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Quantifying streamflow and active groundwater storage in response to climate warming in an alpine catchment on the Tibetan Plateau

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Abstract

Climate warming is changing streamflow regimes and groundwater storage in cold alpine regions. In this study, a headwater catchment named Yangbajain in the Lhasa River basin on the Tibetan Plateau is adopted as the study area for quantifying streamflow changes and active groundwater storage in response to climate warming. The catchment is characterized by alpine glacier and frozen ground which covers about 11% and 86% of the total area, respectively. The changes in streamflow regimes (including quickflow and baseflow) and climate factors are evaluated based on hydro-meteorological observations from 1979 to 2013. Then active groundwater storage in autumn and early winter is quantified by recession flow analysis assuming nonlinearized outflow from aquifers into streams. The results show that annual streamflow increases significantly at a rate of about 12.30 mm/10a during this period. The significant increase of annual air temperature compared with nonsignificant variation of annual precipitation indicates that the climate warming takes responsibilities to the increase of streamflow. It is believed that the increased streamflow is mainly fed by glacier meltwater, which has led to over 25% loss of the total glacial volume in the past 50 years (1960-2009) in this catchment. Moreover, the significant increase of annual baseflow at a rate of about 10.95 mm/10a is the dominant factor for the increase of the total streamflow. Through recession flow analysis, we find that recession coefficient K and active groundwater storage S in autumn and early winter increase significantly at the rates of about 7.70 ($mm^{0.79}d^{-0.21}$)/10a and 19.32

mm/10a during these years. The increase of active groundwater storage can partly be explained by frozen ground degradation, which lead to the enlargement of groundwater storage capacity and accommodate more summer rainfall and meltwater in the wide and flat valley, and then slowly release them into streams in the following seasons. Thus, it is reasonable to attribute the increase of baseflow and the slowdown of baseflow recession process in autumn and early winter to the enlargement of groundwater storage capacity. Through quantifying streamflow changes and active groundwater storage in response to warming-induced changes, this study provides a perspective to clarify the way of glacial retreat and frozen ground degradation on hydrological processes.

Keywords: Climate warming; Streamflow; Groundwater storage; Glacier retreat; Frozen ground degradation; Tibetan Plateau

1. Introduction

Often referred to as the "Water Tower of Asia", the Tibetan Plateau (TP) is the source area of major rivers in Asia, e.g., the Yellow, Yangtze, Mekong, Salween, Indus, and Brahmaputra Rivers (Cuo et al., 2014). The delayed release of water resources on the TP through glacier melt can augment river runoff during dry periods as a pivotal role for water supply for downstream populations, agriculture and industries in these rivers (Viviroli et al., 2007; Pritchard, 2017). However, the TP is experiencing a significant warming trend during the last half century (Kang et al., 2010; Liu and Chen, 2000). Along with the rising temperature, major warming-induced changes have occurred over the TP, such as glacier retreat (Yao et al., 2004; Yao et al., 2007) and frozen ground degradation (Wu and Zhang, 2008). Hence, it is of great importance to elucidate how climate warming influences hydrological processes and water resources on the TP.

In cold alpine catchments, glacier is known as "solid reservoir" that supplies water as streamflow, while frozen ground, especially permafrost, servers as an impermeable barrier to the interaction between surface water and groundwater (Immerzeel et al., 2010; Walvoord and Kurylyk, 2016). Since the 1990s, most glaciers across the TP have retreated rapidly due to global warming and caused an increase of more than 5.5% in river runoff from the plateau (Yao et al., 2007). Meltwater is the key contributor to streamflow increase especially for headwater catchments with larger glacier coverage (>5%) (Bibi et al., 2018). Meanwhile, in a warming climate, numerous studies suggested that frozen ground on the TP has experienced a noticeable degradation during the past decades (Cheng and Wu, 2007; Wu and Zhang, 2008). Frozen ground degradation can modify surface conditions and change thawed active layer storage capacity in the alpine catchments (Niu et al., 2011). Thawing of frozen ground increases surface water infiltration, supports deeper groundwater flow paths, and then enlarges groundwater storage, which is expected to have a profound effect on flow regimes (Bense et al., 2009; Bense et al., 2012; Walvoord and Striegl, 2007; Woo et al., 2008; Ge et al., 2011; Walvoord and Kurylyk, 2016). In cold alpine catchments where large areas of glacier and frozen ground exist, warming-induced glacier and frozen ground co-variations fundamentally affect the water supply and the mechanisms of streamflow generation and change (Cuo et al., 2014; Pritchard, 2017).

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-541
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Discussion started: 29 October 2018

Hydrology and Earth System Sciences
Discussions

It is challenging to understand how glacier melt and frozen ground thaw alters the mechanism of streamflow in a warmer climate due to the complicated interactions between hydrological and cryospheric processes. In earlier phase of glacier melt, accelerated glacier retreat will bring large quantities of meltwater available directly for surface runoff or indirectly for groundwater recharge (Bayard et al., 2005). Meanwhile, frozen ground thawing may allow for increased groundwater recharge from meltwater infiltration (Evans and Ge, 2017). Generally, climate warming is hypothesized to generate a quantitative and temporal shift in the partitioning of meltwater between surface runoff and groundwater flow, and thereby alter the quantity and timing of baseflow (Green et al., 2011; Evans et al., 2018). Evans et al. (2015) found that an increase in mean annual surface temperature of 2°C reduced approximately 28% areal extent of permafrost and tripled baseflow contribution to streamflow using a physically based groundwater model in a headwater catchment of the Heihe River on the northern TP. Qin et al. (2016) discovered that the increasing precipitation and the thawing of frozen ground were the main factors on the increase of baseflow with no significant change in surface runoff in the upper Heihe River basin of the northeastern TP. Previous data-based studies indicated that the baseflow has increased especially during winter with a reduction or no pervasive change in summer streamflow in the central and northern TP (Liu et al., 2011; Niu et al., 2016) as well as the Arctic rivers (Walvoord and Striegl, 2007; Smith et al., 2007; St. Jacques and Sauchyn, 2009). Moreover, Bense et al. (2012) suggested that the increasing groundwater storage caused by frozen ground

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Discussion started: 29 October 2018

degradation would delay baseflow increase possibly by several decades to centuries based on numerical simulations. The slowdown in baseflow recession processes was found in the northeastern and central TP (Niu et al., 2011; Niu et al., 2016; Wang et al., 2017), in northeastern China (Duan et al., 2017), and in Arctic rivers (Lyon et al., 2009; Lyon and Destouni, 2010; Walvoord and Kurylyk, 2016).

While, previous qualitatively studies were important for understanding the effects of climate warming on hydrological changes in cold alpine catchments (Niu et al., 2011; Niu et al., 2016; Wang et al., 2017). However, quantitatively characterizing storage properties and sensitivity to climate warming in cold alpine catchments is important for local water as well as downstream water management (Staudinger, 2017). Moreover, revealing the storage characteristics makes it easier to predict hydrological cycle and streamflow changes response to warming climate in cold alpine catchments (Singleton and Moran, 2010). Thus, this study focuses on quantifying streamflow and aquifer storage volume response to changes in glacier melt and frozen ground thaw at catchment scale on the southern TP. Given the difficulty of direct measurements for catchment aquifer storage (Staudinger, 2017; Käser and Hunkeler, 2016) and low spatial resolution for the GRACE satellites to assess total groundwater storage changes at catchment scale (Green et al., 2011), an alternative method, namely, recession flow analysis, can be theoretically used to derive the active groundwater storage volume in the phreatic aquifer to reflect frozen ground degradation in a catchment (Brutsaert and Nieber, 1977; Brutsaert et al., 2008). For example, the groundwater storage changes

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Discussion started: 29 October 2018

Hydrology and Earth System Sciences Discussions
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have been inferred by recession flow analysis assuming linearized outflow from aquifers into streams (Lin and Yeh, 2017). However, the non-linear of the storage discharge relationship dominates baseflow recession processes for most catchments due to the complex structures and properties of catchment aquifers (Chapman, 1999; Liu et al., 2016). Moreover, groundwater storage computed by assuming the aquifers as linear reservoir cannot reflect the actual storage (Wittenberg, 1999). Lyon et al. (2009) adopted the non-linear reservoir to fit flow recession curves for derivation of aquifer attributes, which can be developed for inferring aquifer storage. Buttle (2017) used Kirchner (2009) approach for estimating dynamic storage in different basins and found that storage and release of dynamic storage may mediate baseflow response to temporal changes.

In this study, the long-term changes in streamflow and climate factors in a glacier-fed headwater catchment with frozen ground in the Lhasa River basin of the south-central TP is analyzed using non-parametric tests during the period 1979-2013. The First and Second Glacier Inventory of China is used to assess the response of glacier variations to climate warming. Changes in streamflow components, baseflow recession process and active groundwater storage are examined. The main objectives of this study are (1) to identify the water source for streamflow changes in climate warming; (2) to discuss the water volume changes in the partitioning between surface runoff and groundwater flow due to changes in glacier melt and frozen ground thaw; (3) to quantify active groundwater storage volume by recession flow analysis assuming nonlinearized outflow from aquifers into streams, and to analyze the impacts of the changes in active groundwater storage on streamflow variation.

2. Materials and Methods

2.1. Study area

Located on the south-central TP, the Yangbajain catchment is a glacier-fed headwater catchment with highly frozen ground coverage in the western part of the Lhasa River Basin (Figure 1a). The catchment has an area of approximately 2,645 km^2 and its elevations range from 4,270 to 6,400 m (Figure 1b). In the east of the catchment, the wide and flat valley (Figure 1b) is located in the Damxung-Yangbajain fault of the southeastern piedmont of Nyainqêntanglha Mountains (Jiang et al., 2016; Yang et al., 2017) with low-lying flat terrain and thicker aquifers due to the great thickness quaternary loose sediment (Wu and Zhao, 2006). The coverage of glacier area is about 11% in the catchment, which is the highest glacierized sub-catchment in the Lhasa River Basin. The total glacier area was about 316.31 km^2 in 1960 according to the First Chinese Glacier Inventory (Mi et al., 2002) and most glaciers were found along the Nyainqêntanglha Mountains range (Figure 1c). The ablation period of the glaciers ranges from June to September with the glacier termini at about 5,200 m (Liu et al., 2011). According to the new map of permafrost distribution on the TP (Zou et al., 2017), the wide and flat valley is underlain by seasonally frozen ground (Figure 1c). It is estimated that seasonally frozen ground and permafrost accounts for about 64% and 22% of the total catchment area, respectively. The lower limit of alpine permafrost is around

4,800 m, and the thickness of permafrost varies from 5 m to 100 m (Zhou et al., 2000).

The climate in the catchment is characterized by semi-arid temperate monsoon climate. The average annual air temperature of the Yangbajain catchment is approximately -2.3°C with monthly variation from -8.6°C in January to 3.1°C in July (Figure 2). The average annual precipitation at the Yangbajain station (4,305 m) in the valley is about 427 mm. The intra-annual distribution of precipitation is extremely uneven due to the pronounced rainy season during the summer monsoon (June-August) and the dry season lasting the rest of the year. Nearly 73% of the total precipitation occurs in summer, while only 1% of the precipitation occurs in winter (December-February) (Figure 2).

The average annual runoff depth is 277.7 mm, and the intra-annual distribution of streamflow is uneven. Approximately 63% of the annual streamflow is observed in summer, whereas in the winter season, streamflow is low and accounts for only 4% of the annual streamflow (Figure 2). Streamflow is recharged mainly by monsoon rainfall and summer meltwater. The river in winter is only recharged by groundwater, which is greatly affected by the freeze-thaw cycle of frozen ground and the active layer (Liu et al., 2011).

2.2. Data

Daily streamflow and precipitation data at the Yangbajain station (4,305 m) during the period 1979-2013 are collected from Tibet Autonomous Region Hydrology and Water Resources Survey Bureau. The monthly meteorological data at the Damxung station (4,289 m), which is neighbor to the Yangbajain catchment (Figure 1a), are obtained from the China Meteorological Data Sharing Service System (http://data.cma.cn/) for the years from 1979 to 2013. In this study, the method of meteorological data extrapolation by Prasch et al. (2013) is adopted to obtain the discretisized air temperature (with cell size as 1 km×1 km) of the Yangbajain catchment based on the air temperature of the Damxung station assuming a linear lapse rate. The mean monthly lapse rate is set to 0.44 °C 100 m^{-1} with elevation below 4,965 m and 0.78 °C 100 m^{-1} with elevation above 4,965 m in the catchment (Wang et al., 2015).

The glacier and frozen ground data are provided by the Cold and Arid Regions Science Data Center at Lanzhou (http://westdc.westgis.ac.cn/). The distribution, area and volume of glacier are based on the First and Second Chinese Glacier Inventory in 1960 and 2009. The distribution and classification of frozen ground are collected from a new map of permafrost distribution on the Tibetan Plateau (Zou et al., 2017).

2.3. Methods

2.3.1. Mann-Kendall test with trend free pre-whitening

The Mann-Kendall (MK) test is applied to detect trends of hydro-meteorological time series, which is robust against outliers and is suitable for data with non-normally distributed or non-linear trends (Mann, 1945; Kendall, 1975). To remove the serial correlation from the examined time series, a Trend-Free Pre-Whitening (TFPW) procedure is needed prior to applying the MK test (Yue et al., 2002). A more detailed description of the Trend-Free Pre-Whitening (TFPW) approach was provided by Yue

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-541
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Discussion started: 29 October 2018

et al. (2002).

The MK test statistic s is calculated as

$$s=\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\operatorname{sgn}\left(x_j-x_i\right) \tag{1}$$

where, x_j and x_i are the data values in sequence, n is the sequence length, and sgn (x_j-x_i) are recorded as

$$\operatorname{sgn}\left(x_j-x_i\right)=\begin{cases}1, & x_j>x_i\\ 0, & x_j=x_i\\ -1, & x_j<x_i\end{cases} \tag{2}$$

The variance of s is proposed by the equation (3)

$$\operatorname{Var}(s)=\frac{n(n-1)(2n+5)}{18} \tag{3}$$

Then, the standardized test statistic Z_C can be transformed from statistical value s, and is computed by equation (4)

$$Z_C=\begin{cases}\dfrac{s-1}{\sqrt{\operatorname{Var}(s)}} & s>0\\ 0 & s=0\\ \dfrac{s+1}{\sqrt{\operatorname{Var}(s)}} & s<0\end{cases} \tag{4}$$

When $|Z_C|\le 1.96$, there is no significant trend. The trend is at the 5% significance level if $|Z_C|>1.96$, and at the 1% significance level if $|Z_C|>2.58$. A positive value of Z_C indicates an upward trend, whereas a negative value indicates a downward trend in the tested time series.

The trend magnitude is computed by Theil-Sen estimator (Sen, 1968)

$$\beta=\operatorname{median}\left(\frac{x_i-x_j}{i-j}\right),\forall j<i \tag{5}$$

where $1<j<i<n$, a positive value of β indicates an upward trend, and a negative value indicates a downward trend.

2.3.2. Baseflow separation

In this paper, the most widely used one-parameter digital filtering algorithms is adopted for baseflow separation (Lyne and Hollick, 1979). The first filter equation is expressed as

$$q_t = \alpha q_{t-1} + \frac{1+\alpha}{2}\left(Q_t - Q_{t-1}\right) \tag{6}$$

$$b_t = Q_t - q_t \tag{7}$$

where q_t and q_{t-1} are the filtered quickflow at time step t and t-1, respectively; Q_t and Q_{t-1} are the total runoff at time step t and t-1; b_t is the filtered baseflow. α is the filter parameter, ranging from 0.9 to 0.95.

2.3.3. Determination of active groundwater storage

The method of recession flow analysis is widely used to investigate the baseflow recession characteristics and the storage discharge relationship of catchments (Gao et al., 2017). Physical considerations based on hydraulic groundwater theory suggest that the groundwater storage in a catchment can be approximated as a power function of baseflow rate at the catchment outlet (Brutsaert, 2008)

$$S = Ky^m \tag{8}$$

where y is the rate of baseflow in the stream in a catchment, S is the volume of active groundwater storage in the catchment aquifers (see in Figure 3), abbreviated as groundwater storage in the following context. And K and m are constants depending on

Hydrology and Earth System Sciences
Open Access
Discussions

the catchment physical characteristics. K represents the time scale of the catchment streamflow recession process, commonly referred to as baseflow recession coefficient.

During a period without precipitation and evapotranspiration, the flow in a stream can be assumed to depend solely on the groundwater storage from the upstream aquifers. For such baseflow conditions, the conservation of mass equation can be represented as

$$\frac{dS}{dt} = -y \tag{9}$$

where t is the time. Substitution of equation (8) in equation (9) yields

$$-\frac{dy}{dt} = ay^b \tag{10}$$

where dy/dt is the temporal change of the baseflow rate during recessions, and the constants a and b are called the recession intercept and recession slope of plots of $-dy/dt$ versus y in log-log space, respectively. The parameters of K and m in equation (8) can be expressed by a and b, where $K = 1/\left[a(2-b)\right]$ and $m = 2-b$. In the storage discharge relationship, the aquifer responds as a linear reservoir if b=1, and as non-linear reservoir if b≠1.

In our study, the baseflow recession data are selected from the streamflow hydrographs, which remarkably decline for at least 3 days after rainfall ceases and remove the first 2 days to avoid the impact of storm flow (Brutsaert and Lopez, 1998). A variable time interval Δt is used to properly scale the observed drop in streamflow to avoid discretization errors on $-dy/dt \sim y$ plot due to measurement noise, especially in the log-log space (Rupp and Selker, 2006; Kirchner, 2009). Meanwhile, the difference of baseflow Δy in the catchment exceeds a critical precision threshold Δy_{crit} of 0.02

mm/day. Then the constants a and b are fit by using a non-linear least squares through all data points of $-dy/dt$ versus y in log-log space for all years (1979-2013) to avoid the difficulty of defining a lower envelop of the scattered points (Lyon et al., 2009). With the fixed slope b during recessions (i.e., $b\neq1$ remains constant), it should be possible to observe changes in catchment aquifer properties by fitting the intercept a as a variable across different years. Since the values of K and m for each year can be calculated by fitting recession intercept a and the fixed slope b, the groundwater storage S in a catchment is obtained through equation (8) based on average rate of baseflow during recessions.

3. Results and Discussion

3.1. Variation of annual streamflow and its components

The annual streamflow of the Yangbajain catchment shows an increasing trend at the 5% significance level with a mean rate of about 12.30 mm/10a over the period 1979-2013 (Table 1 and Figure 4a). Meanwhile, annual mean air temperature exhibits an increasing trend at the 1% significance level with a mean rate of about 0.28 °C/10a (Table 1 and Figure 5a). However, annual precipitation has nonsignificant trend during this period (Table 1 and Figure 5b). The similar variation trends between annual streamflow and annual air temperature indicate that the changes of air temperature may act as a primary climatic factor for streamflow increase.

As the significant rising of air temperature, glacier in the catchment has been retreating continuously. According to the twice Chinese Glacier Inventory (I & II

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-541
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 29 October 2018

volume) in 1960 and 2009, the total glacial area and volume have decreased by 38.06 km^2 (12.0%) and 0.47×10^{10} m^3 (26.2%) over the past 50 years (Figure 6). With the nonsignificant increase of annual precipitation, it is reasonable to attribute annual streamflow increase to the accelerated glacier retreat as the consequence of increasing annual air temperature. This conclusion is also consistent with previous results by Prasch et al. (2013), who suggested that glacial meltwater contribution to streamflow would remain increase in the Yangbajain catchment together with significant increase in streamflow and nonsignificant trend in precipitation by quantifying present and future glacier meltwater contribution to runoff.

Overall, the annual mean baseflow contributes about 59% of annual mean streamflow in the catchment through baseflow separation method. As annual streamflow increases significantly, it is necessary to analyze to what extent the changes in two streamflow components lead to streamflow increase. The result shows that annual baseflow exhibits a significant increasing trend at the 1% level with a mean rate of about 10.95 mm/10a over the period 1979-2013 (Table 1 and Figure 4b). This trend is statistically nonsignificant for annual quickflow during the period (Table 1). Thus, the increase in baseflow is the main contributor to streamflow increase. It can be further concluded that streamflow is recharged by the increased meltwater from the accelerated glacier retreat which may be partly stored in soil and aquifers in the wide and flat valley (Figure 1b), and subsequently discharge into streams as baseflow.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-541
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 29 October 2018

3.2. Variation of seasonal streamflow and its components

The hydrograph of the Yangbajing catchment shows obvious intra-annual variation (Figure 2). Streamflow sources and main components also change with the streamflow magnitude. The variation trends of streamflow regimes also change across seasons. In autumn, winter, and spring, both streamflow and baseflow show significant increasing trends at least at the 5% level (Figures 7c, 7d and 7a). However, quickflow exhibits nonsignificant trend for all seasons (Table 1). Streamflow increases significantly at the 5% level in autumn and the increasing trends reach the significant level of 1% in winter and spring. Baseflow increases significantly at the 1% level in spring and autumn and the increasing trend is at the 5% significance level in winter. However, the trends are not statistically significant for both streamflow and its two components (quickflow and baseflow) in summer (Figure 7b). As to the meteorological factors, mean air temperature in all seasons increase significantly at the 1% level especially during winter with the rate of about 0.51°C/10a (Table 1 and Figure 8), whereas precipitation in each season shows nonsignificant trend during these years (Table 1).

Compared with monsoon rainfall as the main water source for summer which accounts for about 73% of the total precipitation in the whole year, the corresponding meltwater from glacier is considerable but its contribution to streamflow is limited. Moreover, the summer meltwater and rainfall will partly infiltrate into soils and aquifers. Carey and Quinton (2004) suggests that in snow and permafrost catchments with the thin river valley and the steep slopes, meltwater infiltrates soils and resides in temporary storage at the beginning of the melt period, and then are allowed to rapidly drain through surface layers. However, due to thicker aquifers in the wide and flat catchment valley (Figure 1b), summer meltwater and rainfall stored in aquifers are allowed to release slowly from groundwater storage as baseflow in the following seasons, which has led to the stability of baseflow in summer and the significant increase of baseflow in autumn, winter and spring.

3.3. Variation of baseflow recession rate and groundwater storage

Using the data selected procedure mentioned in the section 2.3.3, we adopted daily streamflow and precipitation records from September to December (the autumn and early winter) over the period 1979-2013 in the catchment, during which the hydrograph with little precipitation usually declines consecutively and smoothly. The fitted slope b is equal to 1.79 through the non-linear least square fit of equation (10) for all data points of $-dy/dt$ versus y in log-log space during the period 1979-2013. With the fixed slope b=1.79, the recession coefficient K and groundwater storage S can be quantified by all decades of the 1980s, 1990s and 2000s, and year-to-year from 1979 to 2013. For each decade, the recession intercept a could be fitted by the fixed slope b=1.79. Then, the values of K and m for each decade can be determined with the fitted recession intercept a and the fixed slope b. And the groundwater storage S for each decade can be directly estimated from the average rate of baseflow during recession period and the values of K and m through equation (8). Meanwhile, the recession coefficient K and groundwater storage S for each year can also be calculated according to the above procedure.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-541
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 29 October 2018

Figure 9 shows the non-linear least square fit of equation (10) to the plot of $-dy/dt$ versus y in log-log space for all recession data points of the observation records for each decade of the 1980s, 1990s and 2000s, respectively. As shown in Figure 9, the recession data points and fitted recession curves of each decade gradually move downward as time goes on. It indicates that, with the fixed slope b, the recession intercept a gradually decreases and recession coefficient K gradually increases. The values of recession coefficient K for each decade are respectively 77 $mm^{0.79}d^{-0.21}$, 84 $mm^{0.79}d^{-0.21}$ and 103 $mm^{0.79}d^{-0.21}$ in the 1980s, 1990s and 2000s through recession flow analysis, which is consistent with the results in Figure 9. Figure 10a shows the inter-annual variation of recession coefficient K during the period 1979-2013. The recession coefficient K increases slowly in the 1980s, fluctuates slightly in the 1990s and increases rapidly in the 2000s. But its overall increasing trend is similar to the results obtained from decades analysis. The trend of recession coefficient K shows significant increase at the 5% level at a rate of about 7.70 ($mm^{0.79}d^{-0.21}$)/10a from 1979 to 2013. This long-term variation of recession coefficient K from September to December indicates that baseflow recession process during autumn and early winter gradually slows down in the catchment.

The mean values of groundwater storage S for each decade are 130 mm, 148 mm and 188 mm in the 1980s, 1990s and 2000s, respectively. The trend analysis suggests that the groundwater storage S shows an increasing trend at the 5% significance level with a rate of about 19.32 mm/10a during the period 1979-2013 (Figure 10b). It indicates that groundwater storage has been enlarged during autumn and early winter. The long-term trend of groundwater storage *S* from 1979 to 2013 is consistent with the values across decades. The inter-annual variation of groundwater storage *S* is also similar with recession coefficient *K* (Figure 10a and 10b).

The increased groundwater storage *S* in autumn and early winter is associated with the hypothesis that frozen ground degradation due to the significant rising air temperature during autumn and winter (Figure 8c and 8d), which can enlarge groundwater storage capacity (Niu et al., 2016). Figure 3 depicts the changes of surface flow and groundwater flow paths in a glacier-fed and underlying-frozen ground catchment under past climate and warmer climate, respectively. As frozen ground extent continues to decline and active layer thickness continues to increase in the wide and flat valley, the enlargement of groundwater storage capacity can provide enough storage space to accommodate increasing meltwater, and support more meltwater to percolate into deeper aquifers rather than surface layers, and thereby increase groundwater storage in the valley floor (Figure 3). Then, the increase of groundwater storage in autumn and earlier winter allows more groundwater discharge into streams as baseflow, and lengthens the time scale of the baseflow recession process indicated by recession coefficient *K*. This leads to increase baseflow and slow baseflow recession processes in autumn and early winter, as is shown in Figure 7c, 7d and Figure 10a. In the late winter and spring, the increase of baseflow (Figure 7d and 7a) can be explained by the delayed release of increased groundwater storage.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-541
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 29 October 2018

Hydrology and Earth System Sciences
Open Access
Discussions

4. Conclusions

In this study, the changes of hydro-meteorological variables were evaluated to identify the main climatic factor for streamflow increase during the period 1979-2013 of the Yangbajain catchment, a sub-catchment with larger glacierization and large-scale frozen ground in the Lhasa River basin in the south-central TP. We analyzed the changes of streamflow components through baseflow separation method. We quantified baseflow recession process and active groundwater storage in autumn and early winter by recession flow analysis assuming nonlinearized outflow from aquifers into streams, and analyzed the seasonal variations of streamflow and its components in response to the changes in active groundwater storage.

We find that the increase of annual streamflow is mainly due to the increase of annual baseflow, which is caused by increased temperature rather than precipitation in the long-term period. The decreased glacial volume due to climate warming has supplied large quantities of glacial meltwater which recharges aquifers and resides in temporary storage during summer, and then releases as baseflow during the following seasons. Moreover, the increase of active groundwater storage in autumn and early winter can partly be attributed to the enlargement of groundwater storage capacity by frozen ground degradation, which can provide storage spaces for increased glacial meltwater. This can partly explain why baseflow volume increases and baseflow recession process slows down in autumn, winter, and spring seasons.

This study provides a fundamental understanding of the changes in streamflow and groundwater storage under warming climate. It is of great importance to predict the effects of future climate changes on water resources and hydrological processes in highly glacier-fed and large-scale frozen ground regions. Further analysis is needed to quantify summer meltwater contribution to streamflow, and to explore the change of groundwater storage capacity as frozen ground continues to degrade.

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Table 1. Mann-Kendall trend test with trend-free pre-whitening of seasonal and annual mean air temperature (°C), precipitation (mm), streamflow (mm), baseflow (mm) and quickflow (mm) from 1979 to 2013.

	Air temperature		Precipitation		Streamflow		Baseflow		Quickflow	
	Z_C	β (°C/a)	Z_C	β (mm/a)	Z_C	β (mm/a)	Z_C	β (mm/a)	Z_C	β (mm/a)
Spring	2.73**	0.026	0.90	0.290	3.05**	0.206	2.99**	0.147	0.98	0.042
Summer	2.63**	0.013	1.30	2.139	0.92	0.549	1.27	0.429	0.50	0.128
Autumn	2.65**	0.024	-0.68	-0.395	2.46*	0.546	2.96**	0.476	0.80	0.074
Winter	3.49**	0.051	-0.46	-0.014	3.08**	0.204	2.13*	0.145	1.39	0.016
Annual	4.48**	0.028	1.28	2.541	2.07*	1.230	2.70**	1.095	0.77	0.327

Comment: the symbols of asterisks *and ** mean statistically significant at the levels of 5% and 1%, respectively.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-541
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 29 October 2018

Hydrology and Earth System Sciences
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Discussions

Figure captions

Figure 1. (a) The location, (b) elevation distribution, and (c) glacier and frozen ground distribution (Zou et al., 2017) in the Yangbajain catchment of the Lhasa River basin in the TP.

Figure 2. Seasonal variation of runoff depth (*R*), mean air temperature (*T*), and precipitation (*P*) in the Yangbajain catchment.

Figure 3. Diagram depicting surface flow and groundwater flow due to glacier melt and frozen ground thaw under (a) past climate and (b) warmer climate. Blue lines with arrows are conceptual surface flow paths. Dark blue lines with arrows are conceptual groundwater flow paths (after Evans and Ge. (2017)).

Figure 4. Variations of annual (a) runoff and (b) baseflow depth from 1979 to 2013.

Figure 5. Variations of annual (a) mean air temperature and (b) precipitation from 1979 to 2013.

Figure 6. The total area and volume of glaciers in the Yangbajain catchment in 1960 and 2009.

Figure 7. Variations of seasonal runoff and baseflow depth in (a) spring, (b) summer, (c) autumn, and (d) winter from 1979 to 2013.

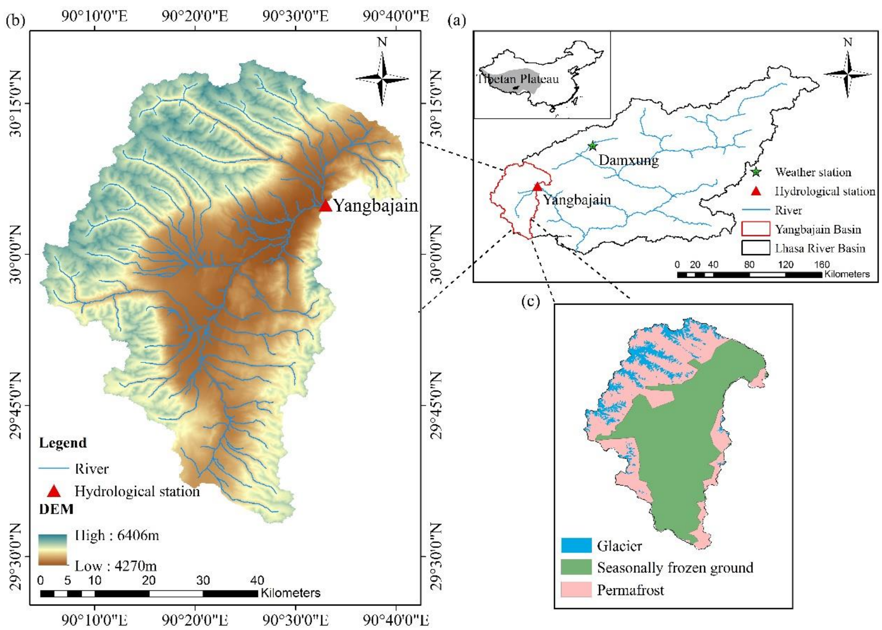
Figure 8. Variations of seasonal mean air temperature in (a) spring, (b) summer, (c) autumn, and (d) winter from 1979 to 2013.

Figure 9. Recession data points of $-dy/dt$ versus y and fitted recession curves by decades in log-log space. The black point line, dotted line, and solid line represent recession

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-541
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 29 October 2018

curves in the 1980s, 1990s, and 2000s, respectively.

Figure 10. Variations of (a) the recession coefficient K and (b) groundwater storage S from 1979 to 2013.



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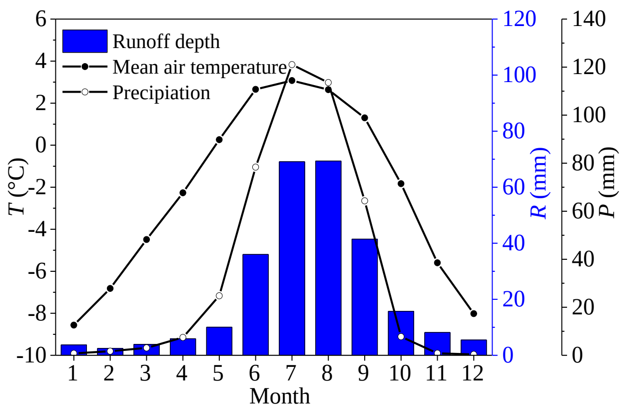

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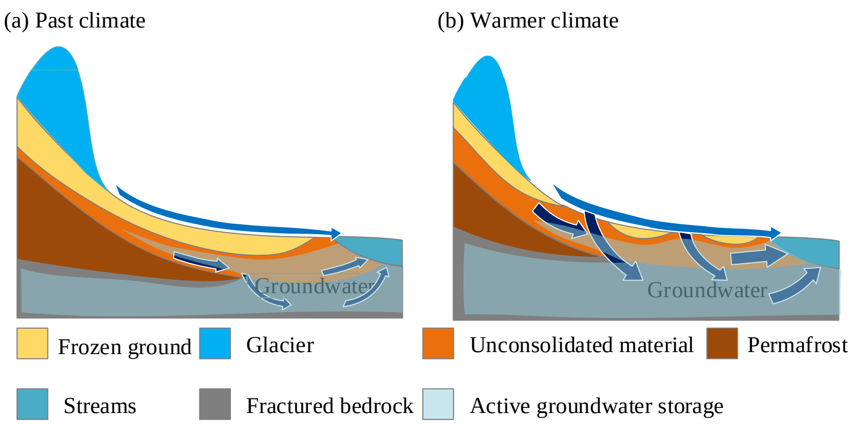

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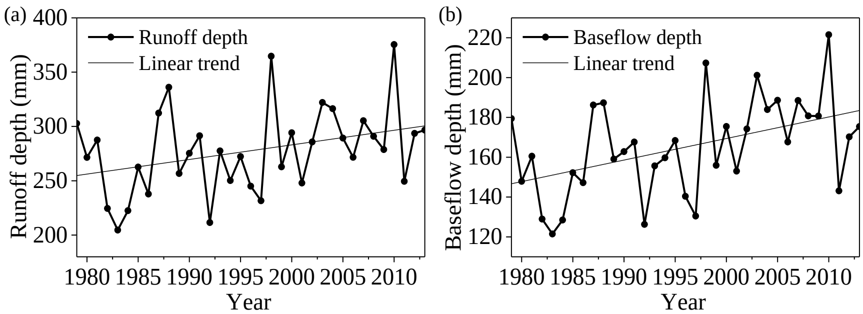

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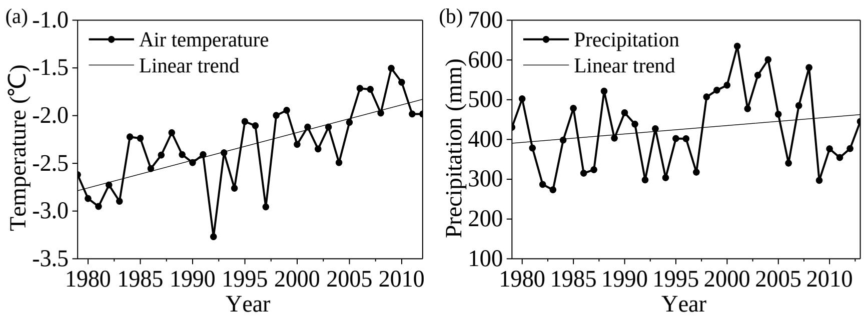

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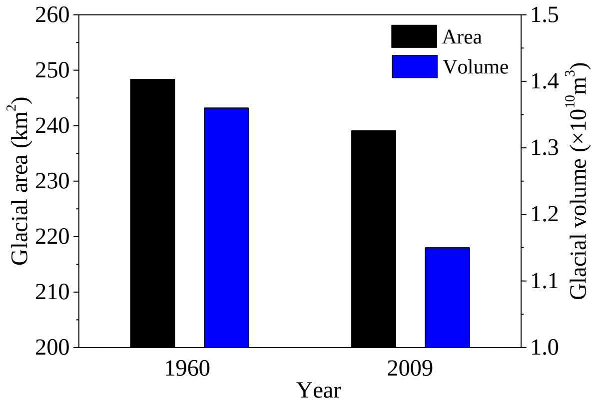
Discussion started: 29 October 2018



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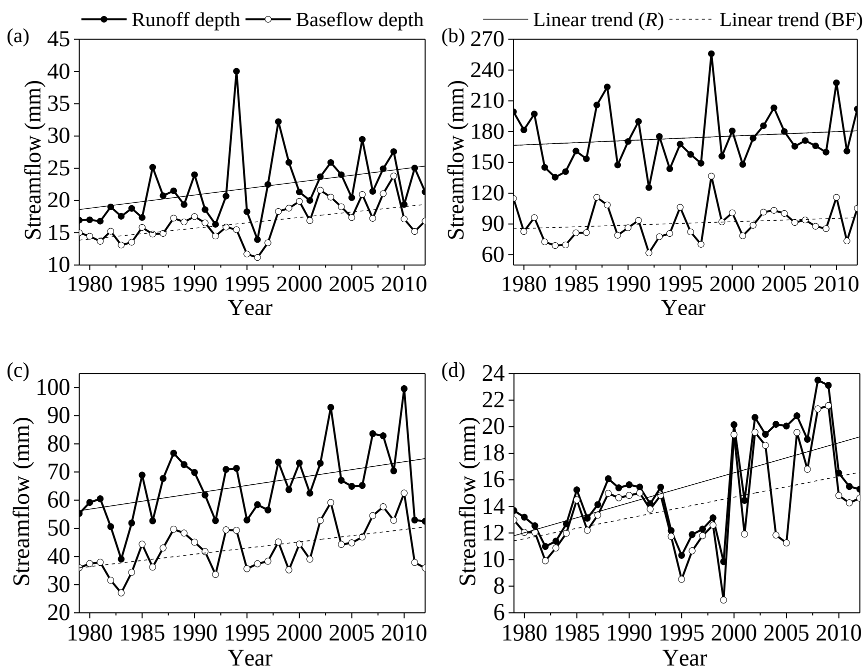

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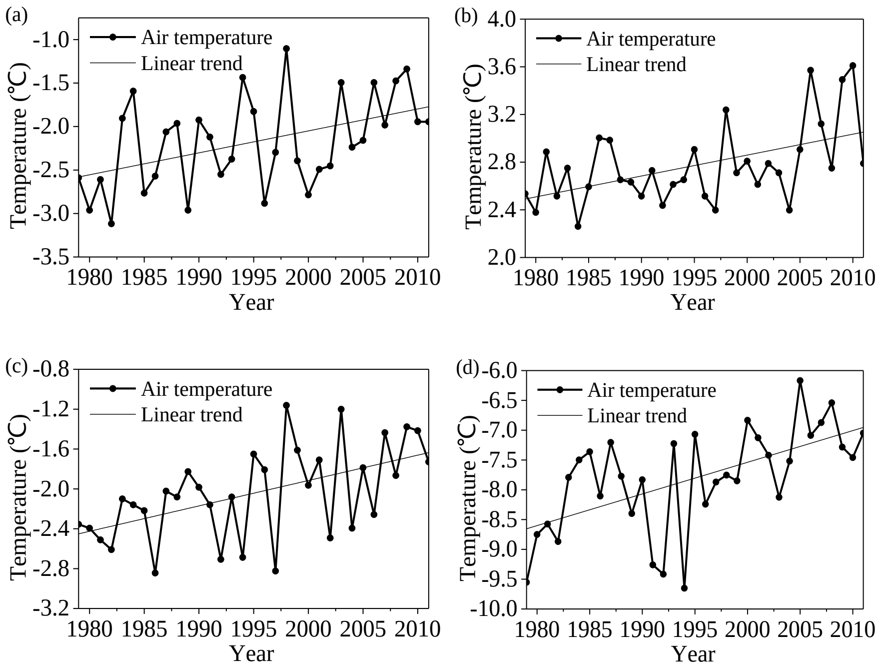

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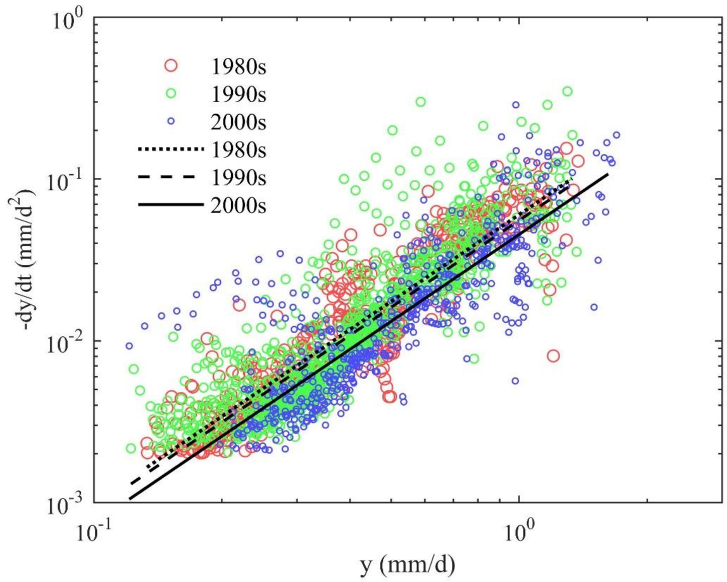

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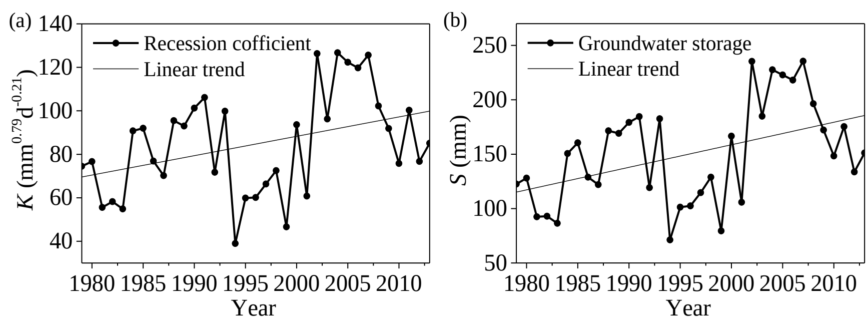

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