Response to the anonymous reviewer 2# (RC2)

The authors investigated streamflow changes and active groundwater storage in response to climate warming in a headwater catchment called Yangbajain in the Lhasa River basin on the Tibetan Plateau. The Mann-Kendall test was applied to detect trends of time series. An existing algorithm was adopted to do baseflow separation. The recession flow analysis method was used to determine active groundwater storage. The authors found out that the increase in streamflow is mainly due to glacier meltwater. The increase of annual baseflow is the main cause of the increase in total streamflow. The manuscript is well written and easy to follow. However, the originality of the study may be weak. The authors used existing methods to analyze data obtained from various agencies. In addition, there are some severe problems in the current manuscript. These problems are list below.

Response: Good comments and they are valuable and very helpful for revising and improving our paper. In fact, it has always been an important issue to find a linkage between the natural process complexity and the process simplicity for model conceptualization (Sivapalan, 2003). As indicated by Sivapalan (2003), it is widely accepted to infer model structures and conceptualization using available data (e.g., rainfall and runoff).

Here in this study, we use relatively simple quantitative models due to the limited data in the hydrological observations of the Tibetan Plateau. For example, the recession flow analysis and theory is proposed by Brutsaert and Nieber (1977) with physical considerations based on hydraulic groundwater theory. It can theoretically reflect the changes in subsurface storage for indirect detection of permafrost change at the catchment scale (Brutsaert, 2005; Brutsaert et al., 2008; Lyon et al., 2009). The main strength of the recession flow analysis is its ability to capture the integral effect of the process complexity present in a catchment's subsurface based on the catchment's streamflow recession characteristics with a much simpler set of equations than if all the complexity were modelled in detail (Lyon and Destouni, 2010). Future work is needed to test this method in other catchments containing permafrost to determine its general applicability across different geomorphologic and climatic settings. Moreover, it is difficult to establish hydraulic groundwater model in the Yangbajain Catchment with the limited data of hydrological observations and the complex underlying critical zone structure (e.g., glaciers, permafrost and fault zone). Thus, we adopt the recession flow analysis as a lumped model for describing the characteristics of streamflow recession and the properties of aquifers in a catchment as a whole.

The major revisions include the suitability of recession flow analysis, the feasibility of several simple combined methods in the complex catchment with limited available data, the improvement of the writing, and the thoroughly revision of the paper. We explained the reasonability of using the data from the meteorological station at Damxung. We clarified the differences between our paper and the paper by Prasch et al. (2013). We compared the coverages of frozen ground and glaciers in four sub-catchments of the Lhasa River Basin to confirm that, in the Yangbajain Catchment, the increased streamflow is mainly fed by glacier meltwater rather than frozen ground degradation (Table S1 and S2).

In the following, we provide point-by-point response to each reviewer comment (blue texts are our responses, while black texts are original comments).

Once again, we appreciate the time you put in reading our manuscript, and the comments were valuable. My co-authors and I hope that we have adequately addressed all the review comments.

Major comments:

1. This study seems like a case study. All methods used are already existed in the literature and the data were obtained from other agencies. In addition, the method of recession flow analysis may not be appropriate in the study area. As a result, the originality of the study may be weak.

Response: One of the limiting factors in the hydrological study of the TP is the availability of observations (Cuo et al., 2014). Due to the harsh natural environmental conditions, many areas on the TP are not accessible, and in situ field measurement stations are difficult to establish and maintain (Cuo et al., 2015). In the Yangbajain Catchment, the available data are relatively less and the study is relatively weak. We have been conducting field observations, such as air temperatures, soil temperatures at different altitudes and active layer depths, etc. But observation period is too short to support long-term data analysis. So we collect the existing data (climatic factors, discharge, glacier, etc) from national database and other agencies as much as possible and adopt suitable methods to reveal the mechanisms of runoff changes based on the available data.

It has always been an important issue to find a linkage between the natural process complexity and the process simplicity for model conceptualization (Sivapalan, 2003). As indicated by Sivapalan (2003), it is widely accepted to infer model structures and conceptualization using available data (e.g., rainfall and runoff). At local scales, such as mountain slopes or experimental small catchments, "surgical approach" is often adopted to acquire the storage and streamflow data. At larger scales, however, direct observations of permafrost change especially on the TP are difficult to perform and there is a need for indirect detection methods of permafrost change and its effects on runoff response at larger scales (Lyon et al., 2009). The recession flow analysis, can theoretically be used to derive the active groundwater storage volume to reflect frozen ground degradation at the catchment scale (Brutsaert and Nieber, 1977; Brutsaert, 2005; Brutsaert et al., 2008). In addition, the recession flow analysis is more like a lumped method for describing the characteristics of streamflow recession and the properties of aquifers in a catchment as a whole, which is more suitable for larger scales rather than local scales.

The recession flow analysis and theory is proposed by Brutsaert and Nieber (1977) with physical considerations based on hydraulic groundwater theory. Recession flow analysis for forecasting drought flows and investigating the groundwater flow regime in basins has over a century-long history (Hall, 1968; Tallaksen, 1995). It remains one of the few analytical tools for estimating aquifer hydraulic parameters at the field scale and beyond (Rupp and Selker, 2006). The main strength of the recession flow analysis is its ability to capture the integral effect of the process complexity present in a catchment's subsurface on the catchment's streamflow recession characteristics with a much simpler set of equations than if all the complexity were modelled in detail (Lyon and Destouni, 2010). For example, permafrost thawing is a complex and variable process. As such, a few local observations of permafrost and permafrost thawing may not be able to capture accurately the overall catchment-scale changes (Lyon and Destouni, 2010). Recession flow analysis provides an elegant methodology for reflecting catchment-scale permafrost changes over time (Lyon et al., 2009).

Many previous studies show that the recession flow analysis can be appropriated at the catchment scale with widespread permafrost (Lyon et al., 2009; Lyon and Destouni, 2010; Sjöberg et al., 2013; Lin and Yeh., 2017). Lyon et al. (2009) used recession flow analysis based on a long-term streamflow record to estimate permafrost thawing at an average rate of about 0.9 cm/yr during the past 90 years in the sub-arctic Abiskojokken Catchment of northern Sweden. Lyon and Destouni (2010) tested the ability of recession flow analysis to reflect thawing of permafrost at the catchment scale for the well-studied Yukon River Basin covering large portions of Alaska, USA and parts of Canada, which the changes in the recession flow properties detected in the Yukon River Basin agree well with observations of permafrost thawing across central Alaska. Sjöberg et al. (2013) illuminated the potential for recession flow analysis based on hydrologic observations to monitor changes in catchment scale permafrost. Further, it opens the door for research to isolate the mechanisms behind the different trends observed and to gauge their ability to reflect actual permafrost conditions at the catchment scale. Lin and Yeh. (2017) adopted recession flow analysis by assuming linearized outflow from aquifers into streams to estimate groundwater storage in northern Taiwan. On the basis of Lyon et al. (2009) and Lin and Yeh. (2017), we further develop this approach by assuming nonlinear outflow and find the increase of groundwater storage in autumn and early winter. This conclusion has been validated by the GRACE satellites to assess total groundwater storage changes at the catchment scale (See response the specific comments 3 to the anonymous reviewer 1#).

Even so, we certainly hope that we get more data to do in-depth analysis at local scale in the future.

2. The authors used very simple methods to analyze the complicated system of the Yangbajain catchment. The results are hence questionable.

Response: A very good comment. Under natural conditions, the hydrological process complexity underlying catchment responses and the complex structures and properties of catchment aquifers are often characterized by strong spatial-temporal distribution and vertical zoning characteristics especially in cold alpine catchments (Guan et al., 1984). In fact, it has always been an important issue to find a linkage between the natural process complexity and the process simplicity for model conceptualization (Sivapalan, 2003). As indicated by Sivapalan (2003), it is widely accepted to infer model structures and conceptualization using available data (e.g., rainfall and runoff).

In fact, it is limited for field hydrological observations in most cold-alpine catchments. For example, there are only 40 hydrological stations (discharge, Precipitation) in the whole Tibet Autonomous Region. That's how it requires us to use the limited available data and select feasible methods for revealing the physical mechanism of catchment. The method of recession flow analysis can be able to estimate groundwater storage and capture accurately the overall catchment-scale permafrost changes only based on a long-term streamflow record (Lyon et al., 2009; Lyon and Destouni, 2010; Sjöberg et al., 2013).

3. The meteorological station seems to be a bit too far away from the Yangbajain station. The authors should explain why use the data from the meteorological station are reasonable.

Response: There are only three national meteorological stations in the Lhasa River Basin

(Damxung Station, Lhasa Station and Medro Gongkar Station). The monthly meteorological data at the Damxung station (4,289 m), which is about 69.2 km to Yangbajain station (Figure S1). We adopted the method of meteorological data extrapolation based on the limited meteorological data. Moreover, the method of meteorological data extrapolation by assuming a linear lapse rate has been successfully used in the Yangbajain Catchment by Prasch et al. (2013).

The specific steps of meteorological data extrapolation are as follows: according to the surface elevation zs (m) of the Damxung station and every grid cell surface elevation zgc (m) of the Yangbajain catchment with cell size of 1km×1km, the every grid cell air temperature Tgc (°C) in the catchment is determined by extrapolating the air temperature Ts (°C) of the Damxung station, assuming a linear lapse rate *r* (°C/100 m) by Equation. (S1)

$$\mathrm{Tgc} = \mathrm{Ts} - \gamma(\mathrm{zgc} - \mathrm{zs}) \qquad \text{(S1)}$$

In this study, the mean monthly lapse rate is set to 0.44 °C/100 m with elevation below 4,965 m and 0.78 °C/100 m with elevation above 4,965 m in the catchment (Wang et al., 2015). The air temperature *T* (°C) over the entire area is the mean grid cell air temperature Tgc (°C) in the catchment.

4. For the equations in the manuscript, if the equation is not derived by the authors, then reference(s) should be added.

Response: Thanks for your nice suggestions. We added the reference(s) for the equations. For examples, the revised sentences are follows as

"Mann (1945) and Kendall (1975) have documented that when $n \geq 8$, the mean of s is zero, the variance of s is proposed by the equation (3)",

"Substitution of equation (8) in equation (9) yields (Brutsaert and Nieber, 1977)" and "The parameters of K and m in equation (8) can be expressed by a and b, where $K=1/[a(2-b)]$ and $m=2-b$ (Gao et al., 2017)."

5. In Line 249, the authors stated that "during a period without precipitation and evapotranspiration...". Is this assumption reasonable? A period without precipitation may be reasonable but without evapotranspiration is not. The authors did not add references here or provide an explanation.

Response: Sorry for the misleading expression in the manuscript. Actually, we mean that evapotranspiration is weak and can be neglected during autumn and winter. And we added the references. In our paper, "the active groundwater storage" is defined as the deep storage that controls streamflow dynamics assuming that streamflow during rainless periods is a function of catchment storage drainage (see Mobile storage also in Staudinger et al., 2017). Since October, the monthly mean air temperature is below 0°C (Figure S1), evaporation is weak and the vegetation is dead especially in winter (Figure S2a). The reference evapotranspiration is simply assumed to be 0 mm when the monthly air temperature is less than or equal to 0°C (Gao et al., 2007). During autumn and winter, seasonally frozen soil in the catchment (Figure S2b) servers as an impermeable barrier to the deep evaporation, under which evaporation can be ignored.

The revised sentences are followed as "During a period when precipitation and evaporation can be ignored, 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)."

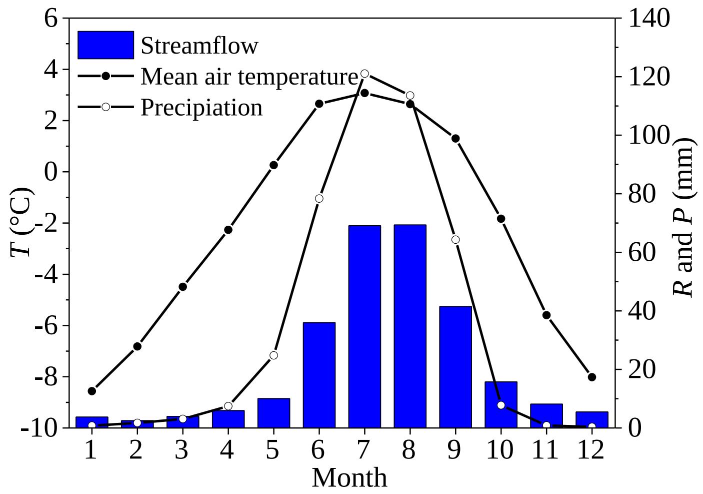

Figure S1. Seasonal variation of streamflow (*R*), mean air temperature (*T*), and precipitation (*P*) in the Yangbajain Catchment.

(a) vegeration

(b) soil

Figure S2. The landscape in autumn and winter in the Yangbajain Catchment (Photographed in winter of 2018).

6. The authors stated that the conclusion on streamflow increase (Lines 291-293) is in consistence with Prasch et al. (2013). The manuscript by the authors seems similar to Prasch et al. (2013). Please clarify the differences between the manuscript and the paper by Prasch et al. (2013).

Response: Prasch et al. (2013) present a model-based analysis to assess the changes of river runoff and ice-melt contribution to river runoff under past and future climatic conditions for the Lhasa River Basin, which focus on how the river runoff changes in the past and future.

We use available data based on several combined methods not only to analysis the changes of streamflow and the two streamflow components (base flow and quick flow) and they are only the results of climate changes. But also we hope to explore how the streamflow as well as the base flow have been changed under the warming climate.

The interesting findings include that: (1) we found the increase of streamflow is attributed to the accelerated glacier retreat due to increased air temperature; (2) Moreover, through recession flow analysis, the increase of active groundwater storage in autumn and early winter can explain why baseflow volume increases.

Minor comments:

1. The authors used "runoff" and "streamflow" simultaneously in the manuscript. Are they means the same thing?

Response: The "runoff" and "streamflow" means the same thing. It is more suitable to say streamflow in the paper. All “runoff” have been replaced by “streamflow” in lines and figures.

2. Lines 23-24: Delete this sentence. Such kind of information can be put into the "Study area" section.

Response: We deleted the sentence “The catchment is characterized by… ”.

3. Line 38: What is the "mm0.79d-0.21" mean?

Response: Sorry for the error unit in the manuscript. It should be [$mm^{0.79}d^{0.21}$]. This is the unit of recession coefficient *K*. We assume nonlinearized outflow from aquifers into streams (i.e. $b \neq 1$). The fitted slope *b* is equal to 1.79 through the non-linear least square fit of equation 10 for all data points of $-dy/dt$ versus *y* in log-log space during the period 1979-2013. The parameters of *K* and *m* in equation 8 can be expressed by *a* and *b*, where $K=1/[a(2-b)]$ and $m=2-b$. The parameter *m* is equal to 0.21. The units of change in streamflow ($-dy/dt$) and streamflow (*y*) are [mm/d^2] and [mm/d]. According to the empirical power-law form $-\frac{dy}{dt} = ay^b$, the unit of recession intercept *a* is [$mm^{-0.79}d^{-0.21}$]. According to $K=1/[a(2-b)]$,the unit of recession coefficient *K* is [$mm^{0.79}d^{0.21}$].

4. Line 216: Is this equation belongs to the MK test or derived by the authors for this study specifically? Why the number on the denominator is 18?

Response: This equation belongs to the MK test. Mann (1945) and Kendall (1975) have documented that when $n \geq 8$, the statistic *S* is approximately normally distributed with the mean and the variance as follows:

$$E(S) = 0$$

$$\mathrm{Var}(S) = \frac{n(n-1)(2n+5) - \sum_t t(t-1)(2t+5)}{18}$$

where *n* is the sequence length, *t* is the extent of any given tie and represents the sum over all ties.

Detailed details of the process can be found in the references (Mann, 1945; Kendall, 1975).

5. Line 212: This is not a new paragraph.
Response: It was corrected accordingly. We deleted the blank space before the paragraph.

6. Line 220: This is not a new paragraph and "When" should be "when".
Response: It was corrected accordingly. We deleted the blank space before the paragraph.

7. Lines 234, 244, 255: This is not a new paragraph.
Response: It was corrected accordingly. We deleted the blank space before the paragraph.

8. Line 238: The authors stated that the recession flow analysis is widely used, however, only one reference was cited in Line 239. Add more references here.
Response: It was corrected accordingly. We added more references in this sentence as "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)."

9. Line 267: Why a threshold of 0.02 mm/day? Is there any physical background or any derivations of this value?
Response: The critical precision threshold Δycrit of 0.02 mm/day is used to correct the low value of streamflow data. If the critical precision threshold Δycrit is not added, a large number of low value of streamflow data with observation errors would be contained. Thus, according to plots of -dQ/dt versus Q in log-log space in the Yangbajain Catchment, a threshold Δycrit is selected subjectively to eliminate the impact of low value of streamflow data. The magnitude of this value has little influence on the result of recession flow analysis.

10. Lines 291-293: The authors attributed the increase in streamflow to accelerated glacier retreat. Is there any contribution of permafrost degradation in the area due to increased air temperature?
Response: 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 Lhasa, Pangdo and Tangga 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) (Figure S3, Table S1).

The MK test showed that, in all the four catchments, the annual mean air temperature had significant increases at the 1% significance level (Figure S4) while the annual precipitation showed non-significant trends (Table S2). The annual streamflow of the Lhasa, Pangdo and Tangga Catchments all had non-significant trends, while the annual streamflow of Yangbajain Catchment showed an increasing trend at the 5% significance level with a mean rate of about 12.30 mm/10a during the period (Figure S5).

Ye et al. (1999) also 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 glacier meltwater rather than frozen ground degradation.

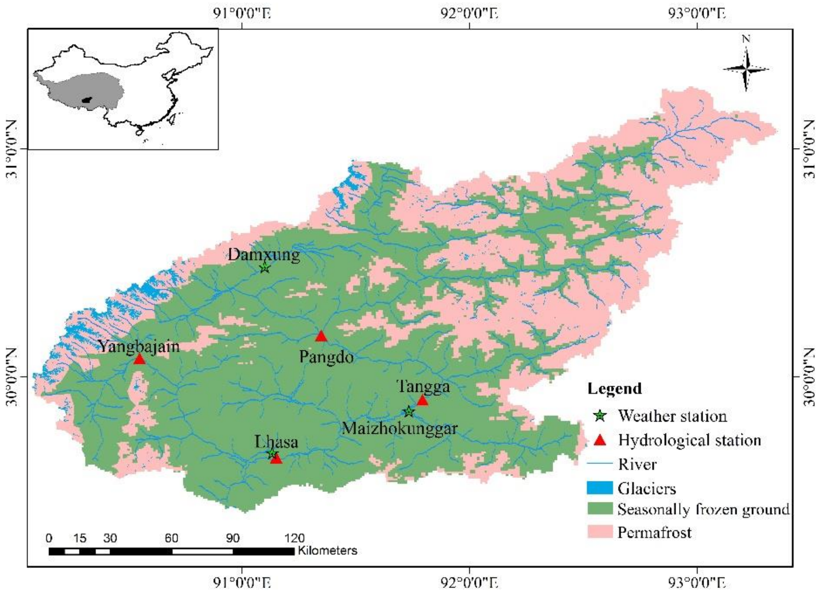

Figure S3. The distribution of glaciers and frozen ground in the Lhasa River Basin.

Table S1. The coverage of glaciers and frozen ground in four sub-catchments of the Lhasa River Basin

Stations	Area (km^2)	Coverage (%)		
		Glaciers	Permafrost	Seasonally frozen ground
Lhasa	26233	1.3	37	63
Pangdo	16425	2.1	50	50
Tangga	20152	1.7	47	53
Yangbajain	2645	12.0	36	64

Table S2. 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

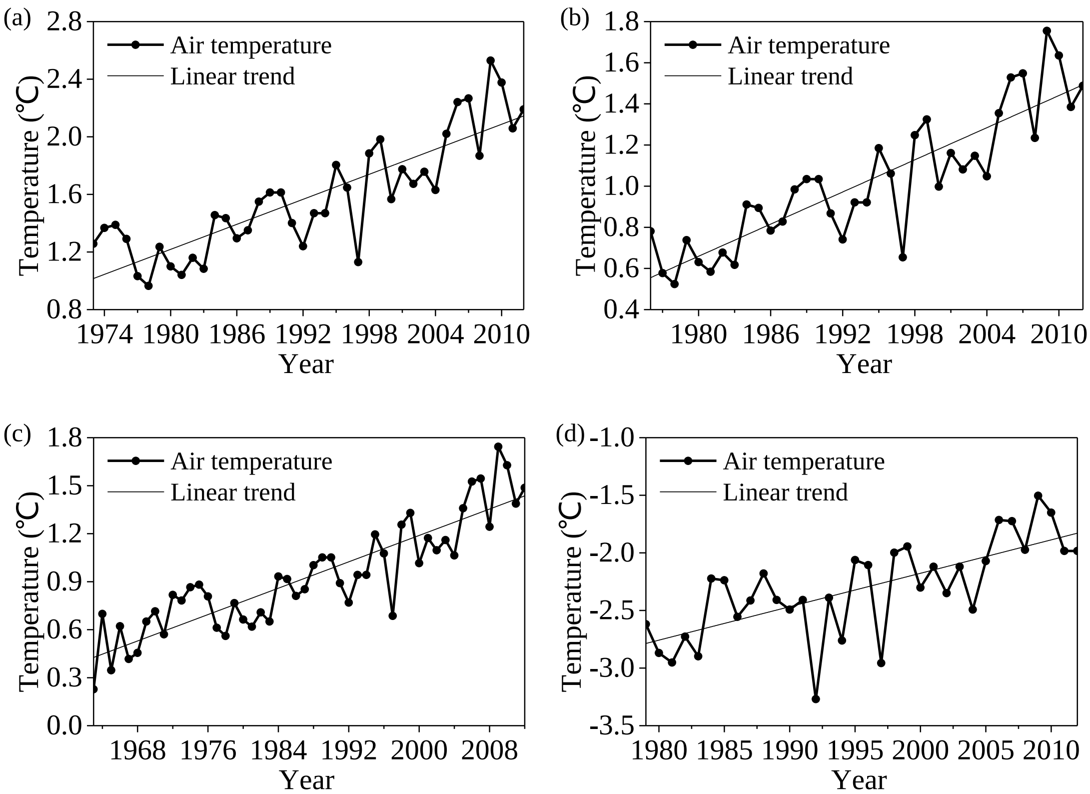

Figure S4. Variations of annual mean air temperature in four catchments of the Lhasa River Basin (a: Lhasa; b: Pangdo; c: Tangga; d: Yangbajain).

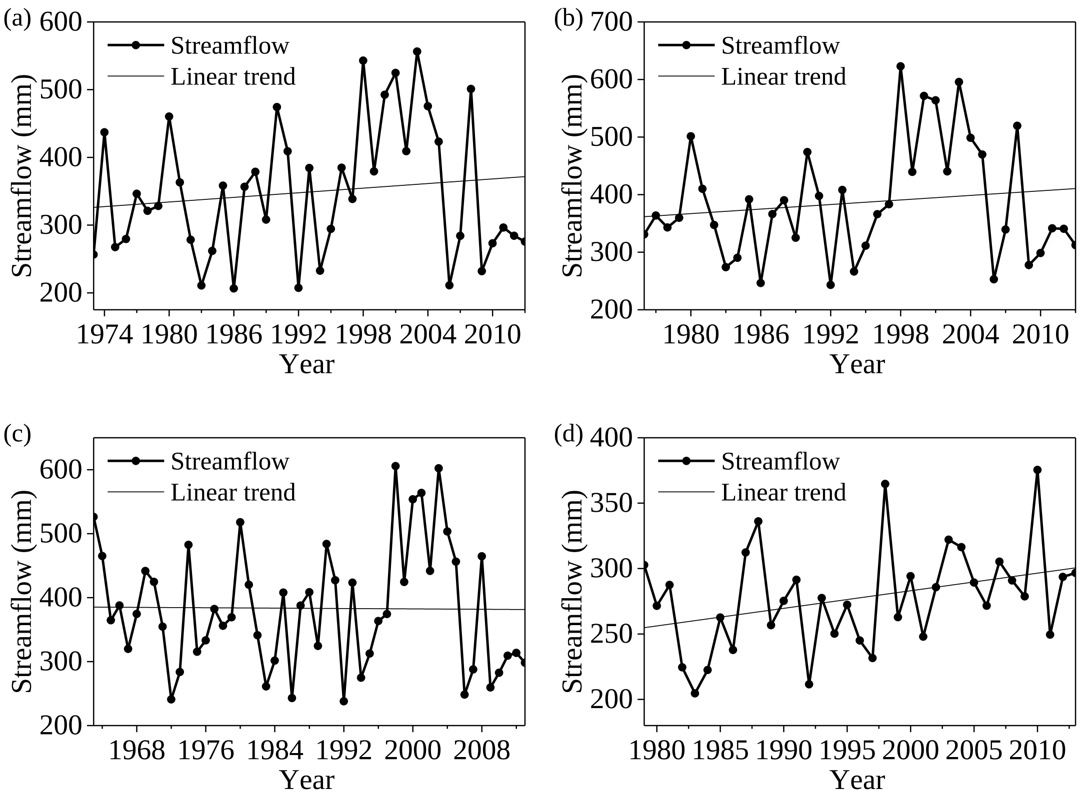

Figure S5. Variations of annual streamflow in four catchments of the Lhasa River Basin (a: Lhasa; b: Pangdo; c: Tangga; d: Yangbajain).

11. Lines 358-359: Same to Line 38, what are these units mean?

Response: See the response for Minor comments 3.

References:

Brutsaert, W., and Nieber, J. L.: Regionalized drought flow hydrographs from a mature glaciated plateau, Water Resources Research, 13(3), 637-643, 1977.

Brutsaert, W.: Hydrology: An Introduction. Cambridge University Press, New York, USA, 2005.

Brutsaert, W.: Long-term groundwater storage trends estimated from streamflow records: Climatic perspective, Water Resources Research, 44(2), 114-125, doi:10.1029/2007WR006518, 2008.

Cuo, L., Zhang, Y. X., Zhu, F. X., and Liang, L. Q.: Characteristics and changes of streamflow on the Tibetan Plateau: A review, Journal of Hydrology Regional Studies, 2, 49-68, doi:10.1016/j.ejrh.2014.08.004, 2014.

Cuo, L., Zhang, Y., Bohn, T.J., et al.: Frozen soil degradation and its effects on surface hydrology in the northern Tibetan Plateau, Journal of Geophysical Research: Atmospheres, 120(16), 8276-8298, 2015.

Gao, M., Chen, X., Liu, J., Zhang, Z., and Cheng, Q.: Using two parallel linear reservoirs to express multiple relations of power-law recession curves, Journal of Hydrologic Engineering, 04017013, doi:10.1061/(ASCE)HE.1943-5584.0001518, 2017.

Gao, G., D. Chen, C. Y. Xu, and E. Simelton.: Trend of estimated actual evapotranspiration over China during 1960–2002, J. Geophys. Res., 112, D11120, doi:10.1029/2006JD008010, 2007.

Guan, Z., Chen, C., and Ou, Y.: Rivers and Lakes in Tibet, Beijing, Science Press, pp238, 1984 (In Chinese).

Hall, F. R.: Base-flow recessions: A review, Water Resour. Res., 4, 973-983, 1968.

Kendall, M. G.: Rank Correlation Methods, 4th ed, Charles Griffin, London, pp. 196, 1975.

Lin, K. T., and Yeh, H. F.: Baseflow recession characterization and groundwater storage trends in northern Taiwan, Hydrology Research, 48(6), 1745-1756, 2017.

Li, S. and Cheng, G.: Map of Frozen Ground on Qinghai-Xizang Plateau, Gansu Culture Press, Lanzhou, 1996.

Lyon, S. W., and Destouni, G.: Changes in catchment-scale recession flow properties in response to permafrost thawing in the Yukon River basin, International Journal of Climatology, 30(14), 2138-2145, doi:10.1002/joc.1993, 2010.

Lyon, S. W., Destouni, G., Giesler, R., Humborg, C., Mörth, M., and Seibert, J., et al.: Estimation of permafrost thawing rates in a sub-arctic catchment using recession flow analysis, Hydrology and Earth System Sciences Discussions, 13(5), 595-604, 2009.

Mann, H.: Non-parametric test against trend, Econometrica, 13, 245-259, 1945.

Mi, D. S., Xie, Z. C., and Luo, X. R.: Glacier Inventory of China (volume XI: Ganga River drainage basin and volume XII: Indus River drainage basin). Xi’an Cartographic Publishing House, Xi’an, pp. 292-317 (In Chinese), 2002.

Prasch, M., Mauser, W., and Weber, M.: Quantifying present and future glacier melt-water contribution to runoff in a central Himalayan river basin, Cryosphere, 7(3), 889-904, doi:10.5194/tc-7-889-2013, 2013.

Rupp, D. E., Selker, J. S.: On the use of the Boussinesq equation for interpreting recession

hydrographs from sloping aquifers, Water Resources Research, 42(12):1675-1679, 2006.
Sivapalan, M.: Process complexity at hillslope scale, process simplicity at the watershed scale: is there a connection? Hydrological Processes, 17(5), 2010.
Sjöberg, Y., Frampton, A., and Lyon, S. W.: Using streamflow characteristics to explore permafrost thawing in northern Swedish catchments, Hydrogeology Journal, 21, 121-131, 2013.
Staudinger, M., Stoelzle, M., Seeger, S., Seibert, J., Weiler, M., and Stahl, K.: Catchment water storage variation with elevation, Hydrological Processes, 31(11), doi:10.1002/hyp.11158, 2017.
Tallaksen, L. M.: A review of baseflow recession analysis, J. Hydrol., 165, 349-370, 1995.
Wang, S., Liu, S. X., Mo, X. G., Peng, B., Qiu, J. X., Li, M. X., Liu, C. M., Wang, Z. G., and Bauer-Gottwein, P.: Evaluation of remotely sensed precipitation and its performance for streamflow simulations in basins of the southeast Tibetan Plateau, Journal of Hydrometeorology, 16(6), 342-354, doi:10.1175/JHM-D-14-0166.1, 2015.
Ye, B. S., Yang, D. Q., Zhang, Z. L., and Kane, D. L.: Variation of hydrological regime with permafrost coverage over Lena basin in Siberia, Journal of Geophysical Research Atmospheres, 114, ZD07102, doi: 10.1029/2008JD010537, 2009.
Zou, D., Zhao, L., Sheng, Y., and Chen, J., et al.: A new map of permafrost distribution on the Tibetan Plateau, The Cryosphere, 11, 2527-2542, doi:10.5194/tc-11-2527-2017, 2017.