Response to Referee #1

First, we would like to give our sincere thanks to the anonymous reviewer for providing valuable suggestions to improve our manuscript. We have responded to the questions as follows:

1). After read the title with great interest about the "temperature-threshold", I found it is essential as a surface soil freeze fraction as the authors described in eq. (2). I suggest that the authors use surface soil "freeze-fraction threshold" much better than the "temperature -threshold".

Here, the “soil temperature-threshold” refers to the soil temperature at which the surface runoff generation and suprapermafrost groundwater discharge would obviously change. We agree with the referee’s suggestion and will use surface soil “freeze –fraction threshold” instead of “temperature-threshold”.

2). p. 5860, lines 18-25: there is a lot of information here, the authors do not provide any references, I am not sure this is the authors’ own work in this paper or the others’ work.

In this study watershed, the meteorological data and vegetation information were from our own observations. We revised this section and provided some references.

3). p. 5961, lines 3-18: here the authors stated that they drilled boreholes up to 1.6 m to measure soil moisture content and soil temperatures. It is not clear how the authors place the FDR in the borehole, how soil moisture content was measured by using FDR in a borehole. It is critical to know how exactly this worked. Borehole temperature measurements are common but borehole soil moisture measurements are rare.

A frequency domain reflectometer (FDR) with a calibrated soil moisture sensor is a common and effective technology for monitoring soil moisture. After the 1.6-m deep boreholes were drilled, the sensor was installed horizontally in the soil at different layer depths. Then, the boreholes were filled and consolidated by using the original soil. Generally, it takes two or three months to recover the FDR after disturbing the soil. Then, the data from the FDR can be used for monitoring natural soil moisture at different layer depths.

4). p. 5962, line18: "... the thawed active layer...", this concept is wrong. The active layer is referred to the maximum thaw depth over permafrost in autumn, so what is the thawed active layer? I guess the authors mean for thaw depth at a given time. If so, say so.

Yes, we are referring to the thaw depth at a given time. According to the referee’s suggestion, we revised this incorrect statement.

5). p. 5964, line 13: what is "... the deep active soil temperature."?

This statement is unclear. We revised this term as follows: T_{SD} is the soil temperature at the lower bound of the active layer or near the bottom of the suprapermafrost groundwater aquifer.

6). The section 1 should be rewritten, especially the second paragraph, the authors just copy from the citations from the paper of Wright (2009). The following lists some sentences. They are as same as the sentences in Wright's paper but changing the authors of citation. a. :, the function of seasonal ice in the active layer is coped from the sentence in Writht (1999) b. The drainage of precipitation and melt water inputs primarily formed the thawed water saturated layer perched above the frost table. c. The depth and distribution of the frost table within the active layer controls the position of the water-saturated zone, which descends through the soil profile during soil thawing. d. On the slope scale, uneven or progressive soil thawing on frozen slopes heavily affects the mode and rate of water flow downslope and the flow concentrations in rivers (Quinton et al., 2004; Wright et al., 2009; Woo, 2012).

We would like to apologize to Wright for these similar statements, which were partially due to our difficulty with English expressions. In the revised manuscript, we rewrote the second paragraph of section 1 as follows:

Permafrost, defined as wherever the ground remains at or below the freezing point of water 0 ℃ (32 ℉) for at least two consecutive years (Brown and. Kupsch, 1974; Van Everdingen, 1998), exhibits two hydrological functions: (1) it functions as an impermeable layer and obstructs groundwater or soil liquid water from infiltrating to deeper layers (Zhou et al., 2000; Woo and Winter, 1993) and (2) it generates a soil temperature gradient and drives soil moisture towards the frozen front (Cheng, 1983; Zhou et al., 2000). Therefore, active soil thawing and freezing changes the soil water storage capacity, the soil water infiltration capacity, and the soil water conductivity, which redistributes water in the soil profile (Woo and Winter, 1993; Quinton and Mash, 1999; Wright et al., 2009). In spring and early summer, rainfall and snow meltwater can saturate the thinly thawed soil when the frost table remains shallow. The water-saturated zone formed the surface saturation excess runoff and stored-full runoff generation processes. Generally, the topographic surface, suprapermafrost groundwater table and frost table control the suprapermafrost groundwater flow and surface flow zones (Woo, 2012). For a given topographic surface, the position of the frost table within the active layer is the dominant factor controlling the distribution of the water-saturated zone, position of suprapermafrost groundwater flow and surface flow zones (Woo, 2012; Wright et al., 2009). The release mode and rate of surface or subsurface water flow from a slope strictly depends on the thawing processes on frozen slopes (Quinton and Marsh, 1999; Wright et al., 2009). Thus, the distribution of the frost table depth controls the suprapermafrost groundwater flow, surface saturation excess runoff and stored-full runoff generation processes and is the critical factor in determining the processes of the watershed flow concentration (Quinton and Marsh, 1999; Woo, 2012). However, there is difficulty in quantifying the effects of the spatial and temporal variability of the frost table depth in terms of runoff generation. It is unclear if and how the variable contributing area concept could be used in a permafrost catchment. Consequently, the goal of the present study is to provide new scientific insights into the seasonal dynamics of runoff-contribution areas in a continual permafrost headwater catchment, to develop a method to quantify the runoff generation processes, and to identify the effects of the freeze-thawing cycle of the active soil layer on river discharge.

7). What is the seasonal dynamics of runoff-contribution areas? How the freeze thawing cycles of the active layer effect on river discharge? The authors don't answer them for their study objectives.

The results of $f(T_s')$ indicated the seasonal dynamics of saturation excess runoff generation areas. We have provided the objectives in the "Summary and Conclusions". According to the opinion of the reviewer, we revised those answers in two ways: First, we added a paragraph to clarify the effects of soil freezing on autumn runoff recession processes in more detail in Results section. Second, we revised the section of "Summary and Conclusions" to state the answers more clearly.

8). The authors refer more than 85% precipitation fall in summer. If so, why is has "no obvious relationship between precipitation and runoff"?

Based on the monitoring data from the meteorological station constructed in this study watershed, we found that more than 85% of the precipitation fell in June to September. The result of the correlative analysis shows that there are no obvious relationship between precipitation and runoff, except for summer flood runoff. There is a nearly linear relationship between summer precipitation and summer flood runoff.

We revised this expression by adding the relationship of flood runoff.

9). The description of parameters in Eq.2 and Eq.3 needs further improvements. What mean of Qs, f(TÊ ́zs), g(Tsd)?

According to the reviewer's comment, we added descriptions of the definition, function and estimating methods of $f(T_s')$, Q_s in Eq. 2 and $g(T_{SD})$, T_{SD} in Eq.3.

$f(T_s')$ is defined as the surface soil freeze-fraction threshold curve, which refers to the ratio of areas with surface soil temperature $\leq T_0$ to the total catchment area. As described above, the thawed soil layer would maintain a water-saturated condition when surface soil temperature $\leq T_0$, $f(T_s')$ is a dimensionless function, could also refer to catchment area with soil water-saturated condition. Under the soil temperature condition, snowmelt water Q_s is an important water balance factor participating in the runoff contributing area (DeBeer and Pomeroy, 2010). The snowmelt water Q_s calculated by using two approaches, one was the degree-day factor method for when there was continuous snow accumulation over the ground for at least two days with the sensor data; and the other method directly used the threshold air temperature method when there was discontinuous snow accumulation and mixed snow and rain contents (Chen et al., 2014).

$g(T_{SD})$,the suprapermafrost groundwater discharge varied with T_{SD}, is determined by using the regression relationship between the autumn runoff recession rate and T_{SD} (Lyon et al., 2009; 2010). T_{SD} is the soil temperature at near the lower bound of active layer or near the bottom of the suprapermafrost groundwater aquifer.

10). How could the authors justify assuming the saturation excess runoff generation is the dominant type of runoff generation during the spring and summer season. In fact, the infiltration excess runoff is common in the snowmelt period when frozen soils limit infiltration. As ground thaw begins, a thin saturated soil layer is formed. The base of this thawed layer is the impervious frost table which restricts percolation such that overland flow is issued from the saturated soil. Thus, in this period when frozen grounds begin to thaw, the transition from infiltration excess runoff to saturation excess runoff cannot be defined rigorously (Woo, 2012). How could explain the transition infiltration excess runoff to saturation excess runoff by the soil temperature threshold?

This is correct, and we agree with the referee’s opinion. In a permafrost watershed with larger winter snow fall and thicker snow accumulation (for example in most arctic regions), the infiltration excess runoff is common in the snowmelt period when frozen soils limit infiltration, and the transition from infiltration excess runoff to saturation excess runoff occurs when frozen grounds begin to thaw. However, in most permafrost regions of the Qinghai-Tibetan Plateau, the winter precipitation is very small (generally less than 21 mm) and the snow cover is irregular, filmy and discontinuously distributed over the ground surface (Zhou et al., 2000; Sato, 2001; Wang et al., 2010). Most snow fall occurs in the spring season, especially from April to May, when the frozen grounds begin to thaw and form the spring flood runoff. As such, there was no runoff before April and after November in the study head watershed. Therefore, the small infiltration excess runoff generated from snowmelt when frozen grounds have not begun to thaw is ignored in this study, and the saturation excess runoff generated when frozen soil starts to thaw after April is considered to be the dominant type of runoff generation in the spring season.

In general, the infiltration excess runoff occurred in the snowmelt period when frozen soils limit infiltration. This can also be explained by a soil temperature threshold because the capacity of frozen soil limiting infiltration is controlled by the surface soil temperature. The infiltration excess runoff occurred during the snowmelt period when frozen grounds have not begun to thaw because the air temperature is higher than the surface soil temperature in the spring. The infiltration excess runoff was defined as follows (Horton, 1935; Brutsaert, 2005):

$$\mathrm{R}_s = \int_{i>f_p}^{t} (i - f_p) d_t \text{ ,, or } R_s = \sum\nolimits_{i>f_p} (i - f_p)\, \Delta t$$

where R_s is the infiltration excess runoff and i, f_p are rainfall intensity and surface soil infiltration capacity, respectively. Here, i is replaced by the snowmelt water intensity, which could be calculated by the energy balance and degree-day factor method. f_p depends on the thawing degree of the frozen ground and is approximately regarded as zero when the surface soil temperature T≤0. Thus, there is a surface soil freeze fraction threshold, T_0, and the precondition of $\mathrm{i} > f_p$ if the surface soil temperature $\mathrm{T} \leq T_0$.

We would like to thank the anonymous reviewer, and we revised the section of 2.2 Analysis Approach in detail.

11). The model only modeling one month in thawing period and freeze period, respectively. It may be too short for the model's calibration and validation process.

In this study, we presented a new analytical approach in equation (2) and (3) based on the theory of the nonlinear variation curve of the water-storage capacity. This approach is used to estimate the runoff according to the water balance theory, which only has one real parametric variable, i.e., $\mathrm{g}(T_{SD})$. The observation system in the headwater catchment was constructed in July 2012, and the valid data from field observation were obtained from September 2012 to July 2015. The field observation data of one freezing season in 2012 and one thawing season in 2013 were used for constructed the model. Thus, two spring thawing season data sets from 2014 and 2015 and two autumn freezing season data sets from 2013 and 2014 could be used to test and verify the approach of the equation (2) and (3).

We revised this shortage by using all of the available data, and the daily runoff in the two spring and autumn seasons were simulated by using the new approach. Thus, there were a total of 64 values that were used for the model's calibration and validation process. The revised simulating results are shown in the new Figure 3 and 5 as follows:

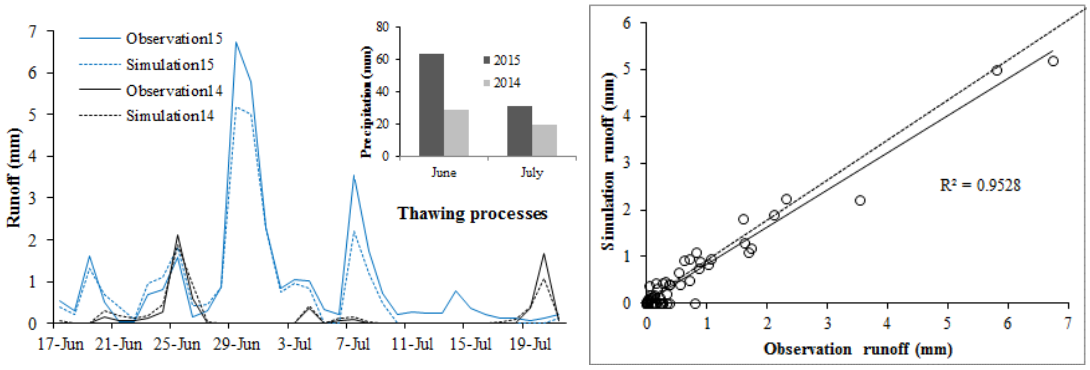


Figure 3 Modelled runoff generation compared with field observed runoff during the

spring thawing period in a permafrost catchment. The left (a) is the referred runoff hydrograph comparison, while the right (b) is the simple scatter of the statistical analysis.

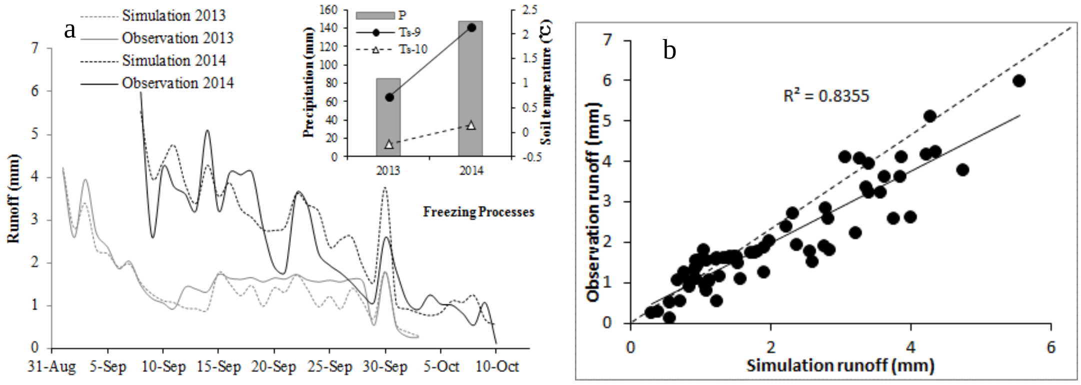


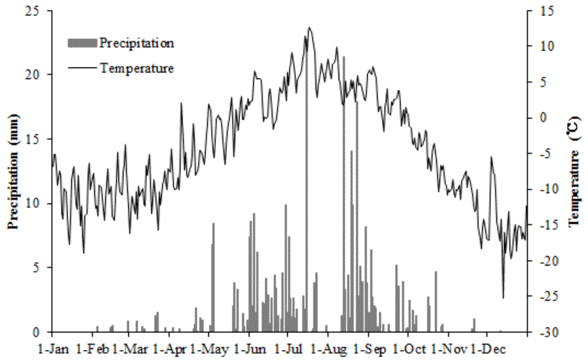
Figure 5 Modelled runoff generation compared with field observed runoff during the autumn freezing periods in a permafrost catchment. The left (a) is the referred runoff hydrograph comparison, while the right (b) is the simple scatter of the statistical analysis. The inset chart in (a) shows the mean soil temperature at the surface and at a 20-cm depth for September (Ts-9) and October (Ts-10), and precipitation is compared between 2013 and 2014.

12). P5959 line 23. The definition of permafrost should be improved. Base to the definition of permafrost by Van Everdingen (1998), it should be "wherever the ground remains at or below 0 _C for at least two consecutive years". The authors should also provide references for their definition of permafrost, etc.

We revised the definition of permafrost according to the reviewer and added two references, Brown and. Kupsch, 1974; and Van Everdingen, 1998.

13). Section 2.1 The temperature, precipitation, soil temperature and soil moisture should be showed for the thaw period and freeze period, respectively.

According to the reviewer, we added Figure 2 and a paragraph in section 2.1 to show the annual distribution of the mean daily air temperature, precipitation, soil temperature and moisture, as follows:



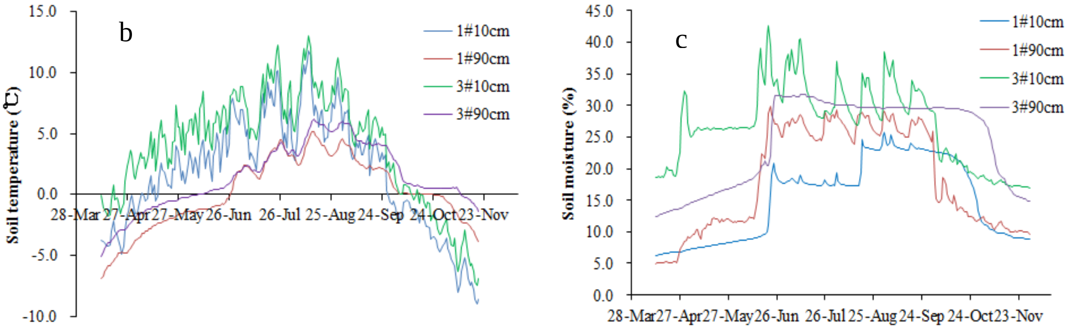


Figure 2. The daily air temperature and precipitation (a), soil temperature at a 10-cm and 90-cm depth at different elevations (b: 1# at 4930 m a.s.l., and 3# at 4847 m a.s.l.), and soil moisture dynamics at a 10-cm and 90-cm depth at different elevations (c).

14). P5960 line 25, The active layer thickness should cite references

We added a reference (Zhou et al., 2000; Wu and Zhang, 2008)

15). There is no location of boreholes in figure 1.

In Figure 1, the monitoring site is the borehole for sensors of soil temperature and moisture monitoring. We revised this unclear statement by adding a sentence to clarify the borehole position as follows:

The soil temperature and moisture monitoring sites (in each site, there was a 1.6-m deep borehole for soil temperature and moisture monitoring) in the headwater catchment are used in this study.

16). There is no table 1.

This is a mistake; there is no table 1 in the manuscript, and we deleted this statement. Table 1 in the revised file is a newly added one.

17). P5961 line 17. The runoff processes monitored and analysis need further description.

We revised this part by adding a paragraph to describe the monitoring activities more clearly, as follows:

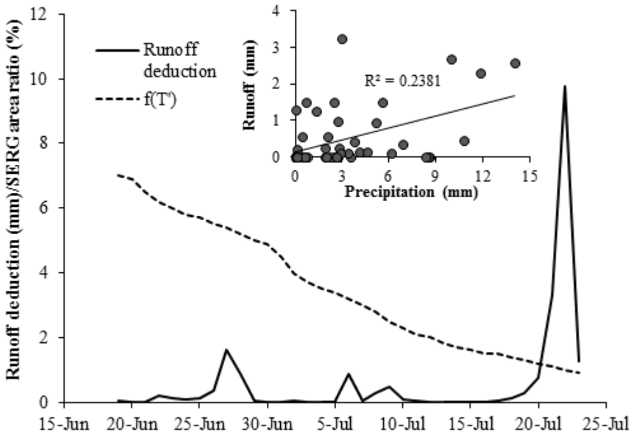
Because the river flow rate was lower than 0.05 m^3/s, the runoff was calculated by monitoring the water level (H) through the V-notch weir with following equation: $Q = 0.014H^{3/2}$(Zhan and Ye, 2000). The water level (H) was monitored once per hour by using a water level logger (U20 HOBO, Onset Computer Corporation, USA).

18). p5965 line 24. Since the snow is monitored by sensor, why do you use the air temperature method to estimate the precipitation? How do you use the snow or snow cover parameters in your model?

Because the snow cover in the study catchment was usually less than 1.0 cm, the error in the data (0.25 mm) obtained by using the monitoring sensor was relatively larger for estimating snow water. Thus, we used two methods that integrated the sensor and air temperature. The snowmelt water Q_S was calculated by using two approaches, one was the degree-day factor method for when there was continuous snow accumulation over the ground for at least two days with the sensor data; the other method directly used the threshold air temperature method when there was discontinuous snow accumulation and mixed snow and rain contents. We then used snow melt water in our model.

19). p5967 line 2-3. This is not in fig.3. How could it is significant while the P>0.15?

After reading the question, we determined that the figure was lost in the typeset PDF file of our manuscript. In the original file, Figure 3 should be the following. The inset chart identifies the insignificant relationship between precipitation and total runoff during the spring season.



20). p5967 line 14. The runoff varied in May should be presented.

Because we mainly discussed the variance of the runoff coefficient and the direct runoff from May to July in the section from line 13 to 15 in p5967 of the text, we added Table 1 to present the variance in the runoff coefficient and direct runoff in different months during the thawing season according to the opinion of reviewer.

Table 1 The runoff coefficient and direct runoff distribution in the thawing season

Month	May	June	July	August	September
Runoff coefficient	1.1 ±0.29	0.65 ±0.17	0.29 ±0.08	0.20 ±0.06	0.47 ±0.15
Direct runoff (mm)	1.8 ±0.3	9.1 ±3.1	2.4 ±0.2	6.3 ±2.3	2.7 ±0.4