Different runoff patterns determined by stable isotopes and multi-time runoff responses to precipitation in a seasonal frost area: A case study in the Songhua River basin, northeast China

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ABSTRACT

Runoff patterns are crucial to determine the hydrological response to climate change, especially in a seasonal frost area. In this study, multi-time runoff responses to meteoric precipitation for the period from July 2014 to June 2016 and the period from 1955 to 2010 were obtained to identify different runoff patterns in the Songhua River basin, northeast China, based on six stations. Two distinctly different runoff responses are exhibited: a periodic one in response to precipitation in the Nen River and a constant one in the Second Songhua River under different scales. Stable isotopes in the plain with diverse characteristics also supported these runoff patterns. What is more, gradual runoff relatively less sensitive to precipitation in the Second Songhua River was attributed to upstream dam constructions. Furthermore, the Second Songhua River contributes more water to the main stream during January to March at the seasonal scale and in the 2000s at the annual scale, with low precipitation during those periods. This study could have implications for the water management in the Songhua River basin.

INTRODUCTION

Climate change has been widely reported in recent years and is expected to continue (IPCC 2007; Han et al. 2018). It is very likely that precipitation has increased over the mid-latitude land areas of the northern hemisphere since 1901. Meanwhile, increases in the number of days with precipitation and intensity of heavy precipitation with some seasonal and/or regional variation have been observed over many regions, even where there had been a reduction in annual total precipitation (Goswami et al. 2006; Donat et al. 2015; Liu et al. 2015). Precipitation is an important driver for the global hydrological cycle (Dai et al. 2009; Sivapalan et al. 2012; Jimenez Cisneros et al. 2014), carbon cycle (Chapin et al. 2011; Fang et al. 2018), and so on, and has attracted the attention of hydrologists and decision-makers.

Precipitation has an important impact on runoff, and runoff patterns with diverse runoff responses to precipitation are vital to assess the impacts of precipitation change on the hydrological cycle (Vogel et al. 1999; Berghuijs et al. 2017). Since precipitation elasticity to runoff was first defined by Schaake (1990), many studies have been conducted to identify the response of runoff to precipitation based on long-term hydrometeorological data (Sankarasubramanian et al. 2001;
Chiew 2006; Novotny & Stefan 2007). In this case, a quick response in which the maximum runoff peak coincided with the rainfall peak was observed (Changnon & Kunkel 1995; Onda et al. 2006), whereas in other cases, the variability of runoff was reduced due to check dams (Batalla et al. 2004; Abbasi et al. 2009), indicating less sensitivity to precipitation. Unraveling runoff patterns and their spatial-temporal variations is critical for the prediction and management of surface water resources (Birsan et al. 2005; Wu et al. 2012).

Runoff patterns in the frost regions are sensitive in response to climate change (Woo & Winter 1995; Kong & Pang 2012), which is affected by seasonal evolution of soil freezing and thawing. The Songhua River basin, located in the far northeast of China, is a typical seasonal frost area. There is a clear decreasing trend in annual precipitation found from 1960 to 2009 in the Songhua River basin (Li et al. 2014). Meanwhile, a declining trend at −0.81 mm season⁻¹ a⁻¹ was also observed for the summer series (Liang et al. 2011). Consequently, the stream flow in the main stream of the Songhua River basin shows a decreasing trend during 1955–2004 with dry years in the 1970s and after 2000 (Miao et al. 2011). Although there are several studies focused on the runoff changes at certain hydrological gauge stations, tributaries, and even the whole basin of the Songhua River (e.g., Xu & Ma 2009; Feng et al. 2011; Meng & Mo 2012; Pan & Tang 2013; Wang et al. 2015), the runoff patterns and their response to precipitation in the tributaries and their contributions to the main stream in the seasonal scale are rarely involved.

The aims of this study are: (1) to display different runoff patterns of the Songhua River with precipitation–runoff relationships in different time scales (daily, monthly, and annual) and isotopic evidence; and (2) to quantify the contributions of the two sources to the runoff of the main stream. This work will provide important insights into future sustainable water resource management and planning in the study area.

**STUDY AREA**

This study was conducted in the Songhua River catchments in northeast China (119°52’–132°31’E, 41°42’–51°38’N). It has a drainage area of 5.57 × 10⁹ km² with the ridges of the Daxinganling Mountain and the Changbai Mountain as its northwestern and southeastern boundaries, respectively. The ridge of the hills is the northwestern watershed and the ridge of the Wanda Mountain is the southeastern watershed of the Songhua River basin (Figure 1). Within the river basin, the highest elevation is 2,691 m at the Baitou Peak of the Changbai Mountain and the lowest elevation is about 57 m at the river outlet. The Songnen and Sanjiang Plains, with an elevation of 57–128 m, are situated in the central and eastern parts, respectively. The areas of mountain, hill, and plain within the basin account for 42.7%, 29.1%, and 27.4% of the total drainage area, respectively.

The Songhua River has a total channel length of 2,309 km with an average channel gradient of about 0.00042. The Nen River in the north and the Second Songhua River in the south are the two sources for the Songhua River (Figure 1). The Nen River, originating from the northern part of the Daxinganling (Greater Khingan) Mountain, has a channel length of 1,370 km and a channel gradient of 0.00066, while the Second Songhua River with a channel length of 958 km and a channel gradient of 0.00196 originates from the Tianchi Lake located in the central part of the Changbai Mountain. The two rivers join the Songhua River at Sanchahe and flow northeastward before joining the Heilongjiang River at the outlet of the river basin (Figure 1).

The Songhua River basin has a mean annual temperature of 3–5 °C with significant monthly temperature difference. Mean temperatures are below −20 °C in January and 25 °C in July. The mean annual precipitation in the river basin during the period 1955–2010 was 525.6 mm, more than 75% of which occurred during the rainy season from June to September (Liu et al. 2012). In comparison, precipitation is very low from December to February and represents only 5% of the total precipitation. Furthermore, spatial distribution of precipitation across the river basin is heterogeneous. The mean annual precipitation in the southeastern part of the river basin is about 700–800 mm, while that in the western part is only 400 mm.

**DATA AND METHODS**

**Data descriptions**

Data used in this study included daily runoff at Jiamusi, Yilan, Tonghe, Harbin, Dalai, and Fuyu stations from 1 July 2014 to
30 June 2016 (Figure 1), which were obtained from the Songliao Water Resources Commission (http://www.slwr.gov.cn). There are two hydrological stations located in the tributaries, which are Fuyu station in the Second Songhua River, and Dalai station in the Nen River. Harbin, Tonghe, Yilan, and Jiamusi stations are in the main stream from the upstream to the lower reach (Figure 1). The lowermost station, Jiamusi station, controls a drainage area of $5.28 \times 10^5$ km$^2$, accounting for 94.8% of the total drainage area. Daily precipitation amount data for the stations during the period of 2014–2016 are available from the National Meteorological Information Center of the China Meteorological Administration (http://data.cma.cn/). Annual runoff data for Dalai and Fuyu stations during 1956–2010 were taken from Wang et al. (2015) and Yu (2015). Isotopic data were obtained from Zhang et al. (2014) and Yang (2008).

Data for the isotopic composition of 61 surface water samples were taken from previously published studies (Yang 2008; Zhang et al. 2014). These samples were collected in both the headwater area and the central plain along the Nen River and the Second Songhua River.

**METHODS**

The double-mass curve plotted between precipitation and runoff is commonly used to reveal the streamflow change.
The basic idea of double mass analysis is the gradual summation of two variables according to the same time span, with one variable as abscissa and the other as ordinate. If the interaction between these two variables is stable, all the corresponding points should lie in a straight line. The cumulative anomaly was used to identify the turning year in runoff changes during the period 1955–2010. The anomaly is defined as annual value minus average value.

To calculate the contributions of total runoff from the two different sources, a two-component mixing model was used. The two-component separation of a runoff hydrograph into runoff from Nen River and runoff from the Second Songhua River can be described as:

\[ q_{N/S} = \frac{Q_N}{Q_N + Q_{SS}} \]  

where, \( Q_N \) and \( Q_{SS} \) are runoff from the Nen River and the Second Songhua River, respectively, and \( q_{N/S} \) is the proportion of the Nen River runoff in the total runoff from the Nen River and the Second Songhua River.

The variation coefficient of runoff was employed to analyze fluctuation of daily or annual runoff based on:

\[ C_v = \frac{\sigma}{\overline{Q}} \sigma = \sqrt{\frac{1}{N} \sum_{t=1}^{N} (Q(t) - \overline{Q})^2} \]  

where \( Q(t) \) is the daily or annual runoff for day/year \( t \), and \( \overline{Q} \) is the average of \( Q(t) \). When the value of \( C_v \) approaches zero, the runoff tends to be constant throughout the period.

RESULTS

Daily precipitation-runoff characteristics

There are four stations in the main stream of the Songhua River. Figure 2 shows the temporal variations in daily runoff at these four stations. Seasonal changes in runoff are similar at all stations with high values in the rainy season. The lowest runoff was observed during January to March at all stations, which is in good agreement with the lowest precipitation recorded during this period (Figure 2). When temperatures are low, the river freezes over, and snow has not melted. The lowest runoff recorded during a year is generally considered as the base flow. Our data show that the base flow increases from upstream to downstream, with a value of 472 m\(^3\)/s at Jiamusi, 423 m\(^3\)/s at Yilan, 380 m\(^3\)/s at Tonghe, and 358 m\(^3\)/s at Harbin. The variation coefficient for the runoff during January to March was 0.14, 0.16, 0.10, and 0.13 for Jiamusi, Yilan, Tonghe, and Harbin stations, respectively, and showed a steady trend during the dry season. Runoff began to increase after March, which can be attributed to snow melt in the basin and the thawing of the river network as temperatures rise, and is referred to as spring flood. Owing to the increase in precipitation (Figure 2), runoff remains high in the rainy season. There are two clear peaks in river runoff during the rainy season from July to September, which are observed at all stations (Figure 2).

Runoff at the main stream (Figure 2(a)–2(d)) started to increase in April, in accordance with the increase in precipitation. There were two or three peaks in runoff observed during the rainy season. Dalai station in the Nen River showed a similar trend to what was observed at the stations in the main stream (Figure 2(e)). The maximum runoff value was 2,840 m\(^3\)/s on 29 June 2015. The lowest values are observed in the winter season with low precipitation, indicating the base flow. Runoff characteristics for Fuyu station in the Second Songhua River were strikingly different, with only gradual variations throughout the year (Figure 2(f)). The only obvious increases were observed in the months of July 2015 and June 2016. Therefore, the runoff mechanism must be different for the two tributaries.

Monthly precipitation-runoff characteristics

To further understand the intra-annual variation in runoff, monthly mean runoff was calculated at six stations (Figure 3). Similar to the daily runoff variations, except for Fuyu station in the Second Songhua River, all gauge stations showed a synchronous tendency with an annual peak flow in the rainy season. On the contrary, although the intra-annual distribution of precipitation is similar to that of other stations, considerable changes in intra-annual
Figure 2 | Daily variations of runoff at Jiamusi, Yilan, Tonghe, Harbin, Dalai, and Fuyu stations in the Songhua River (2014–2016). The dotted lines and the bars present runoff in left axis and precipitation in right axis, respectively.
variability of streamflow were not observed in Fuyu station. Therefore, the mainstream stations of the main stream showed similar intra-annual distributions of discharge to Dalai station of the Nen River, indicating a greater flow contribution from Nen River than the Upper Songhua River.

**Long-term annual runoff changes**

The annual streamflow series from the Harbin, Jiamusi, Dalai, and Fuyu gauging stations are presented in Figure 4. Annual streamflow discharge velocities at the Harbin and Jiamusi stations were mostly concentrated in the ranges 478–3,054 and 877–3,826 m³/s, respectively. The streamflow series at the two stations demonstrate similar fluctuations. Both stations experienced a high extreme flow in 1960 and 1998.

The annual runoff during the period 1956–2010, measured at the two tributaries’ stations, is also presented in Figure 4. Average runoff at Dalai station was 651 m³/s with a range of 146 and 1,971 m³/s and a variation coefficient of 0.56. The highest annual runoff was approximately 13.5 times higher than the lowest value observed. While annual runoff decreased before 1980, it showed an increasing trend in the 1980s. The annual runoff in the 2000s was significantly lower than that in the 1990s. Similar to the
daily/monthly runoff variations (Figures 2 and 3), there is a similar annual changing trend at Dalai station compared to Jiamusi and Harbin stations in the main stream. Fuyu station had an average runoff of 465 m$^3$/s with a range of 170 to 888 m$^3$/s. The variation coefficient was 0.35, indicating a more steady flow when compared to Dalai station, which is in accordance with the daily runoff data presented in Figures 2(f) and 3(f).

**DISCUSSION**

**The runoff responses to monthly precipitation**

To ascertain the controlling factors of runoff change, the monthly cumulative precipitation and cumulative monthly runoff are presented in Figure 5. There is a good relationship between cumulative precipitation and
cumulative monthly runoff for all the stations. Especially in the rainy season, streamflow in the study area corresponded well with precipitation, which indicates that the precipitation is the dominant factor affecting streamflow. Meanwhile, due to low precipitation in the dry season (from November to April in the next year), most points are concentrated in Figure 5. However, they are mostly located above the fitted line with the furthest points observed in April. This indicates that snow melt water contributes a lot to the runoff increase in the spring season.

To further confirm the effect of precipitation on the runoff change in the stations, the monthly precipitation amount and monthly runoff are plotted in Figure 6. At Fuyu station in the Second Songhua River, the monthly runoff is constant when the monthly precipitation amount
is lower than 100 mm (Figure 3(f)). When the monthly precipitation amount is higher than 100 mm, the increasing monthly runoff is observed responsively. In contrast, the obvious increase of monthly runoff is observed when the monthly precipitation amount exceeds 20 mm at other stations. This means that precipitation plays a more important role in the runoff change of the Nen River and the main stream. Therefore, although the spatial distribution of monthly precipitation in one year displays similar periodical change characteristics at these stations (Figure 3), the runoff variations performed in two diverse ways. The different performances were also obvious in the cumulative anomaly of monthly runoff in Figure 7. The stations in the Nen River (Dalai) and in the main stream (Jiamusi, Harbin, Tonghe, and Yilan) displayed a similar curve, with an increasing trend from April to October and a decreasing trend from October to April in the next year. This is in good agreement with the intra-annual variations of precipitation amount. Meanwhile, a steady trend was observed at Fuyu station in the Second Songhua River, which indicates that the influence of precipitation on runoff is relatively weak compared to that of other stations.

**The runoff responses to annual precipitation**

There is an obvious relationship between annual precipitation and runoff at Dalai, Harbin, and Jiamusi stations (Figure 8), indicating the controlling effect of precipitation on runoff changes at these stations in the annual scale. However, the cumulative anomaly of annual runoff at Fuyu station in the Second Songhua River markedly differed from that of other stations both in the Nen River and the main stream (Figure 9(a)), which displayed a gentle trend. There is an obvious jump at Dalai, Harbin, and Jiamusi stations during the year of 1998 (Figure 9(a)). The same ‘turning year’ was also identified in the studies of Wang et al. (2015) and Song et al. (2009).

**Isotopic evidences of runoff mechanisms**

The stable isotope compositions of oxygen and hydrogen, expressed as $\delta^{18}O$ and $\delta^{2}H$ values, respectively, are commonly used to identify water sources (Clark & Fritz 1988). The $\delta^{18}O$ and $\delta^{2}H$ values in the mountain area ranged from $-14.9$ to $-12.0$‰ and $-106.1$ to $-84.4$‰, respectively (Figure 10). The mean values for the Nen River in the mountain area were $-13.5$‰ and $-94.0$‰, respectively. The Second Songhua River had similar $\delta^{18}O$ and $\delta^{2}H$ values of $-13.5$‰ and $-97.0$‰, respectively. These values are more negative than the mean value of summer precipitation at GNIP Qiqihaer station ($-9.6$‰ for $\delta^{18}O$), indicating recharge from higher elevation. The mean elevation of the catchments of the rivers was estimated to be 1,100 m asl above the elevation.
of Qiqihaer (147 m asl) using the isotopic altitude effect of $-0.25\%$ per 100 m (Clark & Fritz 1997). They are in the range of the Changbai or Daxinganling Mountains, strengthening the evidence of recharge from mountainous areas both in the Second Songhua River basin and the Nen River basin.

**Figure 8** | Relationship between annual precipitation amount and annual runoff (1955–2004) at (a) Jiamusi, (b) Harbin, and (c) Dalai stations.
Although similar isotopic values were observed in the headwater area, the two rivers displayed different isotopic characteristics in the central plain. The samples taken in the Second Songhua River plot on a line of $\delta^{2}H = 5.1 \delta^{18}O + 21.2$ ($R^2 = 0.97$) indicating obvious evaporation effects. The samples located on the global meteoric water line (GMWL, black line in Figure 8 of $\delta^{2}H = 8 \delta^{18}O + 10$) are those sampled from the downstream river. The intersection of the GMWL with the river water line (RWL, dotted line in Figure 10 of $\delta^{2}H = 4.3 \delta^{18}O - 28.5$) of the Second Songhua River has $\delta^{18}O$ and $\delta^{2}H$ values of $-10.4\%o$ and $-73.2\%o$, respectively, similar to those of summer precipitation. The isotopic data are therefore in good agreement with the constant runoff observed in the Second Songhua River (Figures 2(f), 3(f) and 4), which indicates that the runoff in the Second Songhua River is mostly...
composed of uniform water. In the downstream, it appears to be affected by significant surface water evaporation. For the Nen River, samples in the plain also plot below the GMWL, indicating the effect of evaporation. However, these samples are dispersive (hollow squares in Figure 10) with no obvious correlation. Considering that the majority of samples plot near the isotopic values of summer precipitation, we conclude that summer precipitation plays an important role in the runoff of the Nen River. This is in accordance with the high runoff flow during the rainy season, shown in Figures 2(e), 3(e), and 4.

The insensitive runoff responses to precipitation and isotopic characteristics in the Second Songhua River may be attributed to its upstream water conservancy facilities. A large number of dams in the Second Songhua River have been constructed since 1953, including the Baishan, Hongshi, and Fengman Dams, which can attenuate flood waves (Jia 2018). On the contrary, dams in the Nen River are relatively fewer, in agreement with the accordant runoff response to precipitation.

**Contributions of tributaries to the main stream**

If the total flow of the Songhua River is composed of water from the two tributary rivers, the proportion originating from the Nen River during each day can be calculated (Figure 11). During the period from January to March, these values are lower than 0.5, which indicates that during this period, the Second Songhua River contributed more water to the total runoff in the main stream. During the rest of the year, the Nen River appears to play a more important role in providing water to the mean stream (Figure 11). We assumed that the base flow is equal to the flow of the catchment during the lowest discharge period, observed from January until March, the months with the

![Figure 11](https://iwaponline.com/hr/article-pdf/doi/10.2166/nh.2020.183/719485/nh2020183.pdf)

**Figure 11** Temporal variations in the contribution of the two tributary rivers to the Songhua River on the daily scale. The gray columns show the proportion of runoff in the main stream originating from Nen River (q(N/S) in the y-axis). The parts between the dashed lines indicate periods during which the main stream receives more water from the Second Songhua River than from the Nen River.

![Figure 12](https://iwaponline.com/hr/article-pdf/doi/10.2166/nh.2020.183/719485/nh2020183.pdf)

**Figure 12** Temporal variations of the proportion of runoff in the main stream originating from Nen River on the annual scale (q(N/S) in the y-axis). The mean annual runoff is from Dalai and Fuyu stations, located in the two tributaries of the Songhua River (1956–2010). The gray areas indicate the period during which the main stream received more water from the Second Songhua River.
lowest precipitation. In other words, the base flow of the Second Songhua River is higher than that of the Nen River.

The annual proportion of runoff from the Nen River is shown in Figure 12. The data showed that the runoff in the main stream was dominated by water originating from the Nen River before 1999, while the Second Songhua River contributed more in the 2000s (gray area in Figure 12). In fact, this was supported by the fact that the precipitation decreased in the 2000s. On the other hand, due to the higher contributions from the Second Songhua River in the 2000s, the cumulative anomaly of annual runoff at Harbin station is less than that of Dalai station (Figure 9(b)).

These trends are in good agreement with the results from daily and monthly runoff calculations discussed in the previous section. In conclusion, our data show that when precipitation is low, either during the dry season (January to March), or during dry years (the 2000s), more runoff in the main stream was received from the Second Songhua River. Therefore, the impact of climate change, especially the precipitation change on streamflow, must be evaluated under different spatial and temporal scales, to obtain more information for water resources management.

CONCLUSIONS

Using observed records of daily runoff at six gauging stations along the Songhua River during July 2014 to June 2016 and annual runoff (1956–2010) at four stations, we analyzed the runoff responses to precipitation change, and quantified the relative contribution of runoff from tributaries. Two different runoff patterns were determined: a periodic one in response to precipitation in the main stream and the Nen River; and a constant one in the Second Songhua River under different scales. The isotopic values in samples from the downstream of the Nen River plot near the isotopic values of summer precipitation, further indicating the influence of precipitation on runoff changes in this area. The steady runoff in the Second Songhua River with less sensitivity to precipitation may be due to upstream dams. A two-component mixing model showed that the Second Songhua River contributes more water to the main stream during January to March on the daily scale, and in the 2000s on the annual scale, both of which correspond to low precipitation periods. The different runoff patterns should be considered in the future water resource management.

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