Understanding the effects of climate warming on streamflow and active groundwater storage in an alpine catchment, upper Lhasa River

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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 is adopted as the study area for assessing streamflow changes and active groundwater storage in response to climate warming. The results show that both annual streamflow and mean air temperature increase significantly at rates of about 12.30 mm/10a and 0.28 °C/10a during 1979-2013 in the study area. The results of gray relational analysis indicate that the air temperature acts as a primary factor for the increased streamflow. Due to climate warming, the total glacier volume has retreated by over 25% for the past half century, and the areal extent of permafrost has degraded by 15.3% in the recent twenty years. Parallel comparisons with other sub-basins in the Lhasa River Basin indirectly reveal that the increased streamflow at the Yangbajain station is mainly fed by the accelerated glacier retreat. Through baseflow recession analysis, we also find that the estimated groundwater storage that is comparable with the GRACE data increases significantly at the rates of about 19.32 mm/10a during these years. That is to say, as permafrost thawing, more spaces have been released to accommodate the increasing meltwater. The results in this study suggest that due to climate warming the impact of glacial retreat and permafrost degradation shows compound behaviors on storage-discharge mechanism, which fundamentally affects the water supply and the mechanisms of streamflow generation and change.

Keywords: Climate warming; Streamflow; Groundwater storage; Glacier retreat; Permafrost 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, giving it 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 period 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; Xu et al., 2019). Hence, it is of great importance to elucidate how climate warming influences hydrological processes and water resources on the TP.

In cold alpine catchments, a glacier is known as a "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; Rogger et al., 2017). 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; Xu et al., 2019). For example, the total discharge increase by 2.7%-22.4% mainly due to increased glacier melt that accounts for more than half of the total discharge increase in the upper Brahmaputra, i.e., Yarlu-Zangbo (Su et al., 2016).

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; Zou et al., 2017). 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 (Kooi et al., 2009; Bense et al., 2012; Walvoord and Striegl, 2007; Woo et al., 2008; Ge et al., 2011; Walvoord and Kurylyk, 2016). For example, Walvoord and Striegl (2007) found that permafrost thawing in an arctic basin has resulted in a general upwards trend in groundwater contribution to streamflow of 0.7-0.9%/yr, however, with no pervasive change in total annual runoff. Similar results have also been found in the central and northern TP (Liu et al., 2011; Niu et al., 2016; Xu et al., 2019). Moreover, a slowdown in baseflow recession 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).

Generally, in alpine regions, climate warming by triggering glacier retreat and permafrost thawing is changing hydrological processes of storage and discharge. However, direct measurement of the changing of permafrost depth or catchment aquifer storage is still difficult to perform at catchment scale (Xu et al., 2019; Staudinger, 2017; Käser and Hunkeler, 2016). Though its resolution and accuracy is relatively low, GRACE data has always been adopted in assessing total groundwater storage changes (Green et al., 2011). Quantitatively characterizing storage properties and sensitivity to climate warming in cold alpine catchments is desired for local water as well as downstream water management (Staudinger, 2017).

Xu et al. (2019) used a simple ratio of the maximum and minimum runoff to indirectly indicate the change of storage capacity as well as the effects of permafrost on recession processes. An alternative method, namely, recession flow analysis, can theoretically be used to derive the active groundwater storage volume to reflect frozen ground degradation in a catchment (Brutsaert and Nieber, 1977; Brutsaert, 2008). For example, the groundwater storage changes can be inferred by recession flow analysis assuming linearized outflow from aquifers into streams (Lin and Yeh, 2017). Due to the complex structures and properties of catchment aquifers, the linear reservoir model may not sufficient to represent the actual storage dynamics (Wittenberg, 1999; Chapman, 1999; Liu et al., 2016). Hence, Lyon et al. (2009) adopted the nonlinear reservoir to fit baseflow recession curves for the derivation of aquifer attributes, which can be developed for inferring aquifer storage. Buttle (2017) used Kirchner's (2009) approach for estimating the dynamic storage in different basins and found that the storage and release of dynamic storage may mediate baseflow response to temporal changes. Generally, the classical recession flow analysis that is based on widely easily available hydrologic data is still widely used to provide important information on storage–discharge relationship of the basin (Patnaik et al., 2018).

In this study, the Yangbajain Catchment in the Lhasa River Basin is adopted as the study area. The catchment is experiencing glacier retreat and frozen ground degradation in response to climate warming. The main objectives of this study are (1) to assess the changes between surface runoff and baseflow in a warming climate; (2) to quantify active groundwater storage volume by recession flow analysis; (3) to analyze the impacts of the changes in active groundwater storage on streamflow variation. The paper is structured as follows. The section of Materials and Methods includes the study area, data sources and methods. The Results and Discussion sections present the changes in streamflow and its components, climate factors, and glaciers, and we will discuss the changes in streamflow volume and baseflow recession in response to the changes in active groundwater storage. The main conclusions are summarized in the Conclusions section.

2. Materials and Methods

2.1. Study area

The 2,645 km^2 Yangbajain Catchment in the western part of the Lhasa River Basin (Figure 1a) lies between the Nyainqêntanglha Range to the northwest and the Yarlu-Zangbo suture to the south. In the central of the catchment, a wide and flat valley (Figure 1b) with low-lying terrain and thicker aquifers is in a half-graben fault-depression basin caused by the Damxung-Yangbajain Fault (Wu and Zhao, 2006; Yang et al., 2017). As a half graben system, the north-south trending Damxung-Yangbajain Fault (Figure 1b) provides the access for groundwater flow as manifested by the widespread distribution of hot springs (Jiang et al., 2016). The surface of the valley is blanketed by Holocene-aged colluvium, filled with the great thickness of alluvial-pluvial sediments from the south such as gravel, sandy loam, and clay. The vegetation in the catchment is characteristic of alpine meadow, alpine steppe, marsh, shrub, etc; meadow and marsh are mainly distributed in the valley and river source (Zhang et al., 2010).

Located on the south-central TP, the Yangbajain Catchment is a glacier-fed headwater catchment with significant frozen ground coverage (Figures 1b & 1c). A majority of glaciers were found along the Nyainqêntanglha Ranges (Figure 1b). Glaciers cover over ten percent of the whole catchment, making it the most glacierized sub-basin in the Lhasa River Basin. According to the First Chinese Glacier Inventory (Mi et al., 2002), the total glacier area was about 316.31 km^2 in 1960. 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 valley is underlain by seasonally frozen ground (Figure 1c). It is estimated that seasonally frozen ground and permafrost accounts for about 64% and 36% of the total catchment area, respectively (Zou et al., 2017). 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 catchment is characterized by a semi-arid temperate monsoon climate. The areal 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 is about 427 mm. The catchment has a summer (June-August) monsoon with 73% of the yearly precipitation, while the rest of the year is dry with only 1% of the yearly precipitation occurring in winter (December-February) (Figure 2).

The average annual streamflow at the Yangbajain Station is 277.7 mm, and the intra-annual distribution of streamflow is uneven (Figure 2). In summer, streamflow is recharged mainly by monsoon rainfall and meltwater, and the volume of summer runoff accounts for approximately 63% of the yearly streamflow (Figure 2). The streamflow in winter with only 4% of the yearly streamflow (Figure 2) 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 four hydrological Stations (Figure 1a) during the period 1979-2013 are collected from the Tibet Autonomous Region Hydrology and Water Resources Survey Bureau. The monthly meteorological data at the three weather stations (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 Lhasa River Basin based on the air temperature of the three stations assuming a linear lapse rate. The mean monthly lapse rate is set to 0.44 °C/100m for elevations below 4,965 m and 0.78 °C/100m for elevations above 4,965 m in the catchment (Wang et al., 2015).

The glaciers and frozen ground data are provided by the Cold and Arid Regions Science Data Center (http://westdc.westgis.ac.cn/). The distribution, area and volume of glaciers are based on the First and Second Chinese Glacier Inventory in 1960 and 2009 (Mi et al., 2002; Liu et al., 2014) (Figure 1b). The distribution and classification of frozen ground (Figure 1c) are collected from the twice maps of frozen ground on the TP (Li and Cheng, 1996; Zou et al., 2017).

The latest Level-3 monthly mascon solutions (CSR, Save et al., 2016) was used to detect terrestrial water storage (TWS, total vertically-integrated water storage) changes for the period from January 2003 to December 2015 with spatial sampling of 0.5°×0.5° from the Gravity Recovery and Climate Experiment (GRACE) satellite. The time series of 2003~2015 for snow water equivalent (SWE), total soil moisture (SM, layer 0~200cm) from the dataset (GLDAS_Noah2.1, https://disc.gsfc.nasa.gov/) were adopted for derivation of the groundwater storage (GWS) (Richey et al., 2015).

2.3. Methods

2.3.1. Statistical methods for assessing streamflow changes

The Mann-Kendall (MK) test, which is suitable for data with non-normally distributed or nonlinear trends, is applied to detect trends of hydro-meteorological time series (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 et al. (2002).

Gray relational analysis was aimed to find the major climatic or hydrological factors that influenced an objective variable (Liu et al., 2005; Wang et al., 2013). In this paper, gray relational analysis is used to investigate the main climatic factor impacting the streamflow.

2.3.2. Baseflow separation

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

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

$$b_t = Q_t - q_t \quad (2)$$

where q_t and q_{t-1} are the filtered quick flow 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; α is the filter parameter, ranging from 0.9 to 0.95; b_t is the filtered baseflow.

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 (Lyon et al., 2009; Lyon and Destouni, 2010; Sjöberg et al., 2013; Lin and Yeh., 2017; 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 S is the volume of active groundwater storage (abbreviated as groundwater storage in the following context) in the catchment aquifers (see in Figure 3). The active groundwater storage S is defined as the storage that controls streamflow dynamics assuming that streamflow during rainless periods is a function of catchment storage (Kirchner, 2009; Staudinger, 2017); K, m are constants depending on the catchment physical characteristics, and K is the baseflow recession coefficient, represented the time scale of the catchment streamflow recession process; y is the rate of baseflow in the stream.

During dry season without precipitation and other input events, the flow in a stream can be assumed to depend solely on the groundwater storage from the upstream aquifers (Brutsaert, 2008; Lin and Yeh, 2017). 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 (Brutsaert and

Nieber, 1977)

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

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 $K = 1/\left[a\left(2-b\right)\right]$ and $m = 2-b$ (Gao et al., 2017). In the storage discharge relationship, the aquifer responds as a linear reservoir if b=1, and as nonlinear 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). Then the constants a and b are fitted by using a nonlinear least squares regression through all data points of $-dy/dt$ versus y in log-log space for all years to avoid the difficulty of defining a lower envelop of the scattered points (Lyon et al., 2009). Theoretically, one can fit a line of slope b to recession flow data graphed in this manner and determine aquifer characteristics from the resulting value of a (Rupp and Selker, 2006). That is to say, with a fixed slope b during recessions, it should be possible to observe the changes in catchment aquifer properties by fitting the intercept a as a variable across different years. Since the values of K and m can be calculated by fitting recession intercept a and the fixed slope b, the average groundwater storage S for dry season can be obtained through equation (8) based on average rate of baseflow.

3. Results

3.1. Assessment of streamflow changes

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 a nonsignificant trend during this period (Table 1 and Figure 5b).

As annual streamflow increases significantly, it is necessary to analyze to what extent the changes in the two components (quick flow and baseflow) lead to streamflow increases. Based on the baseflow separation method, the annual mean baseflow contributes about 59% of the annual mean streamflow in the catchment. The MK test 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). But the trend is statistically nonsignificant for annual quick flow in the same period (Table 1). The increasing trends between the baseflow and streamflow are very close, indicating that the increase in baseflow is the main contributor to streamflow increases.

Furthermore, gray relational analysis is applied to the catchment to identify the major climatic factors for the increasing streamflow. The result shows that the air temperature has the higher gray relational grade at annual scale (Table 2). This indicates that the air temperature acts as a primary factor for the increased streamflow as well as the baseflow.

The annual streamflow and baseflow significantly increase due to the rising air temperature over the period 1979-2013. However, there are diverse intra-annual variation characteristics for streamflow as well as the two streamflow components during the period. Streamflow in spring (March to May), autumn (September to November) and winter (December to February) show increasing trends at least at the 5% significance level (Figure 6a, 6c and 6d), while streamflow in summer (June to August) has a nonsignificant trend during this period (Figure 6b). Baseflow also increases significantly in spring, autumn and winter (Figure 6a, 6c and 6d). The trend is statistically nonsignificant for baseflow in summer (Figure 6b). Quick flow exhibits nonsignificant trend for all seasons (Table 1). 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 7), whereas precipitation in each season shows nonsignificant trend during these years (Table 1). The gray relational analysis shows that the air temperature is the critical climatic factor for the changes in streamflow and baseflow in all seasons (Table 2).

Compared with monsoon rainfall as the main water source for summer runoff, the corresponding contribution of glacial meltwater to the streamflow only accounts for max. 11% in the catchment (Prasch et al., 2013). Moreover, the summer meltwater partly infiltrates into soils and will be stored in aquifers. This can explain why it is statistically nonsignificant for summer runoff.

3.2. Estimation of groundwater storage by baseflow recession analysis

Using the data selection procedure mentioned in the section 2.3.3, we adopted daily streamflow and precipitation records in autumn and early winter (September to December) in which the hydrograph with little precipitation usually declines consecutively and smoothly. The fitted slope b is equal to 1.79 through the nonlinear least square fit of equation (10) for all data points of $-dy/dt$ versus y in log-log space during the period 1979-2013. Moreover, for each decade or year, the intercept a could be fitted by the fixed slope b=1.79. Then, the values of K and m for each decade or year can be determined. And the groundwater storage S for each year can be directly estimated from the average rate of baseflow during a recession period through equation (8).

Figure 8 shows the results of the nonlinear least square fit for each decade's recession data from the 1980s, 1990s and 2000s, respectively. As shown in Figure 8, the recession data points and fitted recession curves of each decade gradually move downward as time goes on. This indicates that, with a fixed slope b, the intercept a gradually decreases and recession coefficient K increases accordingly. The values of recession coefficient K for each decade are 77 $mm^{0.79}d^{0.21}$, 84 $mm^{0.79}d^{0.21}$ and 103

$mm^{0.79}d^{0.21}$. Furthermore, Figure 9a shows the inter-annual variation of recession coefficient K during the period 1979-2013. In total, though there are some large fluctuations or even a rather large decrease at the beginning of the 1990s, the overall increasing trend of 7.70 ($mm^{0.79}d^{0.21}$)/10a at a significance level of 5% is similar to the results obtained from decade analysis. This long-term variation of recession coefficient K from September to December indicates that baseflow recession during autumn and early winter gradually slows down in the catchment.

According to the results of decade data fit (see in Figure 8), the mean values of groundwater storage S estimated for each decade are 130 mm, 148 mm and 188 mm for the 1980s, 1990s and 2000s. The inter-annual variation of groundwater storage S is also similar with recession coefficient K (Figure 9a and 9b). The decreased trend of anomalies changes of groundwater storage (GWS) estimated by the GRACE data is consistent with the annual trend of S during 2003~2015 (Figure 9b). And the reduced volume of groundwater between GWS and S are also comparable (~100-120 mm), which has partly verified our estimations.

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 9b). The annual trend of groundwater storage S from 1979 to 2013 is consistent with the values across decades. This indicates that groundwater storage has been enlarged. Through recent field investigations, we know that groundwater level is rising. The increases of surface water and shallow groundwater storages are changing the land cover and the Normalized Difference Vegetation Index (NDVI) is rising accordingly in the past twenty years (Figure 10). In fact, not only in the study area but in the whole TP as well as surrounding regions, surface water and groundwater storage are increasing due to climate warming, and hence vegetation conditions are improved (Zhang et al., 2018; Khadka et al., 2018).

4. Discussions

The results have revealed that the increase of streamflow especially in dry season is tightly related with climate warming. It is obviously that both glacier retreat and frozen ground degradation in a warmer climate can significantly alter the mechanism of streamflow. In the Yangbajain Catchment as well as the whole Lhasa River Basin, it is experiencing a noticeable glacier retreat and frozen ground degradation during the past decades (Table 3). For instance, according to the twice map of frozen ground distribution on the TP (Li and Cheng, 1996; Zou et al., 2017), the areal extent of permafrost in the Yangbajain catchment has decreased by 406 km^2 (15.3%) over the past 22 years; the corresponding areal extent of seasonal frozen ground has increased by 406 km^2 (15.3%) with the degradation of permafrost.

According to the new map of permafrost distribution on the Tibetan Plateau (Zou et al., 2017), the coverages of permafrost and seasonally frozen ground in each sub-catchment (especially the Lhasa sub-catchments) are comparable to that in the Yangbajain Catchment; but the coverage of glaciers in the three catchments is far lower than that in the Yangbajain Catchment according to the First Chinese Glacier

Inventory (Mi et al., 2002) (Table 3). The MK test showed that, in all the four catchments, the annual mean air temperature had significant increases at the 1% significance level (Figure 4) while the annual precipitation showed nonsignificant trends (Table 4). The annual streamflow of the three Lhasa, Pangdo and Tangga Catchments all had nonsignificant trends, while the annual streamflow of the Yangbajain Catchment showed an increasing trend at the 5% significance level with a mean rate of about 12.30 mm/10a during the period. Ye et al. (1999) stated that when glacier coverage is greater than 5%, glacier contribution to streamflow starts to show up. This indicates that, in the Yangbajain Catchment, the increased streamflow is mainly fed by the accelerated glacier retreat rather than frozen ground degradation. This conclusion is also consistent with previous results by Prasch et al. (2013), who suggested that the contribution of accelerated glacial meltwater to streamflow would bring a significant increase in streamflow in the Yangbajain Catchment. Thus it is reasonable to attribute annual streamflow increases to the accelerated glacier retreat as the consequence of increasing annual air temperature.

Although permafrost degradation is not the controlling factor for the increase of streamflow, a rational hypothesis is that increased groundwater storage S in autumn and early winter is associated with frozen ground degradation, 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 catchment, which is underlain by frozen ground under past climate and warmer climate, respectively. As frozen ground extent continues to decline and active layer thickness continues to increase in the valley, the enlargement of groundwater storage capacity can provide enough storage space to accommodate the increasing meltwater that may percolate into deeper aquifers (Figure 3). Then, the increase of groundwater storage in autumn and early winter allows more groundwater discharge into streams as baseflow, and lengthens the recession time as indicated by recession coefficient K. This leads to the increased baseflow and slow baseflow recession in autumn and early winter, as is shown in Figure 6c, 6d and Figure 9a. In the late winter and spring, the increase of baseflow (Figure 6d and 6a) can be explained by the delayed release of increased groundwater storage.

Thus, as the results of climate warming, river regime in this catchment has been altered significantly. On the one hand, permafrost degradation is changing the aquifer structure that controls the storage-discharge mechanism, e.g., catchment groundwater storage increases at about 19.32 mm/10a. On the other hand, huge amount of water from glacier retreat is contributing to the increase of streamflow and groundwater storage. For example, the annual streamflow of the Yangbajain Catchment increases with a mean rate of about 12.30 mm/10a during the past 50 years. However, the total glacial area and volume have decreased by 38.05 km^2 (12.0%) and 4.73×10^9 m^3 (26.2%) over the period 1960-2009 (Figure 11) according to the Chinese Glacier Inventories. Hence, the reduction rate of glacial volume is 9.46×10^7 m^3/a (about 357.7 mm/10a) on average during the past 50 years. In the ablation on continental type glaciers in China, evaporation (sublimation) always takes an important role, however, annul amount of evaporation is usually less than 30% of the total ablation of glaciers in the high mountains of China (Zhang et al., 1996). Given the 30% reduction in glacial melt, there is still a large water imbalance between melt-derived runoff and the actually increase of runoff and groundwater storage. Our results imply that more than 60% of glacial meltwater would be lost by subsurface leakage.

5. Conclusions

In this study, the changes of hydro-meteorological variables were evaluated to identify the main climatic factor for streamflow changes in the cryospheric Yangbajain Catchment. We find that the annual streamflow especially the annual baseflow increases significantly, and the rising air temperature acts as a primary factor for the increased runoff. Furthermore, through parallel comparisons of sub-basins in the Lhasa River Basin, we indirectly presumed that the increased streamflow in the Yangbajain catchment is mainly fed by glacier retreat. Due to the climate warming, the total glacial area and volume have decreased by 38.05 km^2 (12.0%) and 4.73×10^9 m^3 (26.2%) in 1960-2009, and the areal extent of permafrost has degraded by 406 km^2 (15.3%) in the past 22 years. As a results of permafrost degradation, groundwater storage capacity has been enlarged, which triggers a continuous increase of groundwater storage at a rate of about 19.32 mm/10a. This can explain why baseflow volume increases and baseflow recession slows down in autumn and early winter.

At last we find that there is a large water imbalance (> 5.79×10^7 m^3/a) between melt-derived runoff and the actually increase of runoff and groundwater storage, which suggests more than 60% of the reduction in glacial melt should be lost by subsurface leakage. However, the pathway of these leakage is still an open question for further studies. More methods (e.g., hydrological isotopes) should be adopted to quantify the contribution of glaciers meltwater and permafrost degradation 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 quick flow (mm) from 1979 to 2013.

	Air temperature		Precipitation		Streamflow		Baseflow		Quick flow	
	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 Z_C and β mean the standardized test statistic and the trend magnitude, respectively; positive values of Z_C and β indicate the upward trend, whereas negative values indicate the downward trend in the tested time series; the symbols of asterisks *and ** mean statistically significant at the levels of 5% and 1%, respectively.

Table 2. Gray relational grades between the streamflow/baseflow and climate factors (precipitation and air temperature) in the Yangbajain Catchment at both annual and seasonal scales. Bold text shows the higher gray relational grade in each season.

	G_{oi} with the streamflow		G_{oi} with the baseflow	
	Precipitation	Air temperature	Precipitation	Air temperature
Spring	0.690	**0.778**	0.713	**0.789**
Summer	0.689	**0.784**	0.680	**0.776**
Autumn	0.653	**0.667**	0.648	**0.680**
Winter	0.742	**0.886**	0.748	**0.895**
Annual	0.675	**0.727**	0.665	**0.729**

Comment: G_{oi} is the gray relational grade between the streamflow/baseflow and climate factors. The importance of each influence factor can be determined by the order of the gray relational grade values. The influence factor with the largest G_{oi} is regarded as the main stress factor for the objective variable.

Table 3. The coverage of glaciers and frozen ground in four catchments of the Lhasa River Basin

Stations	Area (km^2)	Glaciers(1960)		Glaciers(2009)		Permafrost (1996)		Permafrost (2017)		Seasonally frozen ground (1996)		Seasonally frozen ground (2017)	
		Area (km^2)	Coverage (%)	Area (km^2)	Coverage (%)	Area (km^2)	Coverage (%)	Area (km^2)	Coverage (%)	Area (km^2)	Coverage (%)	Area (km^2)	Coverage (%)
Lhasa	26233	349.26	1.3	347.14	1.3	10535	40.2	9783	37.3	15698	59.8	16450	62.7
Pangdo	16425	345.24	2.1	339.90	2.1	8666	52.7	8242	50.2	7762	47.3	8184	49.8
Tangga	20152	348.12	1.7	342.27	1.7	10081	50.0	9432	46.8	10071	50.0	10720	53.2
Yangbajain	2645	316.31	12.0	278.26	10.5	1352	51.1	946	35.8	1293	48.9	1699	64.2

Table 4. Mann-Kendall trend test with trend-free pre-whitening of annual mean air temperature (°C), precipitation (mm) and streamflow (mm) in four catchments of the Lhasa River Basin

	Air temperature		Precipitation		Streamflow	
	Z_C	β (°C/a)	Z_C	β (mm/a)	Z_C	β (mm/a)
Lhasa	6.07**	0.028	1.16	1.581	1.09	1.420
Pangdo	6.19**	0.026	0.89	1.435	0.30	0.223
Tangga	7.35**	0.021	1.48	2.005	-0.62	-0.531
Yangbajain	4.48**	0.028	1.28	2.541	2.07*	1.230

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 streamflow (*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 permafrost thawing under (a) past climate and (b) warmer climate.

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

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

Figure 6. Variations of seasonal streamflow and baseflow in (a) spring, (b) summer, (c) autumn, and (d) winter from 1979 to 2013.

Figure 7. Variations of seasonal mean air temperature in (a) spring, (b) summer, (c) autumn, and (d) winter from 1979 to 2013.

Figure 8. 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 curves in the 1980s, 1990s, and 2000s, respectively.

Figure 9. Variations of (a) the recession coefficient K and (b) groundwater storage S from 1979 to 2013.

Figure 10. Variations of annual NDVI from 1998 to 2013 in the catchment.

Figure 11. The total area and volume of glaciers in the Yangbajain Catchment in 1960 and 2009.

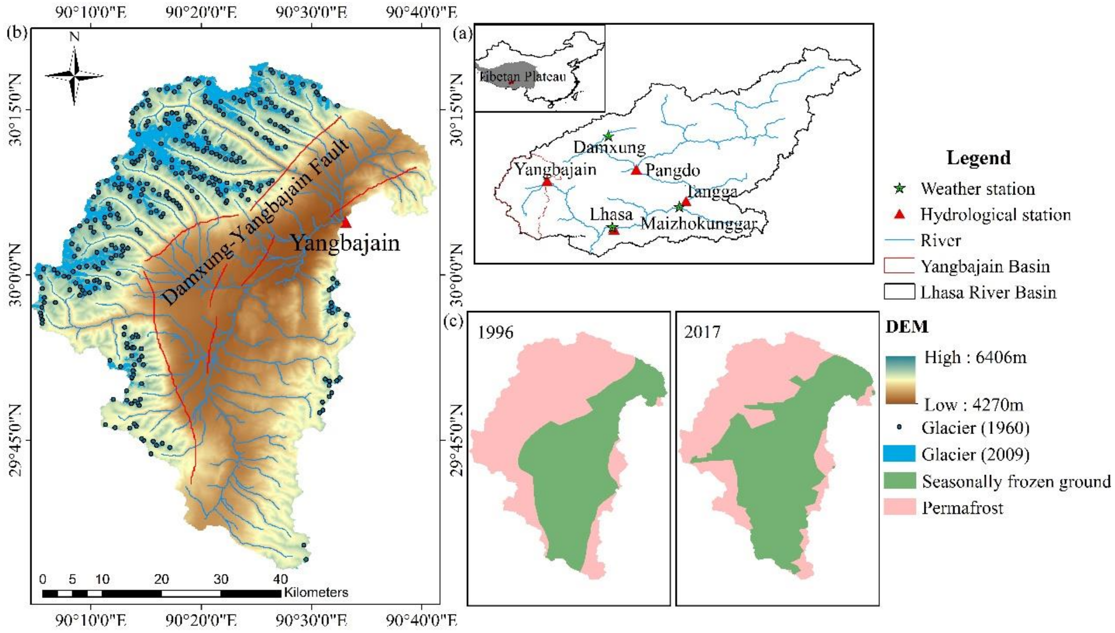
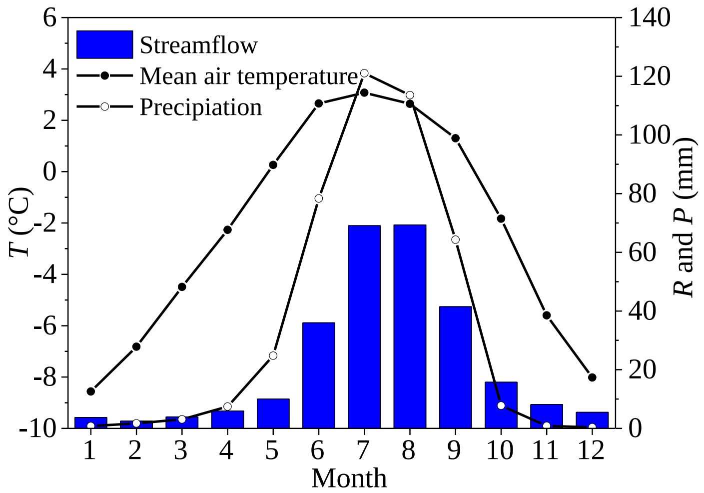


Figure 1. (a) The location, (b) elevation and glacier distribution for the twice Chinese Glacier Inventory, only the location of glacier snouts in 1960 were provided in the first Chinese Glacier Inventory, and the boundaries of glaciers were shown in the second Chinese Glacier Inventory, and (c) twice maps of frozen ground distribution (Li and Cheng, 1996; Zou et al., 2017) in the Yangbajain Catchment.



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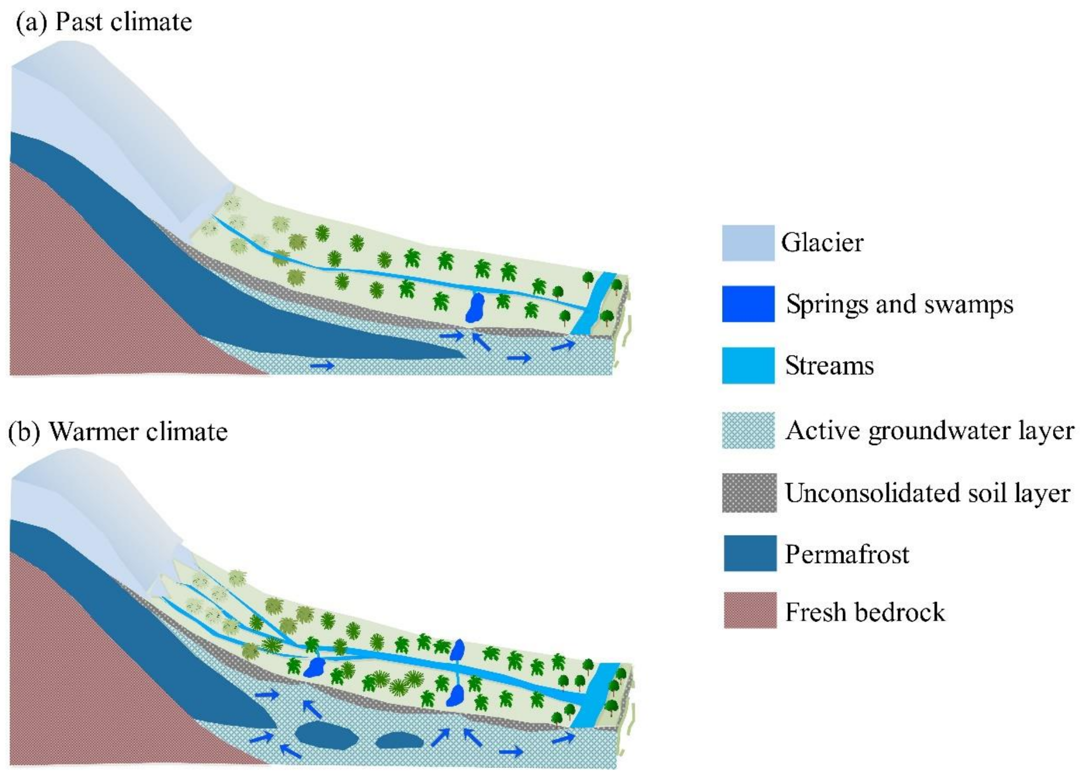

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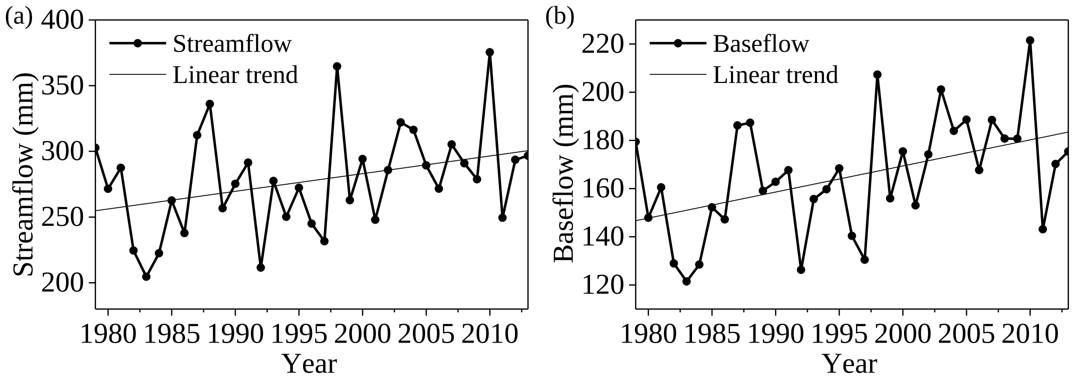


Figure 4. Variations of annual (a) streamflow and (b) baseflow from 1979 to 2013.

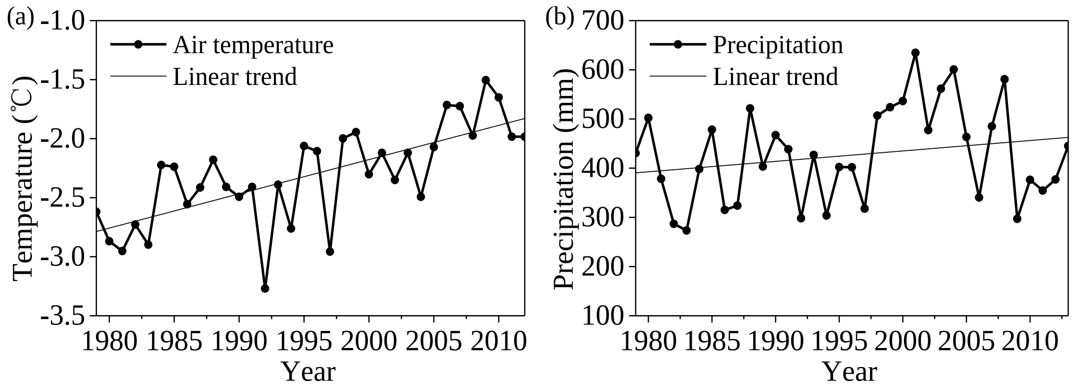
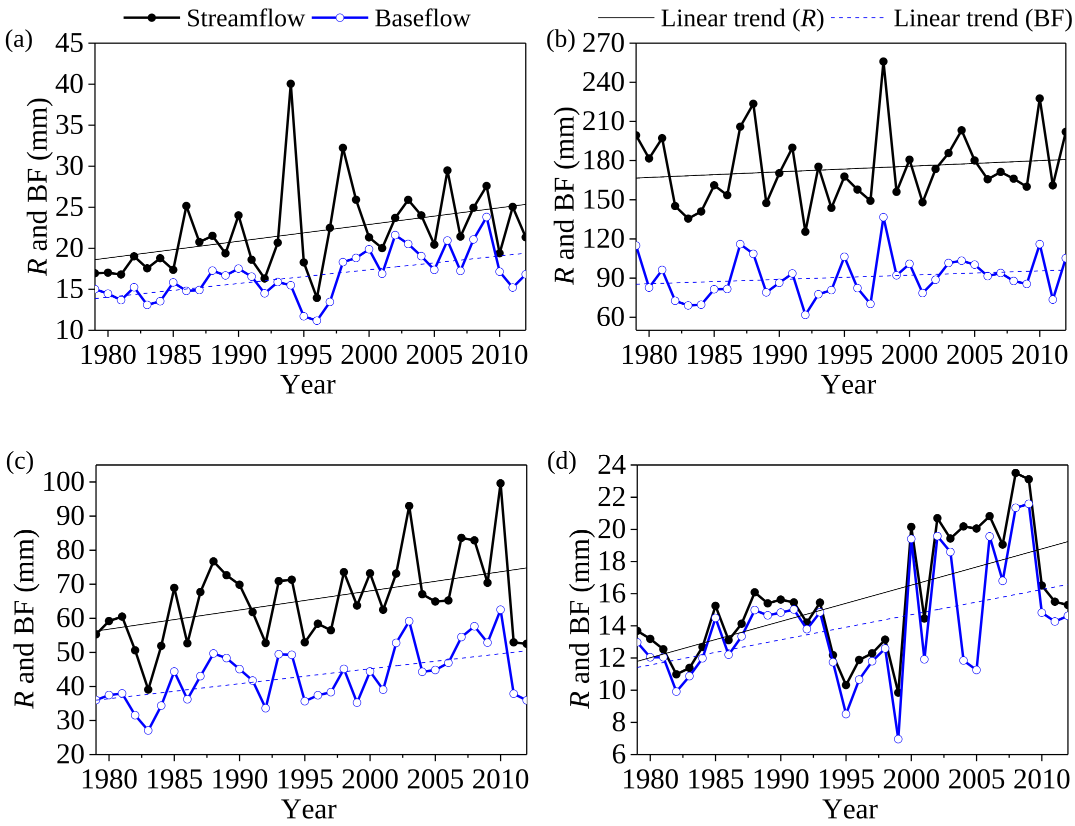


Figure 5. Variations of annual (a) mean air temperature and (b) precipitation from 1979 to 2013.



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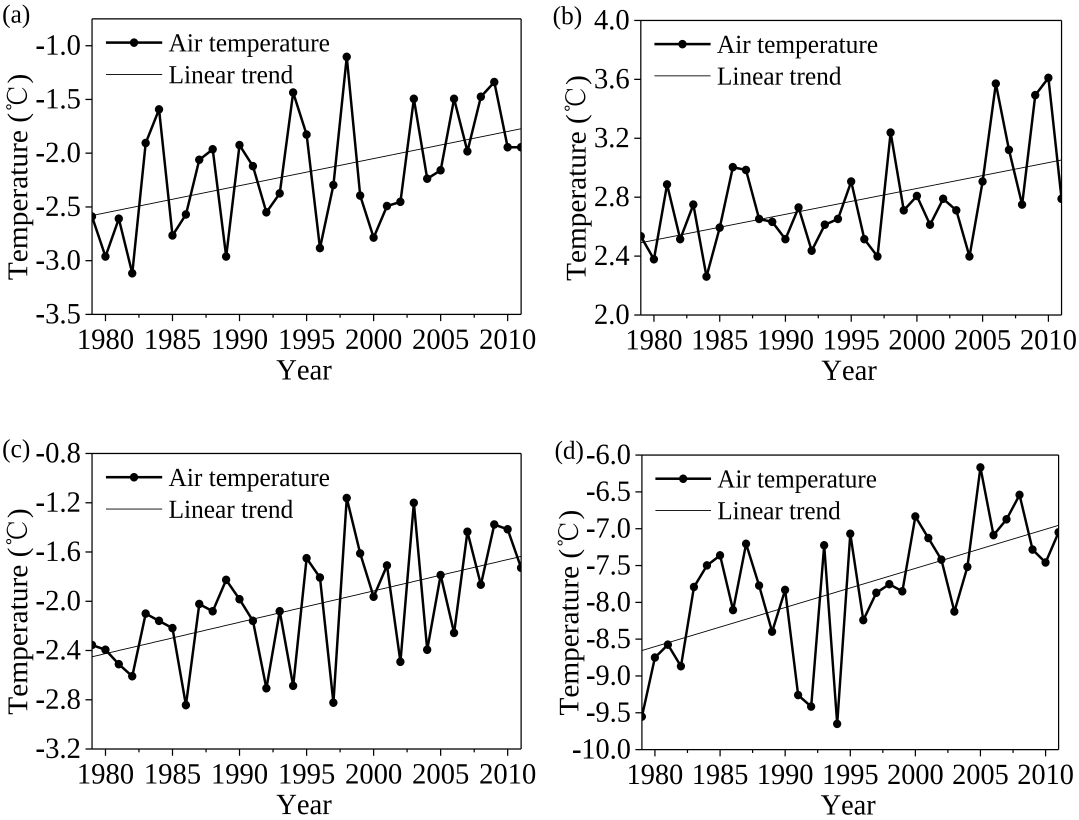

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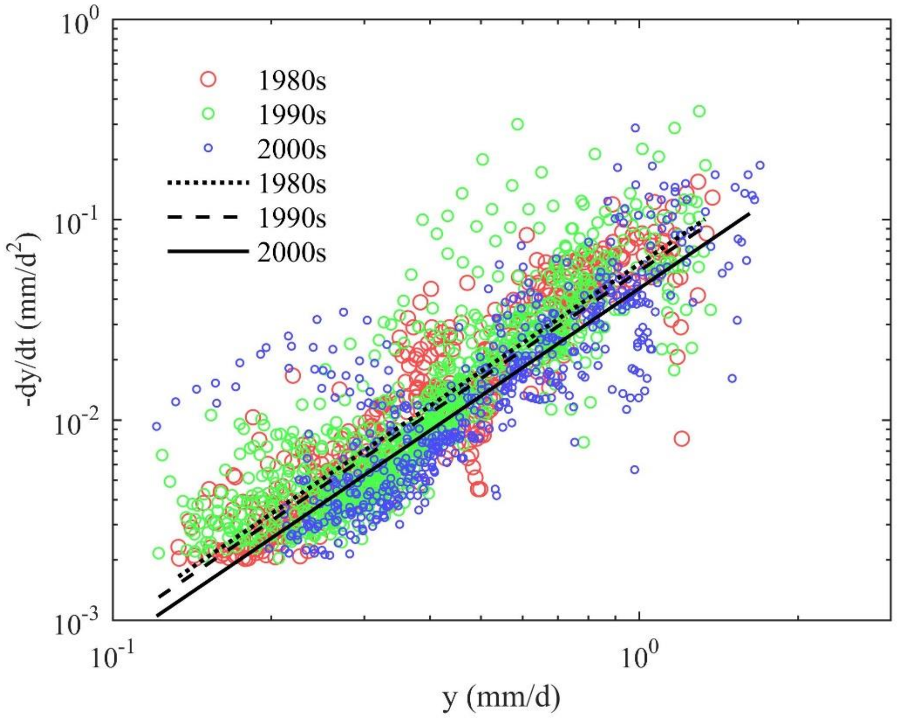

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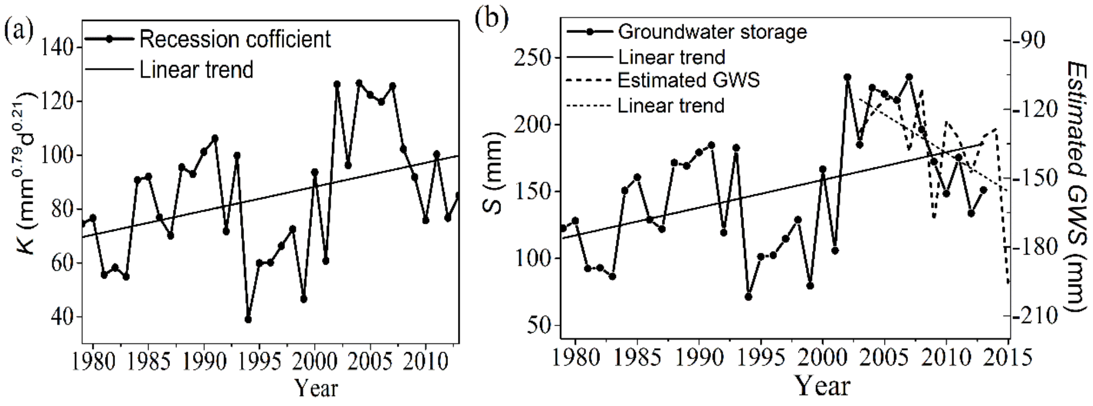
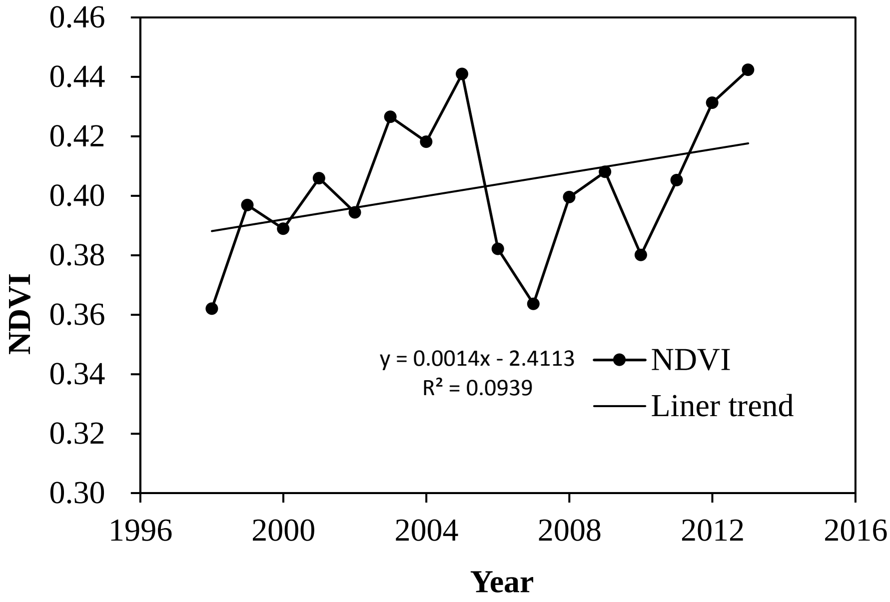


Figure 9. Variations of (a) the recession coefficient *K* and (b) the estimated groundwater storage *S* from 1979 to 2013 and the estimated groundwater storage change from 2003 to 2015 by GRACE data.



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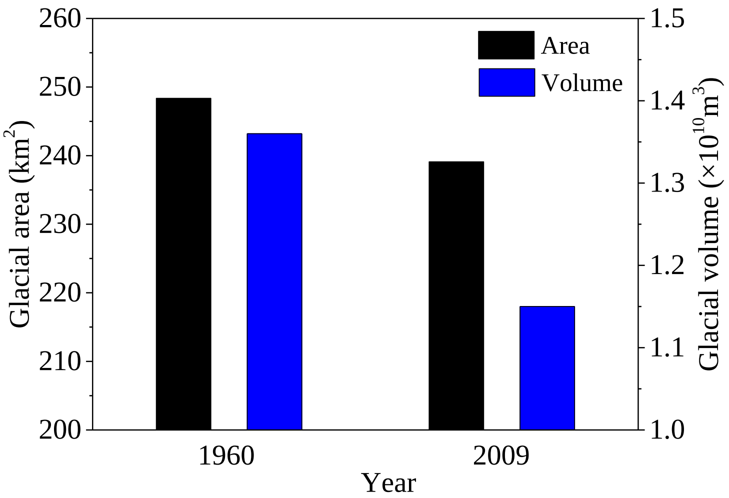

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