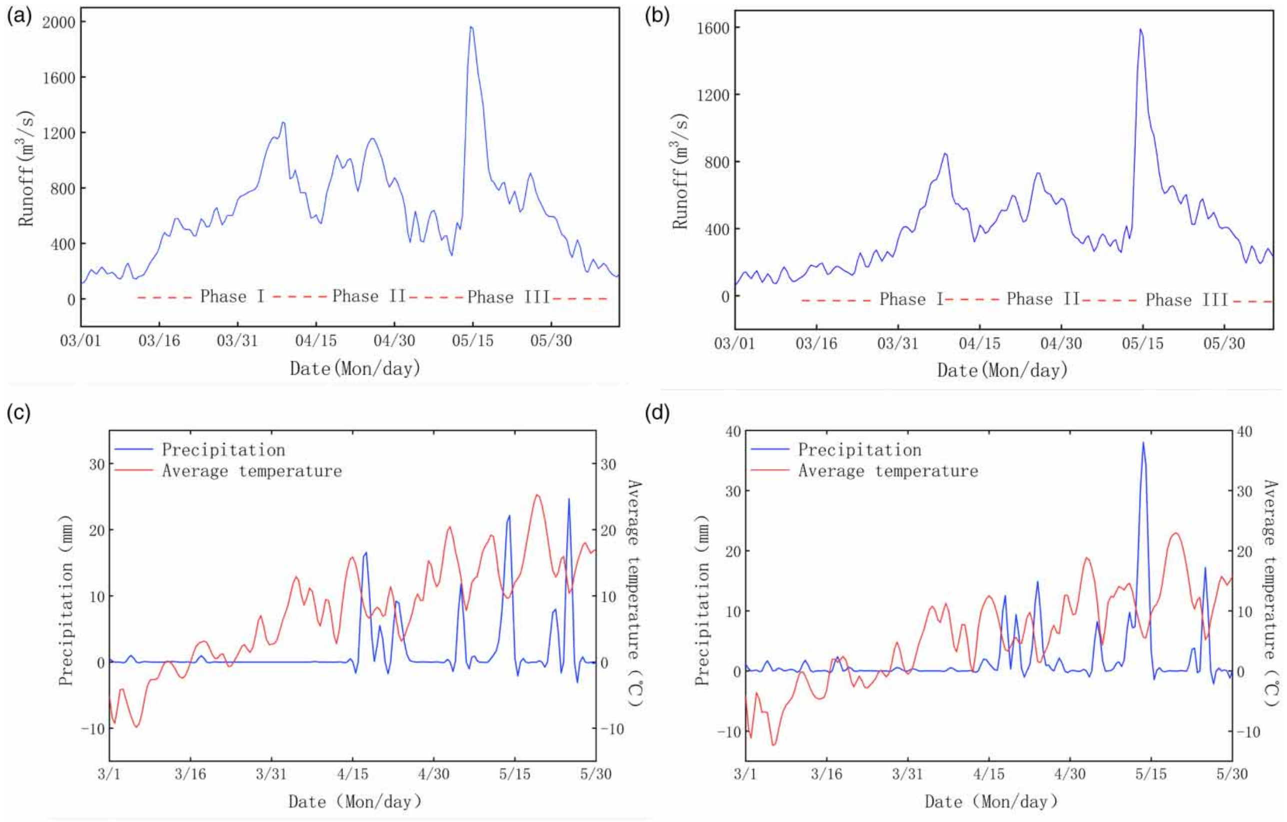

Figure 3 | Annual spring runoff, precipitation and mean temperature processes in the Fengman and Baishan basins (2017). (a,b) Annual spring runoff processes in the Fengman and Baishan basins. (c,d) Annual spring precipitation and mean temperature processes in the Fengman and Baishan basins.

Table 1 | Slope values for annual spring runoff trend changes in the Fengman basin

Phase	Steady rise and slow fall		Steep rise and slow fall		Sharp rise and slow fall	
Trend changes	Rise	Fall	Rise	Rise	Fall	Rise
Slope values	32.2	−88.1	64.6	−37.8	440.3	−33.1
Interval (absolute value of slope)	0–50	50–100	50–100	0–50	>100	0–50

Table 2 | Slope values for annual spring runoff trend changes in the Baishan basin

Phase	Steady rise and slow fall		Steep rise and slow fall		Sharp rise and slow fall	
Trend change	Rise	Fall	Rise	Fall	Rise	Fall
Slope value	22.1	−82.8	33.9	−27.9	350.4	−23.2
Interval (absolute value of slope)	0–30	30–100	30–100	0–30	>100	0–30

Phase stage identification of spring runoff production patterns

Phase period analysis of runoff production based on runoff processes

According to the runoff process of all sample years, the starting and ending dates of each water source were divided by the remarkable valley point as the critical time node, i.e. the start date of snowmelt runoff (snowmelt runoff production phase), the start date of frozen soil runoff (snowmelt and rainfall runoff production phase under frozen soil conditions), the end date of snowmelt runoff (rainfall production phase under frozen soil conditions) and the end date of frozen soil ablation. Such statistics are carried out annually. As an example, the daily runoff processes of the Fengman and Baishan reservoirs (Figure 3(a) and 3(b)) are analyzed as follows:

(1) *Commencing date of snowmelt runoff*: the first phase of runoff is derived from snowmelt and the whole runoff process is characterized by slow rise and steep fall. The first rising date is the commencing date of snowmelt runoff.
(2) *Commencing date of frozen soil runoff*: the second phase of runoff is derived from snowmelt and rainfall under frozen soil conditions, and the whole runoff process is characterized by steep rise and slow fall. The second rising date is the commencing date of runoff under frozen soil conditions, and the second rise is higher than the first.
(3) *Completion date of snowmelt runoff*: the third phase of runoff is derived from rainfall runoff under frozen soil conditions, i.e. snow has disappeared at this phase, the runoff source is spring rainfall runoff under frozen soil conditions and the runoff process is characterized by steep rise, high peak and slow fall. The third rising date is the completion date of the snowmelt runoff.
(4) *Completion date of frozen soil ablation*: the completion date of the third phase is the completion date of rainfall runoff under the frozen soil conditions.

The commencing and completion dates and the duration of each water source in 2017 for the Fengman and Baishan basins are shown in Tables 3 and 4.

Analysis on commencing and completion dates of water source based on base flow ratio

To begin with, based on the long-series and daily runoff data of the Baishan basin and the Fengman basin, the Eckhardt digital wave filtering method is adopted, and the sliding minimum method is applied to determine the convergence parameter and segment the surface runoff and the underground runoff.

Based on the theory of snowmelt runoff production and confluence, the surface runoff obtained by runoff segmentation is deemed as snowmelt runoff; the ratio of underground runoff to total runoff is the base flow ratio, and the total runoff process line and the base flow ratio process line are drawn, respectively; the daily-scale temporal evolution of the two process lines are analyzed based on the base flow ratio method of the daily runoff; the start and end dates of the water source are determined according to the significant peak-to-valley date of the base flow ratio. The following analysis is made with the base flow ratio and the total runoff daily-scale process line in 2017 as an example (Figures 4 and 5):

(1) The first valley of baseflow ratio is seen on the start date of the snowmelt runoff; the first snowmelt surface runoff dominates, while the underground runoff ratio is the lowest, and this date is deemed as the start date of the snowmelt runoff.
(2) The first peak of baseflow ratio happens on the start date of snowmelt under frozen soil conditions. Due to the existence of fissures in the frozen soil, the snowmelt surface runoff resulted from infiltrated snowmelt is weak, while the underground runoff is strong. Therefore, the base flow ratio shows the first peak.
(3) The second peak of baseflow ratio occurs on the end date of the snowmelt runoff. The gradually disappearing snow results in the gradual decrease of snowmelt runoff, hence the underground runoff is once again superior, and the base flow ratio shows the second peak.

Table 3 | Commencing and completion dates of spring runoff production patterns in basin

Feature (date)	Snowmelt runoff starts	Runoff under frozen soil conditions starts	Snowmelt runoff ends	Frozen soil ablation ends
Fengman basin	15 March	17 April	6 May	28 May
Baishan basin	12 March	14 April	11 May	6 June

Table 4 | Duration of each spring runoff production phase of basin

Feature (day)	Snowmelt runoff	Snowmelt and rain runoff under frozen soil conditions	Rain runoff under frozen soil conditions
Fengman basin	33	19	18
Baishan basin	33	27	26

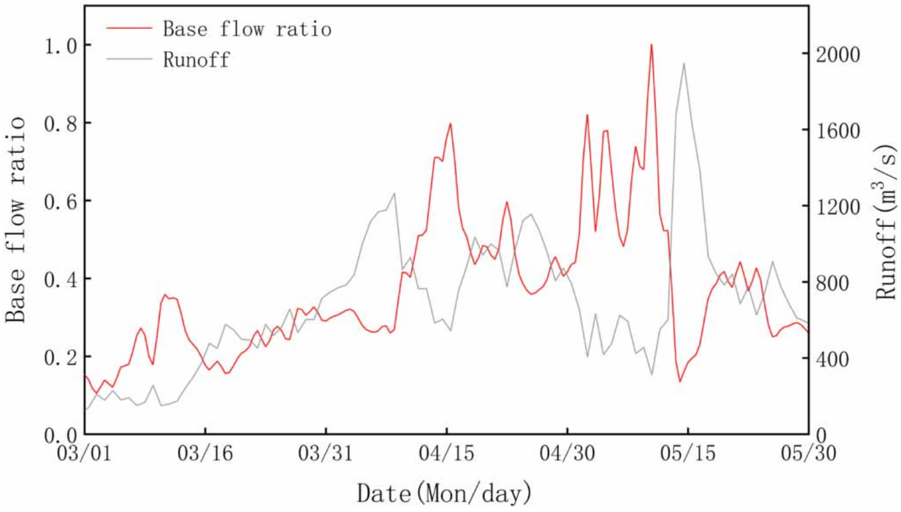

Figure 4 | Spring runoff and baseflow ratio process in the Fengman basin (2017).

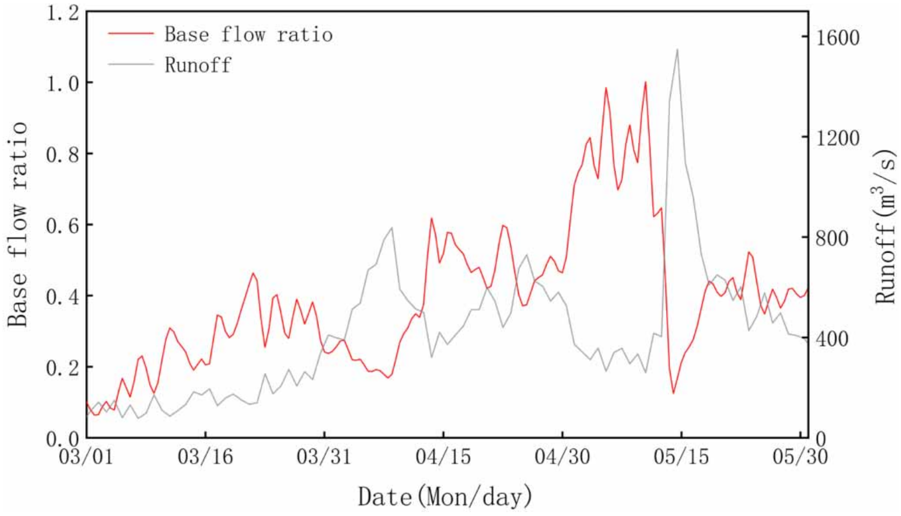

Figure 5 | Spring runoff and baseflow ratio process in the Baishan basin (2017).

(4) The third peak of baseflow ratio appears on the end date of frozen soil ablation. The frozen soil is ablated, the rainfall can directly supply groundwater and the base flow ratio shows the third peak.

Tables 5 and 6 show the commencing and completion dates and the duration of each water source of the Fengman and Baishan basins in 2017.

Using 2017 as a case study, according to the method of identifying the commencing and completion dates of each production pattern and the phase period in spring, the daily variation of base flow ratio and runoff volume from 1960 to 2017 of the Fengman and Baishan basins is analyzed, the commencing date and the completion date are divided (Figure 6). Fengman basin annual each water source start and end dates are more concentrated. While the start date of snowmelt runoff,

Table 5 | Commencing and completion dates of spring runoff production patterns in basin

Feature (date)	Snowmelt runoff starts	Runoff under frozen soil conditions starts	Snowmelt runoff ends	Frozen soil ablation ends
Fengman basin	3 March	16 April	5 May	22 May
Baishan basin	10 March	14 April	11 May	24 May

Table 6 | Duration of each spring runoff production phase of basin

Feature (day)	Snowmelt runoff	Snowmelt–rainfall runoff under frozen soil conditions	Rainfall runoff under frozen soil conditions
Fengman basin	30	19	17
Baishan basin	35	27	13

the start date of frozen soil condition runoff and the end date of snowmelt runoff in Baishan basin there is a downward trend. It is known that the snowmelt runoff process is relatively stable in the Fengman basin, while there is a tendency to advance the snowmelt runoff process in the Baishan basin.

The results of the duration of runoff production pattern phase statistics are shown in Figure 7, and the duration of each runoff production phase in the Fengman basin is more concentrated. The Baishan basin duration of the snowmelt runoff production phase is more concentrated, while the duration of snowmelt and rainfall runoff production phase under frozen soil conditions and rainfall runoff production phase under frozen soil conditions exist there is an upward trend.

An analysis of the start and end dates and phase durations of the runoff production patterns in the Fengman and Baisan basins shows that there is a tendency for snowmelt runoff to advance in the basin, while the duration of the rainfall runoff production phase is becoming longer in the Baishan basin, so it is clear that climate change is advancing the snowmelt runoff process (Wang & Li 2005; Ye *et al.* 2012).

Statistical analysis on the law of commencing and completion dates and the duration of runoff production phases

Statistical analysis on the law of commencing and completion dates of the runoff production phases

(1) The sample is organized according to the following principles: when both methods can determine the commencing and completion dates of the runoff production phases, the baseflow ratio process analysis method prevails; when only one

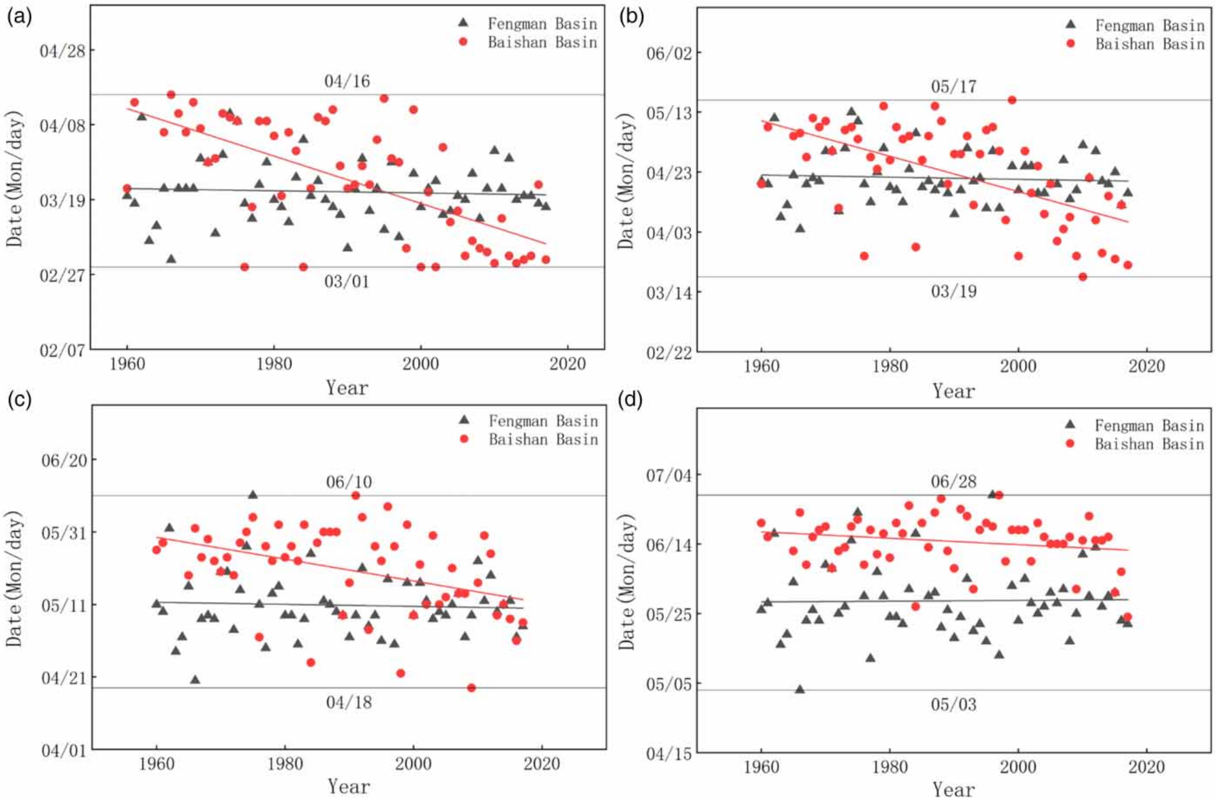

Figure 6 | Analysis of commencing and completion dates of each runoff production pattern in the Fengman and Baishan basins. (a) Commencing date of snowmelt runoff. (b) Commencing date of frozen soil condition runoff. (c) Completion date of snowmelt runoff. (d) Completion date of frozen soil ablation.

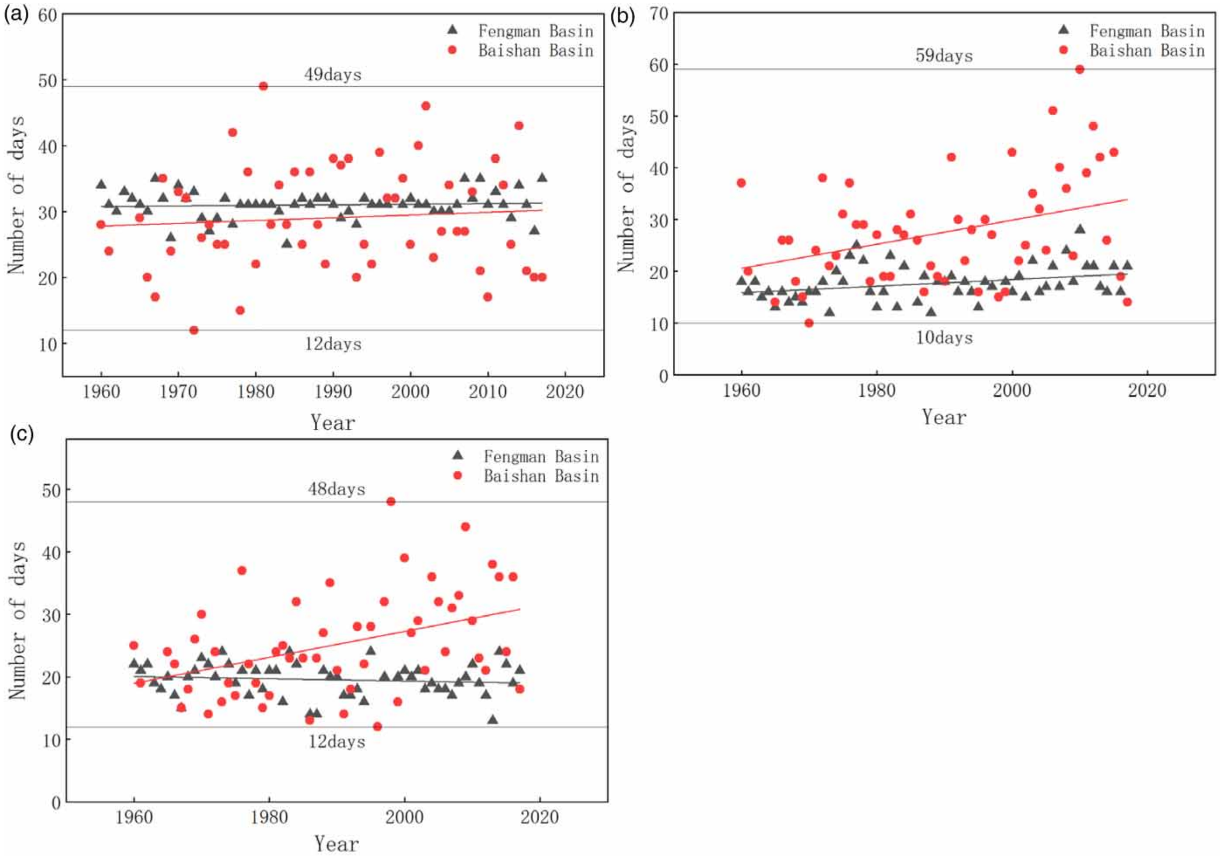

Figure 7 | Analysis of each runoff production phase duration in the Fengman and Baishan basins: (a) Duration of snowmelt runoff. (b) Duration of snowmelt–rainfall runoff under frozen soil conditions. (c) Duration of rainfall–runoff under frozen soil conditions.

method can determine such dates, the dates determined by that method prevails; when neither method can determine such dates, the commencing and completion dates of the runoff production phases, no statistics are taken for that year.

(2) Analysis method of the statistical law: the box plot analysis tool was used to carry out statistical law analysis of the commencing and completion dates of each runoff production phase. The five statistical values of the earliest date, the lower quartile date, the average date, the upper quartile date and the latest date of each runoff production phase were derived, respectively.

The results of the statistical analysis of the commencing and completion dates of each runoff production phase in the Fengman and Baishan basins using box plots are shown in Figures 8 and 9, and the statistical results are shown in Tables 7 and 8.

Under the multiyear average condition, the earliest date for the start of snowmelt production is 21 March, the earliest date for the start of frozen soil conditions production is 21 April and the latest date for the completion of frozen soil ablation is 15 June.

Analysis on the statistical law of runoff production duration

Based on the commencing and completion dates of the snowmelt runoff as well as the commencing date of runoff under frozen soil conditions and the end date of yearly ablation, samples of each runoff production phase have been formed over the years for the three phases of snowmelt runoff, snowmelt and rainfall runoff under frozen soil conditions and rainfall runoff under frozen soil conditions.

The box plot statistical tool is applied to analyze five indicators of the aforementioned three phases, i.e. the longest duration, the lower quartile duration, the average duration, the upper quartile duration and the latest duration, as well as one abnormal duration, which are used to comprehensively describe the statistical laws of spring runoff production phase duration.

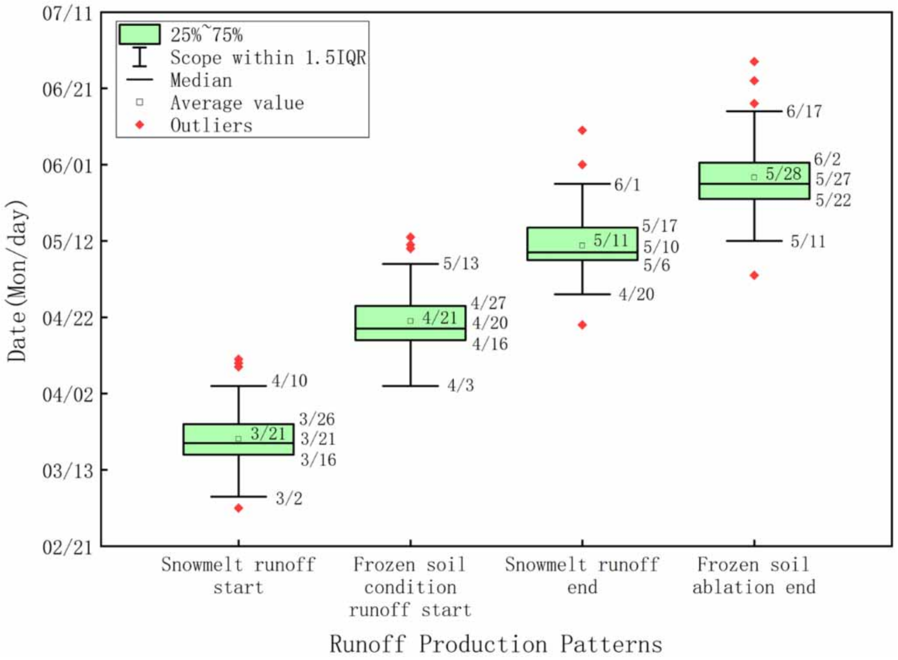

Figure 8 | Statistical analysis of the commencing and completion dates of each runoff production pattern in the Fengman basin.

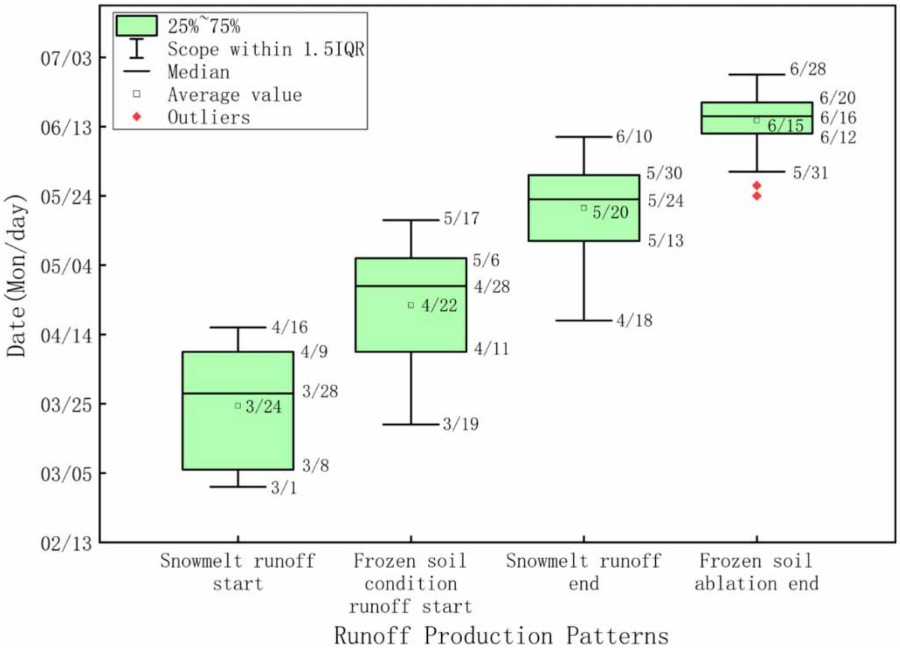

Figure 9 | Statistical analysis of the commencing and completion dates of each runoff production pattern in the Baishan basin.

The statistical results of runoff production phase duration statistics in the Baishan and Fengman basins are shown in Figure 10 and Table 9.

The statistical analysis shows that the duration of the snowmelt runoff production phase in the basin is 28–31 days, the duration of the snowmelt and rainfall runoff production phase under frozen soil conditions is 20–26 days, and the duration of the rainfall runoff production phase under frozen soil conditions is 18–24 days.

Table 7 | Statistical law on commencing and completion dates of each runoff production pattern in the Fengman basin

Feature (date)	Earliest	Early	Average	Late	Latest	Abnormal
Snowmelt runoff commencing date	2 March	16 March	21 March	26 March	10 April	11 April 27 February
Runoff under frozen soil conditions commencing date	3 April	16 April	21 April	27 April	13 May	Nil
Snowmelt runoff completion date	20 April	6 May	10 May	17 May	1 June	Nil
Frozen soil ablation	11 May	23 May	28 May	2 June	17 June	3 May

Nil means no outliers.

Table 8 | Statistical law on commencing and completion dates of each runoff production pattern in the Baishan basin

Feature (Date)	Earliest	Early	Average	Late	Latest	Abnormal
Snowmelt runoff commencing date	1 March	8 March	28 March	9 April	16 April	Nil
Runoff under frozen soil conditions commencing date	19 March	11 April	28 April	6 May	17 May	Nil
Snowmelt runoff completion date	18 April	13 May	20 May	30 May	10 June	Nil
Frozen soil ablation	31 May	12 June	15 June	20 June	28 June	27 May

Nil means no outliers.

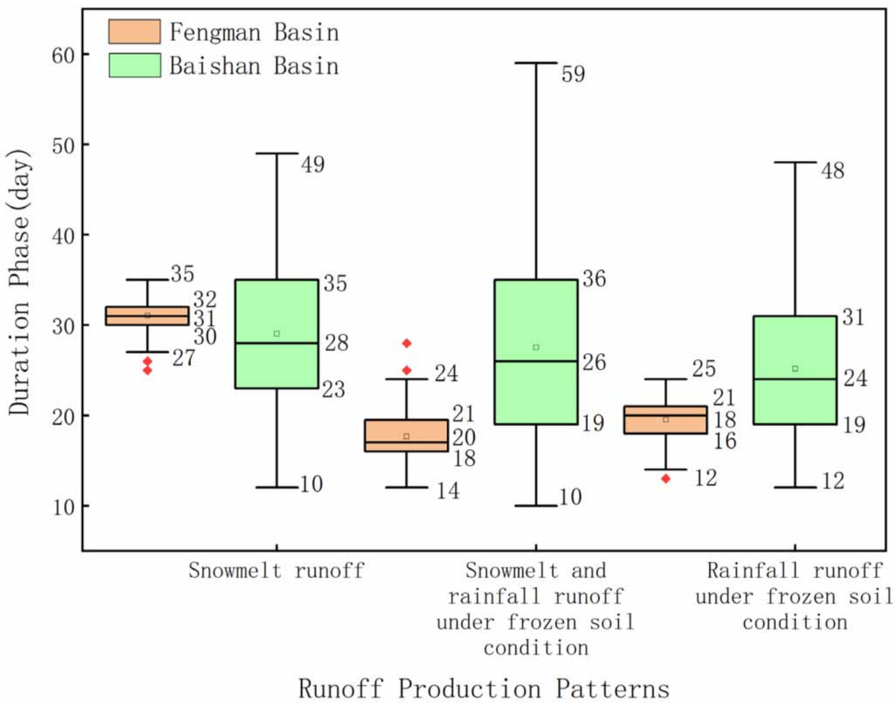

Figure 10 | Statistical analysis of each runoff production phase duration in the basin.

DISCUSSION

As can be seen from the comparative analysis of the spring runoff process in the Baishan and Fengman basins, the commencing of snowmelt runoff and frozen soil ablation are relatively late in the Baishan basin, since this area is located in the upper reaches of the Second Songhua River, with higher altitude and lower temperature; in terms of the start and end dates of the water sources in the Baishan and Fengman basins, the Baishan basin comes late as well. It indicates that the analysis result of the runoff production start and end dates is reasonable.

Table 9 | Statistical law on each runoff production phase duration in the Fengman and Baishan basins

Feature (Day)	Basin	Shortest	Short	Average	Long	Longest	Abnormal
Snowmelt runoff	Baishan	10	23	28	35	49	Nil
	Fengman	27	30	31	32	35	25, 26
Snowmelt and rain runoff under frozen soil condition	Baishan	10	19	26	36	59	Nil
	Fengman	14	18	20	21	24	13
Runoff under frozen soil condition	Baishan	12	19	24	31	48	Nil
	Fengman	12	16	18	21	25	28

Nil means no outliers.

It can be seen from the results that the duration of each runoff measured by the average start and end dates of each runoff production in the Fengman basin matches with the average duration generated from statistical analysis, as the corresponding relationship is shown in Table 10. For the Baishan basin, the snowmelt runoff duration is 31 and 28 days, respectively, the snowmelt and rainfall runoff under the frozen soil conditions are 24 and 26 days, respectively, and the rain runoff under frozen soil conditions is 27 and 24 days. These two statistical results match quite well, as the maximum error is no more than 3 days. The reason why the Fengman basin results are better than the Baishan basin is that the former has a larger area, twice that of the latter, and the larger the area is, the more stable the hydrological law is; otherwise, it will be more random. The woodland cover of the Fengman basin is smaller than that of the Baishan basin, which, on the one hand, affects solar radiation exposure and slows snowmelt and, on the other hand, increases the roughness of branches and leaves affecting runoff production, while at the same time reducing runoff production through entrapment.

The commencing date of snowmelt runoff and the frozen soil ablation date are judged according to the change of the groundwater level in the basin. Figure 11 shows the groundwater depth changing process 2017 (January–June) in groundwater buried monitoring wells in Huadian and Jiaohe in the catchment area (Figure 1). Jiaohe is within the Fengman basin, which is flatter, and Huadian is near the Baisan basin, which is steeper, so the infiltration in the Fengman basin is stronger than in the Baisan basin, resulting in a smaller groundwater depth in Jiaohe than in Huadian. At the same time, the commencing date of snowmelt runoff and the ablation end date of frozen soil can be analyzed from the groundwater depth at both stations, as follows.

Commencing date of snowmelt runoff

The lowest groundwater level at both stations appeared in March, after which the snow began to melt. Due to the existence of frozen soil fissures, the snow melting underwater infiltrated into the earth and the groundwater level gradually increased. Hence, the date of the lowest water level is the commencing date of the snowmelt runoff.

End date of frozen soil ablation

From late March to late May, the groundwater level showed a slow upward trend, after which the groundwater level rapidly rose and the summer rainfall runoff occurred. The date when the groundwater level changes abruptly is the end date for frozen soil ablation.

Based on the divided spring runoff production patterns, the contribution of each production volume to runoff was calculated. Under the multiyear average condition, the total spring runoff of the Second Songhua River Basin, the snow melt runoff accounts for 34.9%, and snowmelt and rainfall runoff under frozen soil conditions accounts for 30.8% and the rainfall

Table 10 | Average commencing and completing dates and duration of each runoff production pattern in the Fengman basin

Feature	Average date	Feature	Average duration
Snowmelt runoff start	21 March	Snowmelt runoff	31
Runoff start under frozen soil condition	21 April	Snowmelt and rain runoff under frozen soil conditions	20
End of snowmelt runoff	10 May	Runoff under frozen soil conditions	18
End of frozen soil ablation	28 May		

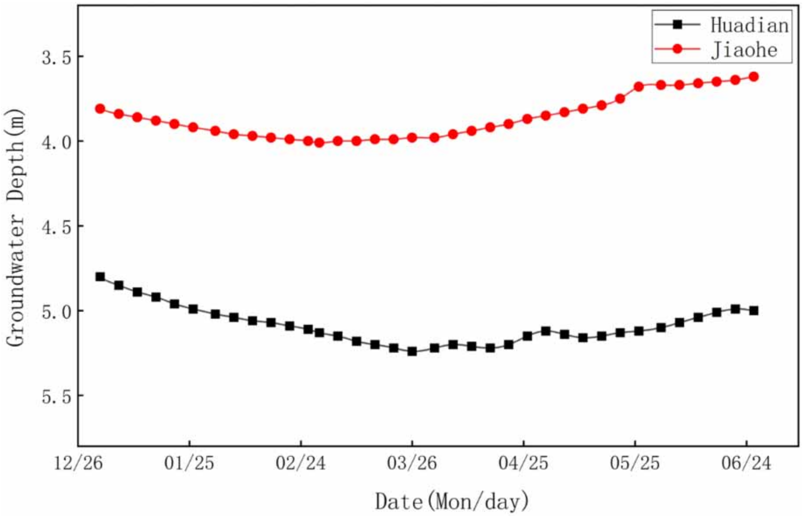

Figure 11 | Processes of groundwater-level depth change in the basin.

runoff under frozen soil conditions accounts for 24.7%; the annual total runoff of the Second Songhua River Basin, snowmelt runoff accounts for about 11.5%, snowmelt and rainfall runoff under frozen soil conditions accounts for about 10.1% and rainfall runoff under frozen soil conditions accounts for about 8.4%. The results of this study are supported by many researchers in China who have studied snowmelt runoff in cold regions (Ding *et al.* 2020; Zhang *et al.* 2021).

CONCLUSIONS

Most of the runoff simulation methods for production volume calculations are based on empirical equations, energy balances and physical principles of rainfall production volume calculation. Spring runoff has a variety of production patterns due to the influence of pre-accumulated snowfall and frozen soil, so the single method of existing calculating runoff production does not apply. As a result, most runoff simulation methods have large errors in simulating spring runoff in seasonally stable snow areas. Some researchers have also proposed methods for simulating snowmelt runoff in snow areas, where the snowmelt water is produced in the form of rainfall. Although this method considers the diversity of runoff production patterns for different precipitation forms, it ignores the impermeability, the inhibition of evaporation and the regulation of water storage of frozen soil, leading to small simulation for spring runoff. In this study, a method is proposed to identify spring runoff production patterns under the combined effect of snow and frozen soil. A theoretical basis is provided for the simulation method of spring runoff in snowy areas.

In this study, a method for identifying the composition and phase period of spring runoff water sources in the high-latitude mid-temperate cold region is proposed by analyzing the process changes of important parameters in the hydrological cycle, following the law of water balance in the water cycle. The pattern of spring runoff production is revealed based on the response of runoff and baseflow to precipitation. The trend analysis of hydrometeorological parameters identifies the water source composition of spring runoff. It illustrates that the pattern of spring runoff production in cold regions is not the same as the conventional rainfall production pattern. Spring runoff is affected by rainfall snowmelt and frozen soil. The complex runoff production relationships of combined rainfall, snow and frozen soil are simplified in the stable snow areas. The production of spring runoff is divided into a clear combined production pattern. This will improve the spring runoff simulation accuracy of the hydrological model.

Because of the lack of additional data, more experiments will be set up at a later stage to reveal the impermeability, inhibit evaporation and regulate water storage in terms of freezing and thawing of frozen soil, as well as to investigate the influence of snowmelt runoff production and confluence, and confirm the results of the study.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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