Dear Editor and Reviewers,

The manuscript entitled “Quantifying streamflow and active groundwater storage in response to climate warming in an alpine catchment, upper Lhasa River” has been thoroughly revised according to the anonymous reviewers’ comments. Many revisions have been made for improving its quality. Major revisions include:

(1) We have changed the title as “Understanding the effects of climate warming on streamflow and active groundwater storage in an alpine catchment, upper Lhasa River”.

(2) Modifications for more accurate descriptions of the results have been provided according to the suggestions of the editor and reviewers. In addition, many results have been updated. For example, Figure 3 was re-draw according to the real situations of topography and distribution of glaciers and permafrost in the Yangbajain catchment according to the two reviewer’s suggestions. And we added another figure about NDVI (Figure 10 in the manuscript) to provide an evidence for the estimated increasing water storage.

(3) Many part of the manuscript including abstract, introduction, conclusions and some parts of other sections have been re-organized and re-written.

For any further corrections and requirements, the authors are ready here for your critiques.

Correspondence and phone calls about the paper should be directed to Prof. Liu Jintao at the following address, phone and fax number, and e-mail address: State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University; Adress: 1 Xikang Road, Nanjing 210098, People’s Republic of China; Tel：+86-25-83787803; Fax: +86-025-83786606; E-mail：jtliu@hhu.edu.cn.

Thanks very much for your attentions to our paper again．

Sincerely yours，

Liu Jintao

Response to Reviewer #1

Interactive comment on “Quantifying streamflow and active groundwater storage in response to climate warming in an alpine catchment, upper Lhasa River” by Lu Lin et al.
Anonymous Referee #1 Received and published: 6 July 2019

This paper presents the temperature, precipitation and stream variation in the Yangbajain catchment. Interestingly, the estimate the base flow and connect the baseflow variation with the climate change. This is important for the local water resources management and well as for the global groundwater-climate change research. But it should be accepted after a minor revision.

Response: Many thanks for the positive comments and suggestions. We have addressed the reviewer’s concerns and suggestions carefully. In the following, we provide point-by-point response to each reviewer comment (blue texts are our responses, while black texts are original comments).

My major comments are:

1. The accuracy of base flow and groundwater storage estimation. As I pointed out in the specific comment, the authors should provide more evidences to show the estimated groundwater storage are correct.

Response: Yes, we agree that the results need to be verified by more evidences. However, as we know, at catchment scale, especially in Alpine regions, there are few direct methods to measure water storage at catchment scales, and direct observations of permafrost are even difficult to perform (Lyon et al., 2010; Creutzfeldt et al., 2014; Rogger et al., 2017; Patnaik et al., 2018).

Several alternatively indirect methods have been proposed to try to validate the estimation from recession analysis. Vannier et al. (2014) compared the recession analysis based estimation of groundwater storage capacity with the method that estimates storage capacity by multiplying the soil thickness and specific yield. Birkel et al. (2011) used a tracer-constrained process-based conceptual model to validate storage dynamic estimated from the recession analysis based method. These indirect methods are considerable at small catchment with humid climate. Although superconducting gravimetry can measure the storage dynamic directly (Creutzfeldt et al., 2014), it is costly and only available at specific location.

Instead, the GRACE data were used to verify our estimations in this study. In addition, we know that groundwater level is rising through recent field investigations. The increases of surface water and shallow groundwater are changing the land cover and NDVI (Figure 1) is rising accordingly in recent years. All these provide evidences to the estimated rising groundwater storage.

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).

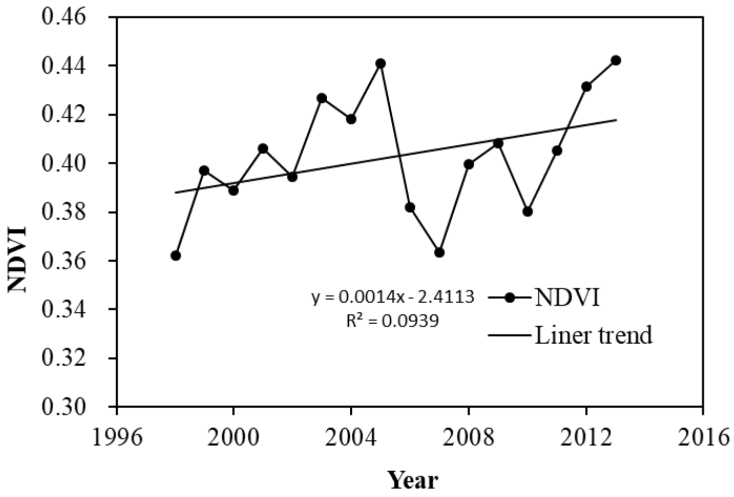

Figure 1. Variations of annual NDVI from 1998 to 2013 in the Yangbajain catchment.

2. The explanation on the glacier loss should be deleted. Please see the specific comment (Line 408-413).

Response: it has been revised accordingly.

3. The schematic model (Figure 3).

(1) The glacier thickness should increase with the altitude;

(2) 'Unconsolidated material' changes 'Unconsolidated soil layer';

(3) Take care of the width of the arrows.

Response: Thank you very much for your suggestions. According to your suggestions and those of the second reviewer, we have made corresponding modifications by considering local real situations in the study region, as shown in figure 2.

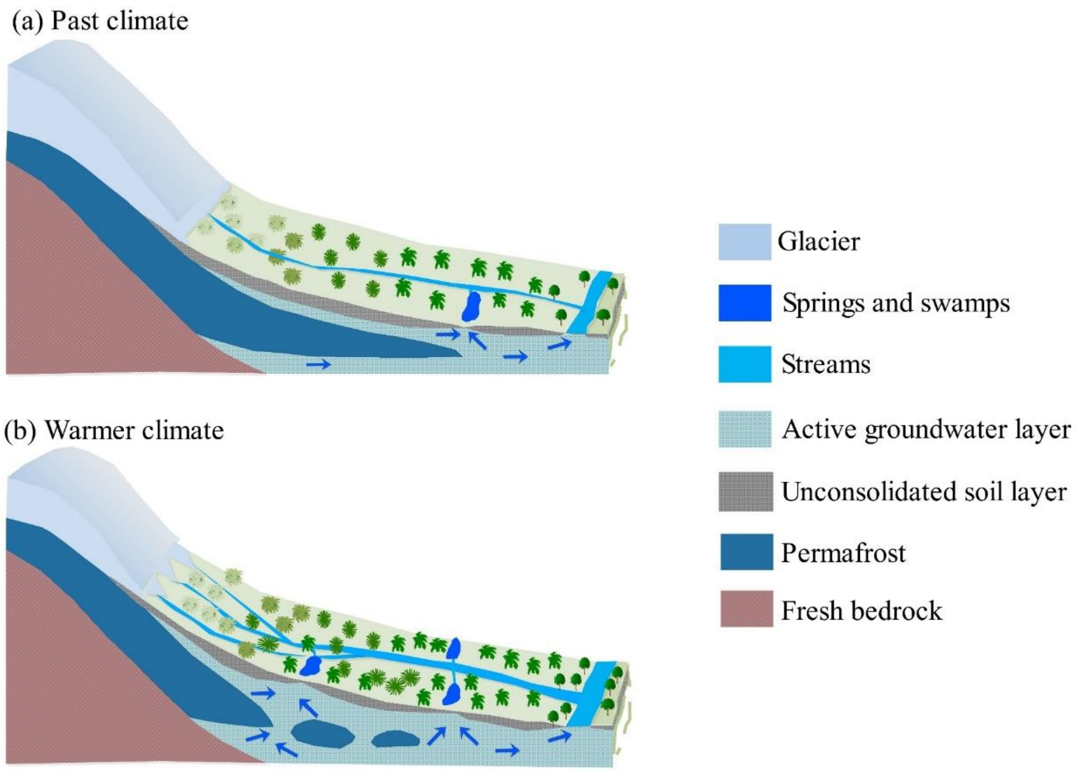

Figure 2. Diagram depicting surface flow and groundwater flow due to glacier melt and permafrost thawing under (a) past climate and (b) warmer climate (after Ding et al. (2017)).

Specific comments:

Line 115&117 What is the method difference between Lyon et al. (2009) and Kirchner et al. (2009)? And what is the latest advance of the recession analysis? Please clarify.

Response: Lyon et al. (2009) method is based on the recession flow analysis developed on the basis of hydraulic groundwater theory by Brutsaert and Nieber (1977) and Brutsaert (2008). However, Kirchner (2009) derived a nonlinear first-order dynamical equations by the conservation-of-mass theory for simulate the streamflow hydrograph from precipitation and evapotranspiration. The power law recession relationship which is used to characterize catchments based on nonlinear reservoir model or a Boussinesq representation of subsurface flow is only a special case in Kirchner's study.

In hydrology, the storage-discharge relationship is a fundamental catchment property and can provide a functional form for recession analysis (Lyon et al., 2010; Creutzfeldt et al., 2014). However, to date, there are few direct methods to measure water storage at catchment scales, let alone to measure permafrost change in Alpine regions (e.g., the Qinghai-Tibet Plateau). Thus explicit storage-discharge relationship still remains unknown to us. Creutzfeldt et al. (2014) adopted direct measurements of terrestrial water storage dynamics by means of superconducting gravimetry in a small headwater catchment to derive empirical storage-discharge relationships. As direct measurement remains a major challenge, Birkel et al. (2015) and Soulsby et al. (2015) use a tracer-aided hydrological model to characterize catchment storage.

Though many new methods (e.g., tracer-aided model) are proposed, to date, the classical technique of recession flow analysis according to recession flow or flow during no - rain periods sustained by basin storage (*S*) is still widely used to provide important information on storage–discharge relationship of the basin (Patnaik et al., 2018). This is because many methods are limited by observations. For instance, in many catchments, especially in Alpine regions, hydrological observations are sparse and direct observations of permafrost are difficult to perform. Most importantly, the recession flow analysis is based on widely available hydrologic data (i.e., streamflow data).

As an important component of hydrograph, the nonlinear properties and inconsistency of recession segments among events are emphasized to give better parameterization of recession process through both hydrograph analysis and analytical and numerical simulation (Bogaart et al., 2013; Dralle et al., 2015, 2017; Gao et al., 2017; Hogarth et al., 2014; Roques et al., 2017; Sawaske and Freyberg 2014; Stoelzle et al., 2013). Recession analysis now works as an effective tool to explore catchment-scale physical attributes, such as catchment-scale hydrogeological parameters (saturated hydraulic conductivity, aquifer thickness), active river network dynamic, and storage capacity (Biswal and Kumar, 2014; Pauritsch et al., 2015; Shaw et al., 2016; Troch et al., 2013, Vannier, 2014). The catchment hydrological functions are also revealed through recession analysis. Hydrologic fluxes (actual evaporation, different streamflow components) and state-variables (like storage dynamic) can be estimated from recession analysis (Creutzfeldt et al., 2014; Shaw and Riha, 2012; Szilagyi et al., 2007;). A simple dynamic model can be even developed based recession analysis (Kirchner, 2009; Rusjan and Mikoš, 2015; Teuling et al., 2010). Besides, the streamflow recession patterns are used to unravel the co-evolution of landscape (Bogaart et al., 2016) and also the impact of climate change on permafrost degradation (Lyon et al., 2009; Ploum et al., 2019).

Line 163, 164&168. Please describe the number clearly on the period as well as the hydrologic station.

Response: it has been revised accordingly. The air temperature of the Yangbajain Catchment is the areal average value over the whole catchment, which is calculated by the method of meteorological data extrapolation by Prasch et al. (2013). The precipitation and streamflow is the statistical values at the Yangbajain station.

Line 169-171 How do you get the number of 63% from Fig. 2. And I do not think you can get this number easily only with the data of temperature, precipitation amount and runoff.

Response: it is a little bit puzzling. Here we mean the runoff volume in summer account for 63% of the annual streamflow volume and it has been revised accordingly.

Line286-288 The higher grade relational grade is found at the annual scale, how can you say the air temperature also acts a primary role for the base flow?

Response: According to the trend analysis of hydro-meteorological factors (e.g., precipitation, Air temperature, etc), we found that baseflow as well as streamflow are both increasing. Through gray relational analysis, we aim to identify the major climatic factors for the increasing streamflow. The result shows that the air temperature compared with precipitation has the higher gray relational grade at annual scale (Table 2). This indicates that the air temperature instead of precipitation acts as a primary factor for the increased streamflow as well as the baseflow. The continuous warming has led to glacier loss and permafrost degradation that contribute to the increasing of streamflow.

Line 339-344 I suggest to shift these sentences above the lines 335-339. Before discussing the trend of the groundwater storage, you should firstly explain the obtained results of groundwater storage are reasonable. I also ask the authors to give more explanation on their obtained groundwater storage, because it does seem consistent between the Grace data and your data. Could the authors give more evidences of the monitored groundwater level?

Response: these sentences have been shifted accordingly. As you know in the harsh Yangbajain catchment there are no monitored groundwater wells observed by either official departments or scientific community. At this stage, we have to seek to public data (e.g., GRACE data) for verifications of our estimations.

In addition, we know that groundwater level is rising through recent field investigations. The increases of surface water and shallow groundwater are changing the land cover and NDVI (Figure 1) is rising accordingly in recent years. All these provide evidences to the estimated rising groundwater storage.

In fact, 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)

Line 356-370 I understand the authors try to draw the conclusion ‘the increased streamflow is mainly fed by the accelerated glacier retreat rather than frozen ground degradation’ through the comparison between four catchments. This is something kind of ‘circumstantial evidence’. Could you explain why the frozen ground degradation does not increase the streamflow?

Response: Yes, we agree that it is some kind of circumstantial evidence. The frozen ground degradation also contributes to the increasing of streamflow. However, through parallel comparison of different sub-basins (Table 3), we can conclude that the contribution of glacier retreat is much larger than frozen ground degradation. While the mostly significant effects of frozen ground degradation on runoff is that it can increase groundwater storage space and change the behavior of storage-discharge in the catchment. Similar results can be found in many other studies, e.g., Xu et al. (2019), Khadka et al. (2018) and Walvoord and Striegl (2007). 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.

Line 408-413. This is quite arbitrary. Although the estimation of glacier loss is reasonable, the loss can be explained in many ways. For example, it could be delivered through the different pathways of shallow aquifer; and it could be exchanged with the aquifers outside the studied region. Sure, it may also infiltrate into the deep fault. But all of these hypotheses need evidences. If you take the one of deep circulation, you should describe clearly the hydrogeologic features of the fault. Is it conductive or not? What is the depth of it? What is the groundwater flow direction inside it? Could you provide the hydrogeologic section map here? If the authors could not provide the discussion above, I suggest the authors to delete this paragraph and leave the glacier loss as an open discussion question here.

Response: Yes, we agree with the reviewer’s comments and it has been deleted.

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Response to Reviewer #2

Interactive comment on “Quantifying streamflow and active groundwater storage in response to climate warming in an alpine catchment, upper Lhasa River” by Lu Lin et al.
Anonymous Referee #2 Received and published: 10 July 2019

Journal: HESS Title: Quantifying streamflow and active groundwater storage in response to climate warming in an alpine catchment, upper Lhasa River MS No.: HESS_2019_302 In this work, Lin et al. has investigated the changes in streamflow regimes and climate factors are evaluated based on hydro-meteorological observations from 1979 to 2013. The work is very interesting. This study provides a perspective to clarify the impact of glacial retreat and frozen ground degradation on hydrological processes, which fundamentally affects the water supply and the mechanisms of streamflow generation and change. However, I have some issues with this paper, which prevents me from giving a positive recommendation.

Response: Thank you for your valuable comments. Major revisions have been made to response to the reviewer’s critiques. In the following, we provide point-by-point response to each reviewer comment (blue texts are our responses, while black texts are original comments).

1.The title of this paper is: Quantifying streamflow and active groundwater storage in response to climate warming in an alpine catchment, upper Lhasa River. However, the main content of this paper is the relationship between streamflow and active groundwater storage and temperature and precipitation. Moreover, the response of runoff on climate warming is not clearly quantified in this paper. So this topic may not be suitable for this article.

Response: Yes, the title is somewhat unsuitable. There are not more evidences for quantifying the pathway and assessing the accurate contribution of each factor to runoff increasing. It tends to be a qualitative assessment of the effects of climate warming on hydrological processes. Thus in the revised version of the manuscript, we have changed the title as “Understanding the effects of climate warming on streamflow and active groundwater storage in an alpine catchment, upper Lhasa River”.

2.In this paper, the mechanism of hydrological process, hydrological cycle and the relationship between recharge and drainage of water in alpine region are not described in detail. Please add it.

Response: Yes, we have re-reviewed several latest or key studies in alpine regions. For example, Rogger et al. (2017)’s study about mountain permafrost, Xu et al. (2019)’s study about climate change on water budget in cryospheric-dominated watershed, Walvoord et al. (2007)’s analysis of increased groundwater to discharge by permafrost thawing in an arctic basin, and Su et al. (2016) and so on. Anyway, through reviewing these important studies, it helps us to re-organize the structure of our manuscript. We have re-written the section of introduction and conclusion and parts of other sections.

In the manuscript, we have made it clear that 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. So quantitatively characterizing storage properties and sensitivity to climate warming in cold alpine catchments is desired. Hence, in this study, recession flow analysis is adopted to quantify active groundwater storage volume.

3. “ the annual streamflow especially the annual baseflow increases significantly, and the rising air temperature acts as a primary factor for the increased runoff. ”. Climate warming has been a fact. Glacier could be reduced by the increasing of temperature is a fact, too. However, this conclusion should be for the ablation period only in your study areaïij´LCold regionsïijL’. I suggest authors make a more detailed analysis of the Year, Month, the ablation period and freezing period, which may be more reasonable and interesting.

Response: Sure, it is important to analyze hydro-climatic responses in different seasons. In fact, we have added such contents in our manuscript. We found that there are diverse intra-annual variation characteristics for streamflow 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). 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).

4.Diagram depicting surface flow and groundwater flow due to glacier melt and frozen ground thaw of Figure 3 should not be in the alpine region, at least not in the Qinghai-Tibet Plateau. I suggest that the author make major revisions according to the current studies.

Response: Thank you very much for your suggestions. According to your suggestions and those of the other reviewer, we have made corresponding modifications according to the topography and distribution of glaciers and permafrost in the Yangbajain catchment. The details are available in **2.1 Study area** of the manuscript. In figure depicting, we referred to the book of Ding et al. (2017) that is an introduction to hydrology in the cold regions especially in China.

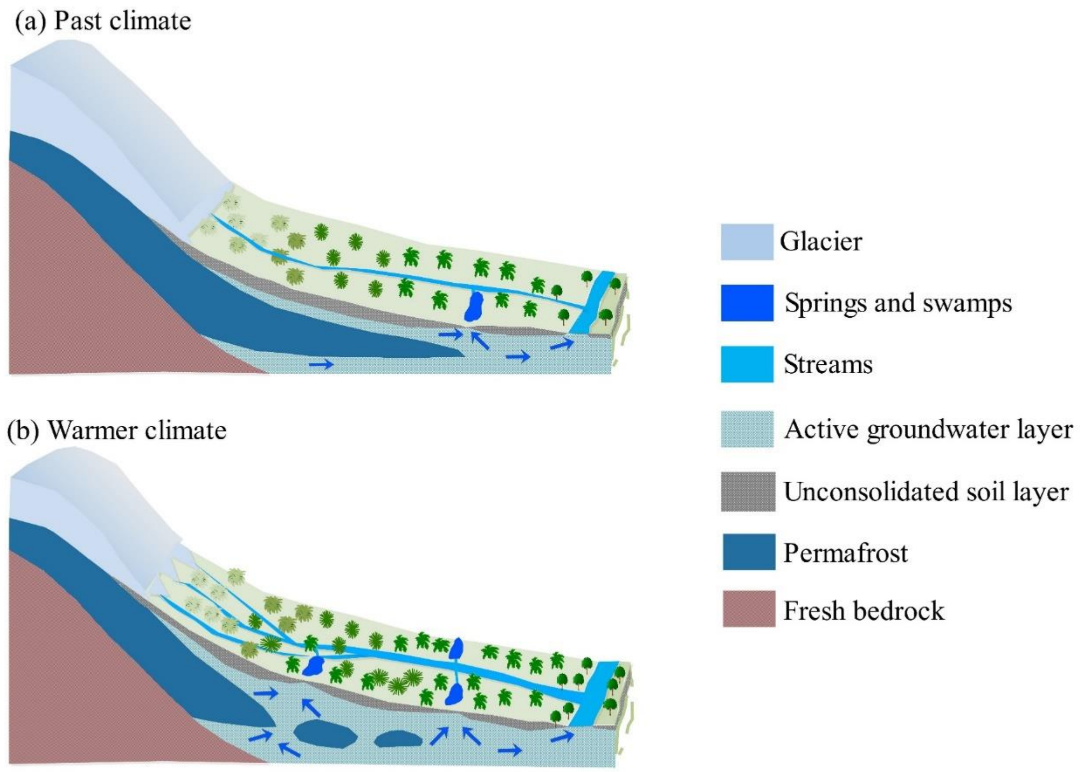

Figure 1. Diagram depicting surface flow and groundwater flow due to glacier melt and permafrost thawing under (a) past climate and (b) warmer climate (after Ding et al. (2017)).

5. This work has been found that the increased streamflow is mainly fed by the accelerated glacier retreat due to climate warming. There are many factors for the increase of streamflow. The accelerated glacier is just one of all factors. For example, the increase of precipitation, the degradation of frozen soil, the melting of underground ice, and the supply of supra-permafrost water. So I suggest that authors first figure out what is the main sources of streamflow in the study area? Then analyzed the contribution of the recharge sources to runoff based on the variation of all factors under the climate warming. Finally, the main reason for the increase for runoff is obtained.

Response: thank you for your kindly suggestions. Many parts of this manuscript have been re-organized based on the reviewer's suggestions.

The main water source for summer runoff in the study area is monsoon rainfall. And the runoff volume in summer account for 63% of the annual streamflow volume. As estimated by Prasch et al. (2013), the corresponding contribution of glacial meltwater to the streamflow only accounts for max. 11% in the catchment. Thus if precipitation increases/decreases significantly, runoff will change accordingly. However, in the catchment, precipitation in each season shows nonsignificant trend during these years (Table 1). The results of gray relational analysis indicate that the air temperature acts as a primary factor for the increased streamflow. As a results of climate warming, the areal extent of permafrost in the Yangbajain catchment has decreased by 406 km^2 (15.3%) over the past 22 years, 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. All these changes have contributed to the changes of streamflow.

At last, through parallel comparison of different sub-basins (Table 3 in the manuscript), we can indirectly conclude that the contribution of glacier retreat is much larger than frozen ground degradation. While the mostly significant effects of frozen ground degradation on runoff is that it can increase groundwater storage space and change the behavior of storage-discharge in the catchment. Similar results can be found in many other studies, e.g., Xu et al. (2019), Khadka et al. (2018) and Walvoord and Striegl (2007). 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.

6.This study also found that the decreased glacial volume has supplied large quantities of glacial meltwater which recharge aquifers and reside in temporary storage during summer, and then release as baseflow during the following seasons. So I suggest that the authors learn more about the mechanism of the hydrological process in the cold regions.

Response: Yes, we have re-reviewed many references and added some of them in the revised version. Many parts of the manuscript have been re-written. See details in Response 2.

7. I don’t think the discussion section is well written, so I think the discussion section may need to be re-written.

Response: Thank you for your suggestion. The discussion section has been re-written as below.

In this study, the changes of hydro-meteorological variables were evaluated to identify the main climatic factor for streamflow increases 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 (> 5.79×107 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.

8.On the whole, the idea of this paper is very good, the conclusion of this paper is interesting, but the data support and supporting materials are lacking. In addition, the mechanism of water transformation in alpine region needs to be further studied.'

Response: Thank you for your positive comments. According to your suggestions, we have revised our topic as "Understanding the effects of climate warming on streamflow and active groundwater storage in an alpine catchment, upper Lhasa River". As we don't have more evidences for quantifying the pathway and assessing the accurately contribution of each factor to runoff increasing, we tend to present the manuscript as a qualitative assessment of the effects of climate warming on hydrological processes instead of a quantitative study.

Moreover, we deleted some arbitrary conclusions. For instance, in the original version of the manuscript (Line 408-413.), we argue huge amount glacier loss is through deep fault. However, it is only a hypotheses and it still need further evidences. So we deleted this paragraph and leave the glacier loss as an open discussion question here.

Anyway, we have made a major revision to present correct results and appropriate conclusions. Thank you again for you critiques.

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Response to editor

Editor Decision: Publish subject to revisions (further review by editor and referees) (12 Sep 2019) by Fuqiang Tian

Comments to the Author:

Dear Authors,

As you can see and has responded already, the comments raised by the two Referees are very constructive. Your response to the comments are clear and meaningful. I suggest that you revise the manuscript thoroughly and submit for further review.

Response: Many thanks for the positive comments and suggestions. Many revisions have been made for improving its quality. Major revisions include:

(1) According to the reviewer's suggestion, we have changed the title as "Understanding the effects of climate warming on streamflow and active groundwater storage in an alpine catchment, upper Lhasa River".

(2) Modifications for more accurate descriptions of the results have been provided according to the suggestions of the editor and reviewers. In addition, many results have been updated. For example, Figure 3 was re-draw according to the real situations of topography and distribution of glaciers and permafrost in the Yangbajain catchment according to the two reviewer's suggestions. And we added another figure about NDVI (Figure 10 in the manuscript) to provide an evidence for the estimated increasing water storage.

(3) Many part of the manuscript including abstract, introduction, conclusions and some parts of other sections have been re-organized and re-written.

The following are my comments, which can be considered together when you revise your manuscript.

1) L42-43, please use the full names of these transboundary rivers. For example, Mekong should be Lancang-Mekong.

Response: it has been revised accordingly.

2) L104, thaw should be thawing? please check.

Response: it has been revised accordingly.

3) L177, you only get the monthly meteorological data?

Response: Yes, only monthly data is adopted to calculate the seasonal variation of mean air temperature (T) and precipitation (P) in the Yangbajain Catchment (Figure 2 in the manuscript).

4) L211, Section 2.3.2, it is interesting to use baseflow separation method to quantify active groundwater storage. I understand the method is adopted from literature(s). But we cannot clearly see this from current description of the method. It seems to me that the method is more like a new (at least a modified) method. Please check and revise the description accordingly.

Response: Yes, the method was firstly derived by Gao et al. (2017). Here we use it for estimating the active groundwater storage. We have revised this part accordingly.

5) L306, it is interesting to know summer meltwater partly infiltrates into soils and will be stored in aquifers. But in this paragraph this point shows up suddenly. It is better to add more sentences to discuss. I know it is difficult to obtain measured data for underground things, but still we need more deep/logical explanations. Also, in my opinion it can be stated as a hypothesis.

Response: Yes, it is a little bit abrupt here. We move it the section of Discussions and make it as a hypothesis supported by our finding (e.g., figure 8 & 9)

6) L369-370, similar to comment 5).

Response: Yes, the sentence has been deleted and we re-wrote this part in the revised manuscript.

7) L399, I suggest to use same unit (mm) for total glacial value (decrease).

Response: it has been changed accordingly.

Best,
Editor

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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, Lancang-Mekong, Yarlu Zangbo-Brahmaputra, and Nu-Salween, Indus 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, glacier is known as "solid reservoir" that supplies water through 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 changing regimes of streamflow volume and baseflow recession in response to the changes of active groundwater storage and glaciers. The main conclusions are summarized in the section of Conclusions.

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 characterized by alpine meadow, alpine steppe, marsh, shrub, etc, and 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-thawing cycle of frozen ground and the active layer (Liu et al., 2011).

2.2. Data

Daily streamflow and precipitation data at 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 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 factors 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

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

$$b_t = Q_t - q_t \tag{2}$$

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 that ranging from 0.9 to 0.95; b_t is the filtered baseflow.

2.3.3. Determination of active groundwater storage

In this study, the active groundwater storage (also abbreviated as groundwater storage in the following context) is assumed as a storage that directly controls streamflow dynamics during rainless periods (Kirchner, 2009; Staudinger, 2017).

Based on hydraulic groundwater theory, 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, and S is the volume of active groundwater storage in the catchment aquifers (see in Figure 3). Here K, m are constants depending on the catchment physical characteristics, and K is the baseflow recession coefficient, which represents the time scale of the catchment streamflow recession process.

During dry season without precipitation and other input events, 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. In the storage discharge relationship, the aquifer responds as a linear reservoir if b=1, and as nonlinear reservoir if b≠1. In addition, with a fixed slope *b*, the changes in catchment aquifer properties by fitting the intercept *a* as a variable ban be observed (Rupp and Selker, 2006).

According to Gao et al. (2017), 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 $m=2-b$. Furthermore, the constants *a* and *b* can be determined through the technique of recession slope curves. In this study, the two constants are curve-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). According to the values of *a* and *b*, *K* and *m* can be calculated. Thus 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).

3.2. Estimation of groundwater storage by baseflow recession analysis

Daily streamflow and precipitation records in autumn and early winter (September to December) was adopted. In this dry season, hydrograph usually with little precipitation 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 $\mathrm{mm}^{0.79}\mathrm{d}^{0.21}$, 84 $\mathrm{mm}^{0.79}\mathrm{d}^{0.21}$ and 103 $\mathrm{mm}^{0.79}\mathrm{d}^{0.21}$. 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 ($\mathrm{mm}^{0.79}\mathrm{d}^{0.21}$)/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. For example 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, surface water and groundwater storage are increasing due to climate warming, and hence vegetation conditions have been 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 areal extent of seasonal frozen ground has increased by 406 km^2 (15.3%) with the corresponding 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 induced by climate warming starts to show up. As reported by Prasch et al. (2013), 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 1788 mm (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 ($> 5.79\times10^7$ 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.

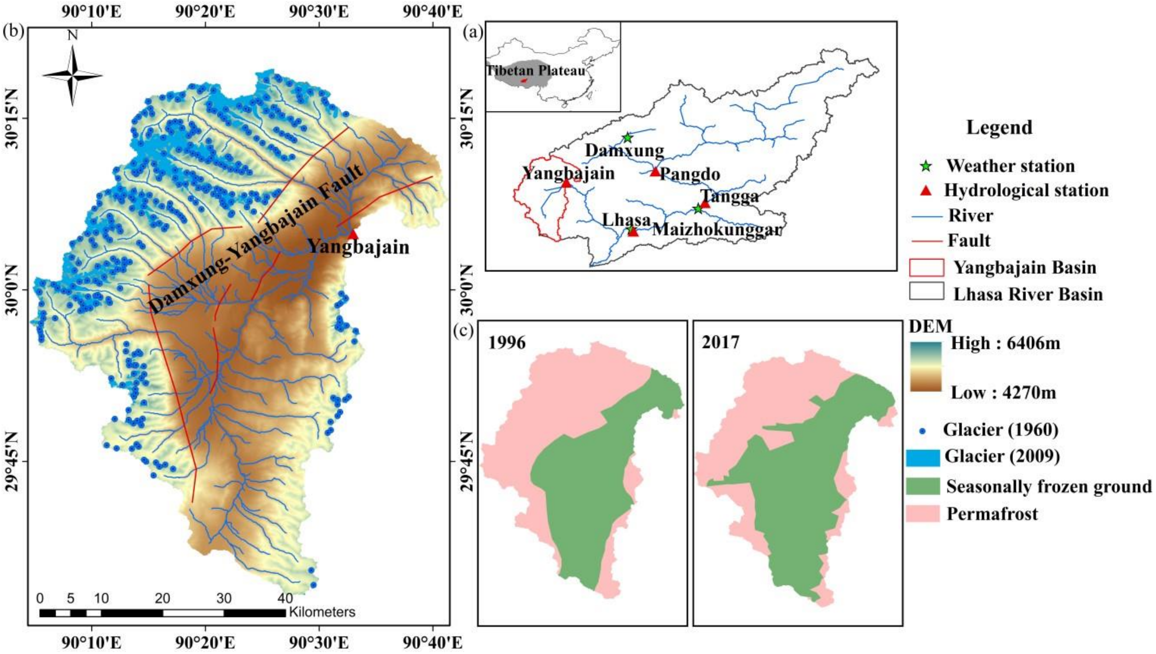

Figure 1. (a) The location, (b) elevation and glacier distribution for the twice Chinese Glacier Inventory, only the location of glacier snouts in 1960 were provided in the first Chinese Glacier Inventory, and the boundaries of glaciers were shown in the second Chinese Glacier Inventory, and (c) twice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

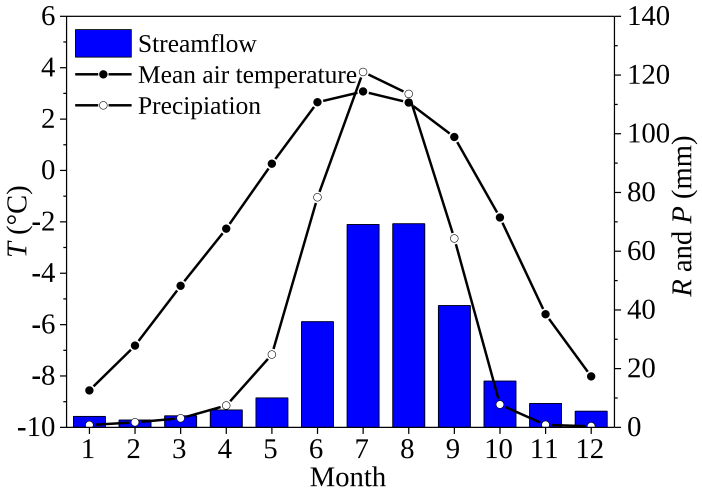

Figure 2. Seasonal variation of streamflow (*R*), mean air temperature (*T*), and precipitation (*P*) in the Yangbajain Catchment.

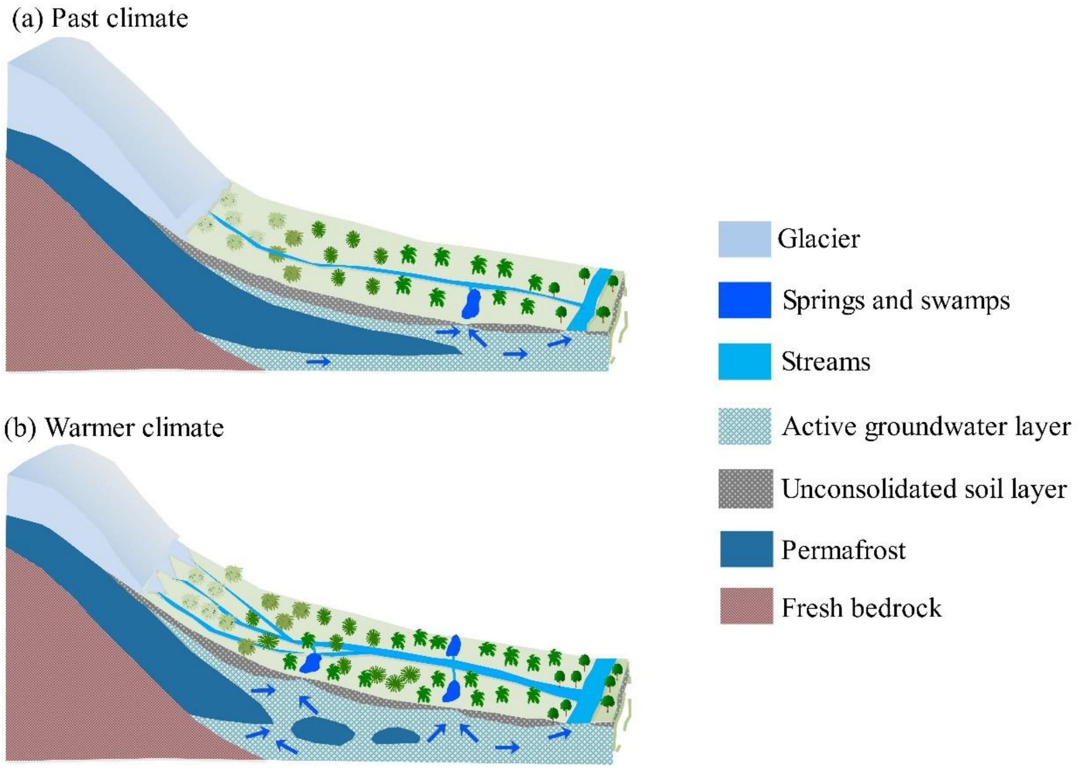

Figure 3. Diagram depicting surface flow and groundwater flow due to glacier melt and permafrost thawing under (a) past climate and (b) warmer climate.

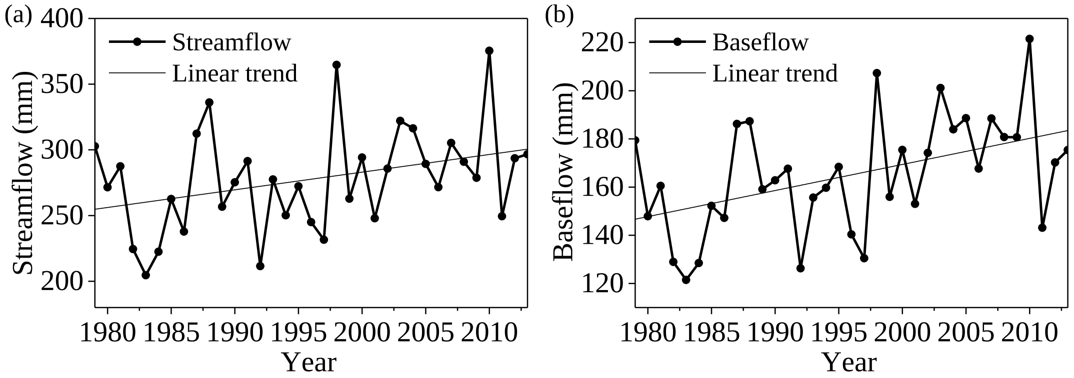

Figure 4. Variations of annual (a) streamflow and (b) baseflow from 1979 to 2013.

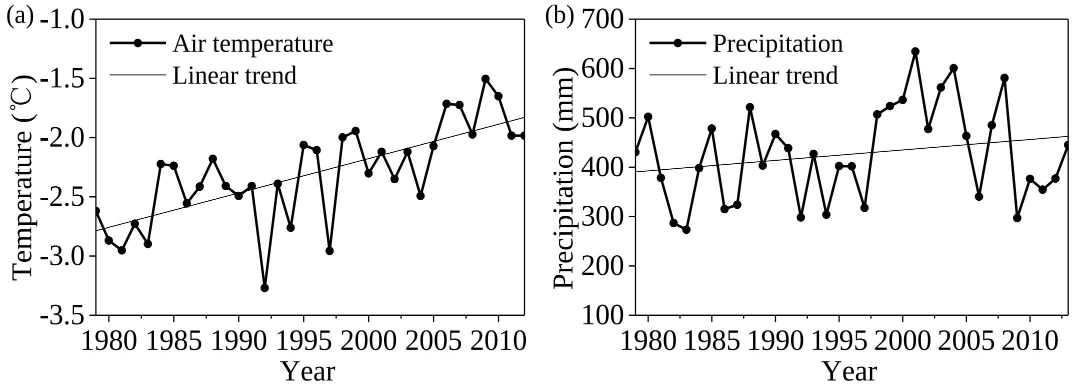

Figure 5. Variations of annual (a) mean air temperature and (b) precipitation from 1979 to 2013.

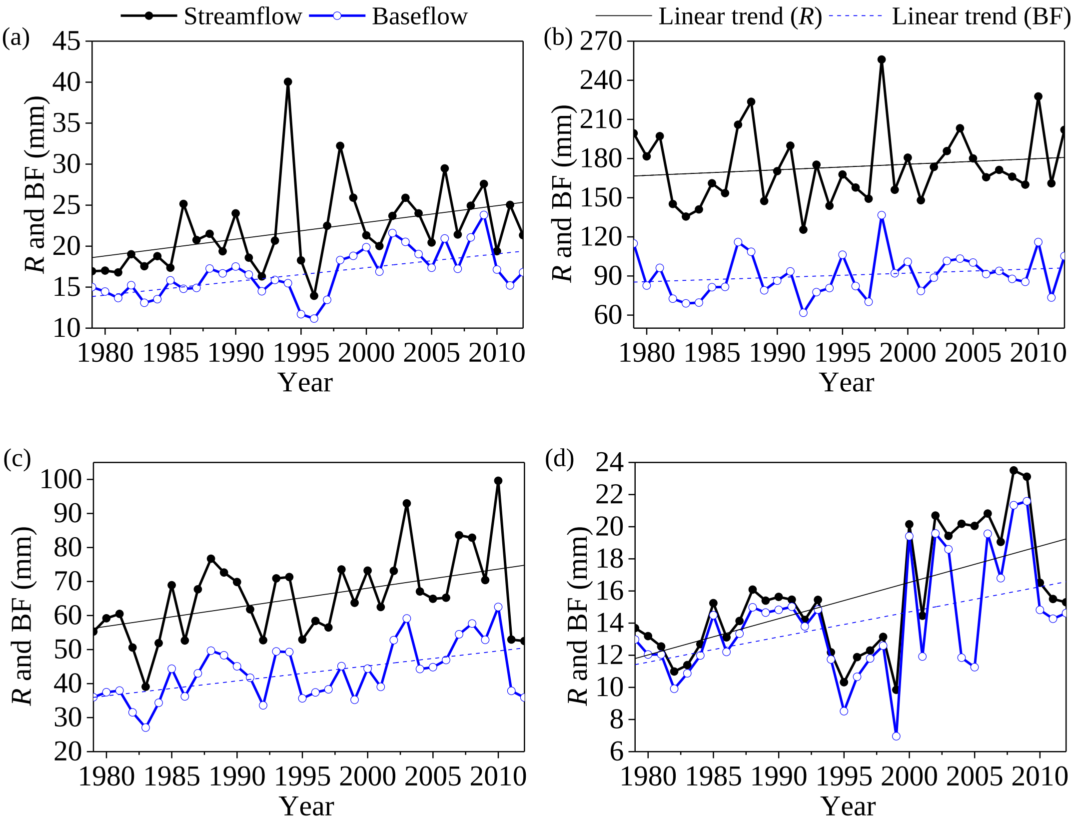

Figure 6. Variations of seasonal streamflow and baseflow in (a) spring, (b) summer, (c) autumn, and (d) winter from 1979 to 2013.

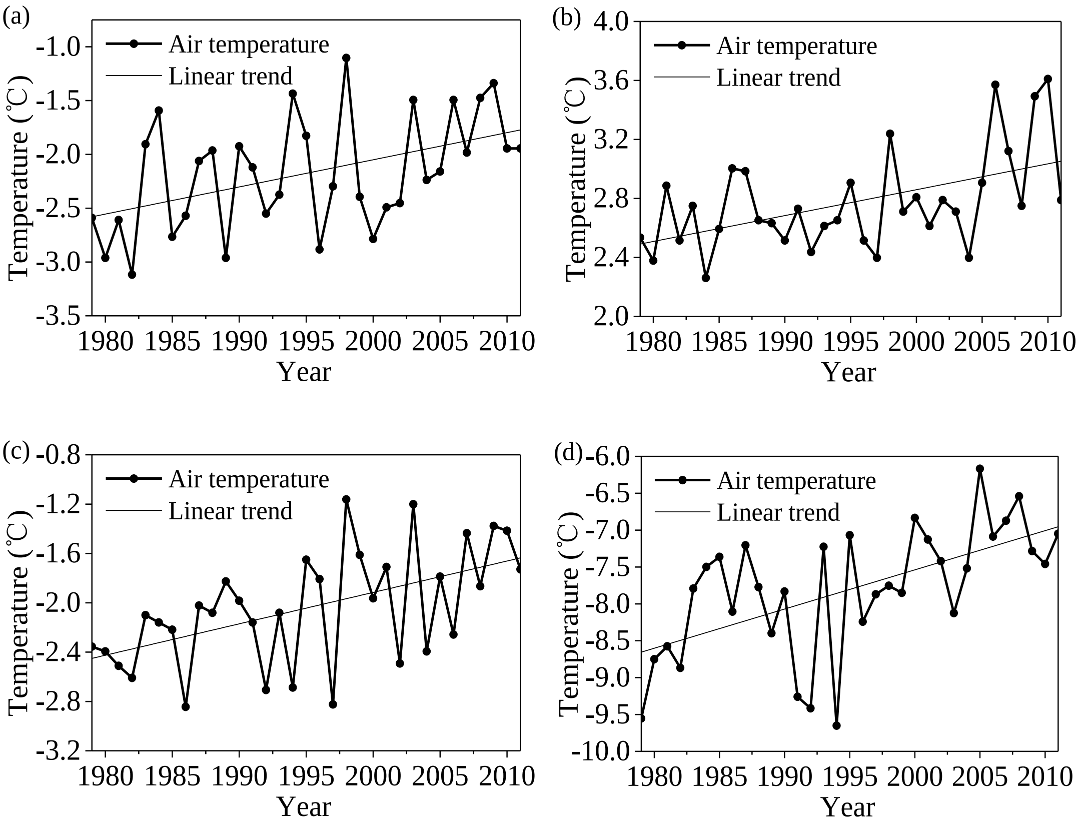

Figure 7. Variations of seasonal mean air temperature in (a) spring, (b) summer, (c) autumn, and (d) winter from 1979 to 2013.

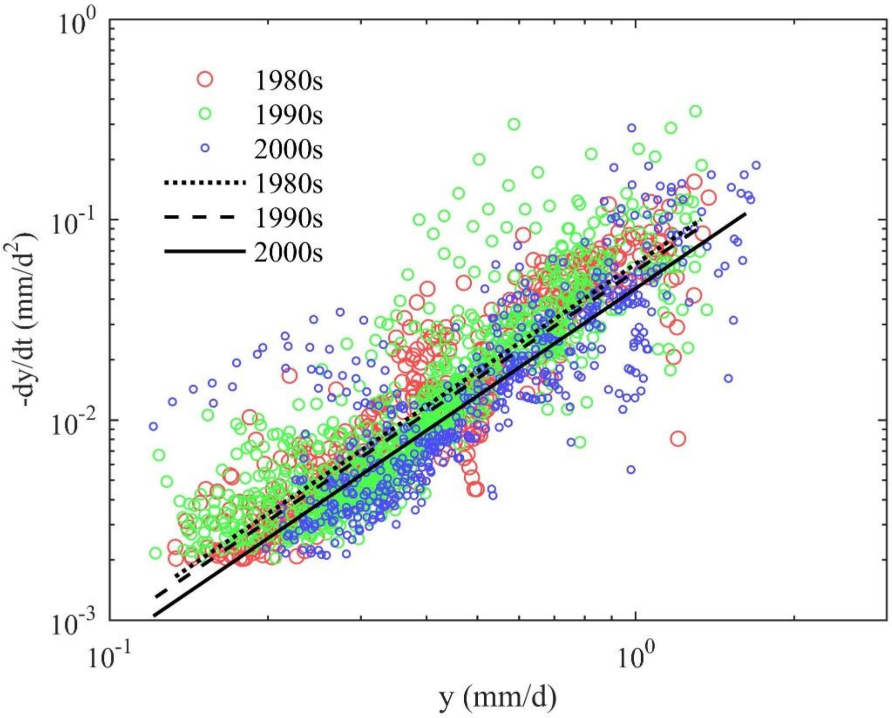

Figure 8. Recession data points of -*dy*/*dt* versus *y* and fitted recession curves by decades in log-log space. The black point line, dotted line, and solid line represent recession curves in the 1980s, 1990s, and 2000s, respectively.

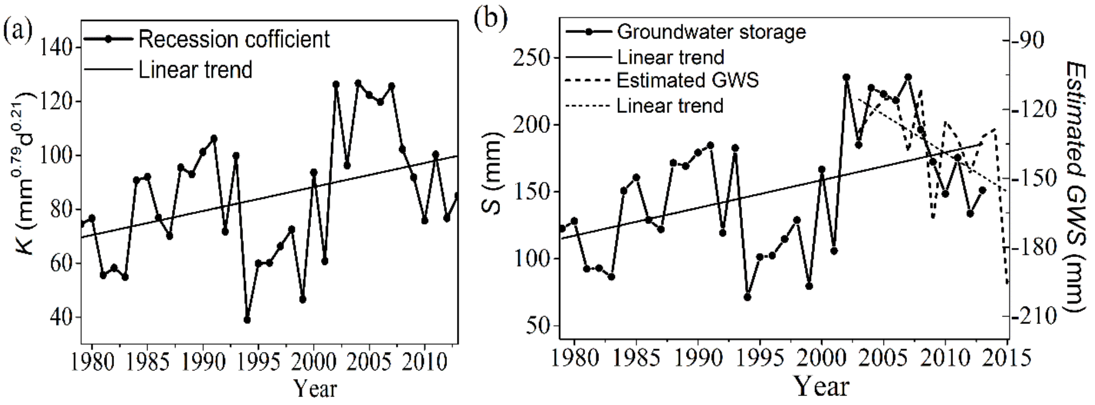

Figure 9. Variations of (a) the recession coefficient *K* and (b) the estimated groundwater storage *S* from 1979 to 2013 and the estimated groundwater storage change from 2003 to 2015 by GRACE data.

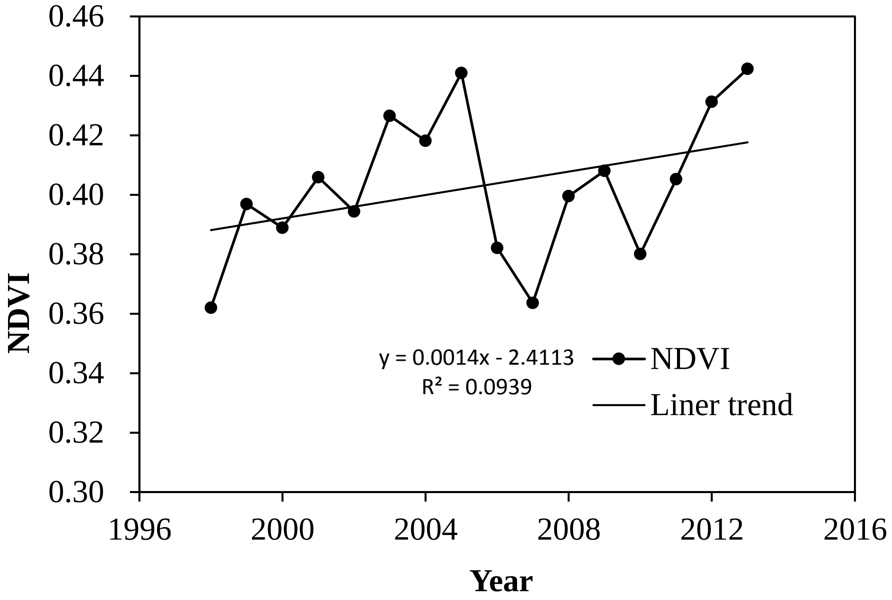

Figure 10. Variations of annual NDVI from 1998 to 2013 in the catchment.

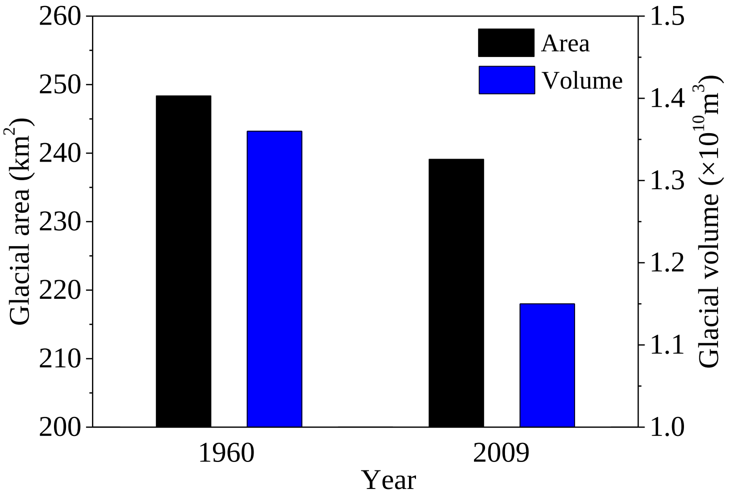

Figure 11. The total area and volume of glaciers in the Yangbajain Catchment in 1960 and 2009.