Response to Review Comments

Response to the comments from the Editor

Comments: I received review comments from two reviewers, both confirm the contribution of the manuscript, and think it's could be a good paper and also would be interesting to the HESS readers. Both reviewers think the manuscript need revision, and provide specific suggestions to revise the manuscript.

After receiving the comments, I carefully read the manuscript again, and concur with the two reviewers. The manuscript may need some rearrangement as suggested by the second reviewer, and the writing need to be polished.

Response

Accepted. The comments and critiques as noted by the editor and reviewers have been fully addressed in the revised manuscript. Our specific responses to these noted comments and critiques are provided in a point-by-point reply given below. The English writing was thoroughly revised by ourselves and an English copyediting service.

Response to Reviewer #1's Comments

General Comments: This study addresses an important issue of hydrological connectivity between glaciers in high mountains and river in the low plain within the alpine headwater catchment with big elevation difference and complex hydrogeological settings. The hydraulic head, temperature, and chemical and isotopic composition of groundwater, streamflow, precipitation and glacier meltwater were monitored along altitude gradient. The work has produced a remarkably rich data set that is clearly presented by the authors. The authors interpret the data to indicate that supra- and subpermafrost aquifers, as well as stream channels and slope surfaces, play an important role in transporting glacier, snow-meltwater and precipitation from the high mountains to the plain and then to the mainstem. The authors also suggest that a decline in hydro logical connectivity between the piedmont plain aquifer and the downstream channel in cold seasons may be the mechanism maintaining streamflow (baseflow) in winter. It is worth pointing out that the authors present a logical and clearly illustrated conceptual model of hydrological connectivity in the alpine catchment by combining the above results. Given the wide distribution of this kind of headwater "mountain-plainriver" catchments in the Qinghai-Tibet Plateau and other cold regions, this conceptual model may contribute fundamentally to permafrost hydrology and can be more broadly utilized. The authors tentatively suggest that river icing and riverbank soil freezing may form a confining layer to reduce groundwater discharge from the plain to the stream, i.e., reduce the hydrological connectivity between the two pools. This is a very interesting hypothesis that can expand the existing mode for interpreting the slow release of stored groundwater during cold seasons, and it may be testable using field hydrometric measurement and numerical simulation. Overall the manuscript is well written and quite clear. I also have a few minor comments that I hope the authors to address before publication as listed in below.

Response: We thank the reviewer for carefully evaluating our manuscript and for constructive and helpful comments and suggestions. Our specific responses are given in below.

Comment 1: P2, L5: 'surface-water' should be 'surface water'.

Response: Changes have been made as suggested.

Comment 2: P2, L24 and L25: Two ';'s after 'hydrogeological' should be type errors.

Response: The type error has been corrected as suggested.

Comment 3: P3, L6: 'Heihe Basin' should be 'Heihe River Basin'.

Response: 'Heihe Basin' has been changed to 'Heihe River Basin'.

Comment 4: P3, L22: 'Qinghai-Tibet plateau' should be 'Qinghai-Tibet Plateau'.

Response: 'Qinghai-Tibet plateau' was changed to 'Qinghai-Tibet Plateau'.

Comment 5: P4, L15: Is 'the October to May cold season' a type error? 'ice covered' should be 'ice-covered'.

Response: Here we mean that the period from October to May is cold season. To avoid confusion, we have changed 'the October to May cold season' to 'the cold season (from October to May)'. 'ice covered' has also been changed to 'ice-covered' as suggested.

Comment 6: P6, L14: Citation is missing for the Gran titration method.

Response: We have added the citation for the Gran titration method as given in below.

Gran G.: Determination of the equivalent point in potentiometric titrations. Part II, Analyst, 77: 661-671, 1952.

Comment 7: P7, L27: What value does the $\delta 13C_{rech}$ take?

Response: As described in the texts (P8, L14-15 in the revised manuscript), the $\delta^{13}C_{rech}$ was taken −18‰ as suggested by Han et al. (2011) for north China.

Comment 8: P8, L22-23: This sentence is hard to understand. Please rewrite it.

Response: We have rewrote this sentence as following to make it more readable. The revised sentence reads now:

"Although the groundwater depth differed greatly between the cold and warm seasons, it was relatively stable during each of the two seasons."

Comment 9: P10, L15: Two 'respectively' should be removed.

Response: They have been deleted as suggested.

Comment 10: P11, L9-17: These results contrast with the statements in Abstract section.

Response: We have revised the abstract and make them to be consistent. In the revised abstract, we deleted the sentence "^{3}H and ^{14}C data indicated that the age of supra- and sub-permafrost groundwater, and groundwater in Quaternary aquifer of seasonal frost zone, ranges from 30-60 years."

Comment 11: P13, L9: 'in water' should be 'in water table'.

Response: Change has been made as suggested.

Comment 12: P13, L29: I don't think that the dry sediment layer at depths between 12 m and 12.5 m is related to the subpermafrost groundwater.

Response: This sentence has been deleted.

Comment 13: P13, L29-31: Citation is missing for this statement.

Response: We have added citation for this statement as shown in below.

Zhang, R., Liang, X., Jin, M., Wan, L., Yu, Q.: Fundamentals of Hydrogeology (6th Edition) (in Chinese), Geological Publishing House, Beijing, 2011.

Comment 14: P14, L24-25: Citation is missing for this statement.

Response: We have added citation for this statement as shown in below.

Clark, I. D. and Fritz, P.: Environmental Isotopes in Hydrogeology, CRC Press/Lewis Publishers, Boca Raton, Florida, USA, 1997.

Response to Reviewer #2's Comments

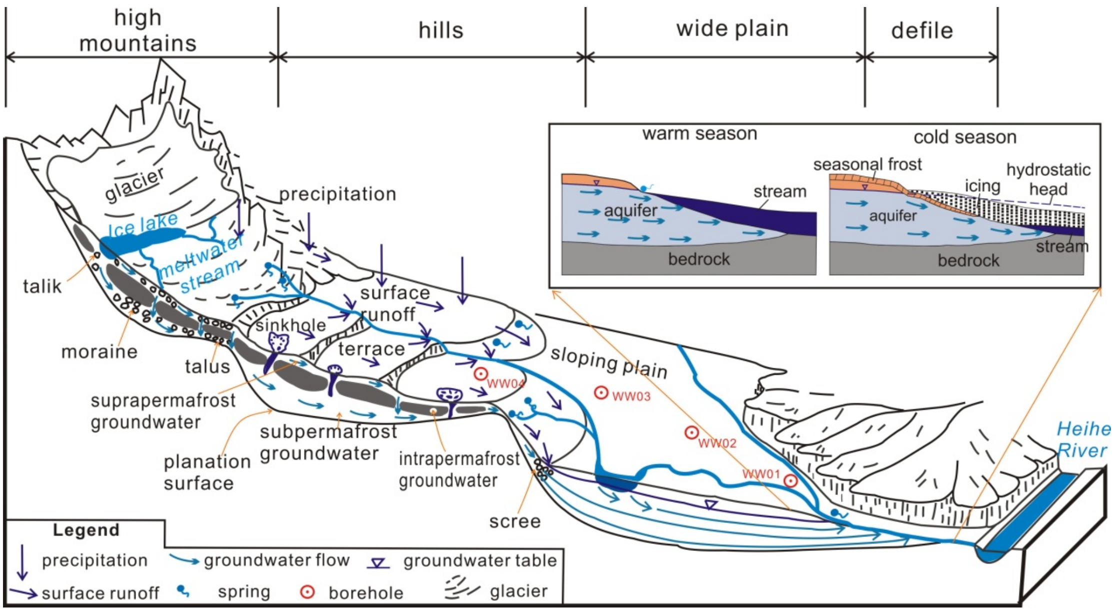
General comment:

The authors studied the role of permafrost in controlling groundwater flow and the hydrological connections between glaciers in high mountain and river in the low plain with hydraulic head, temperature, geochemical, and isotopic data. The paper is generally well written, and should be of very interest to the research community.

Response: We thank the reviewer for carefully evaluating our manuscript and for constructive and helpful comments and suggestions. Our responses to the specific comments are provided in a point-by-point reply given below.

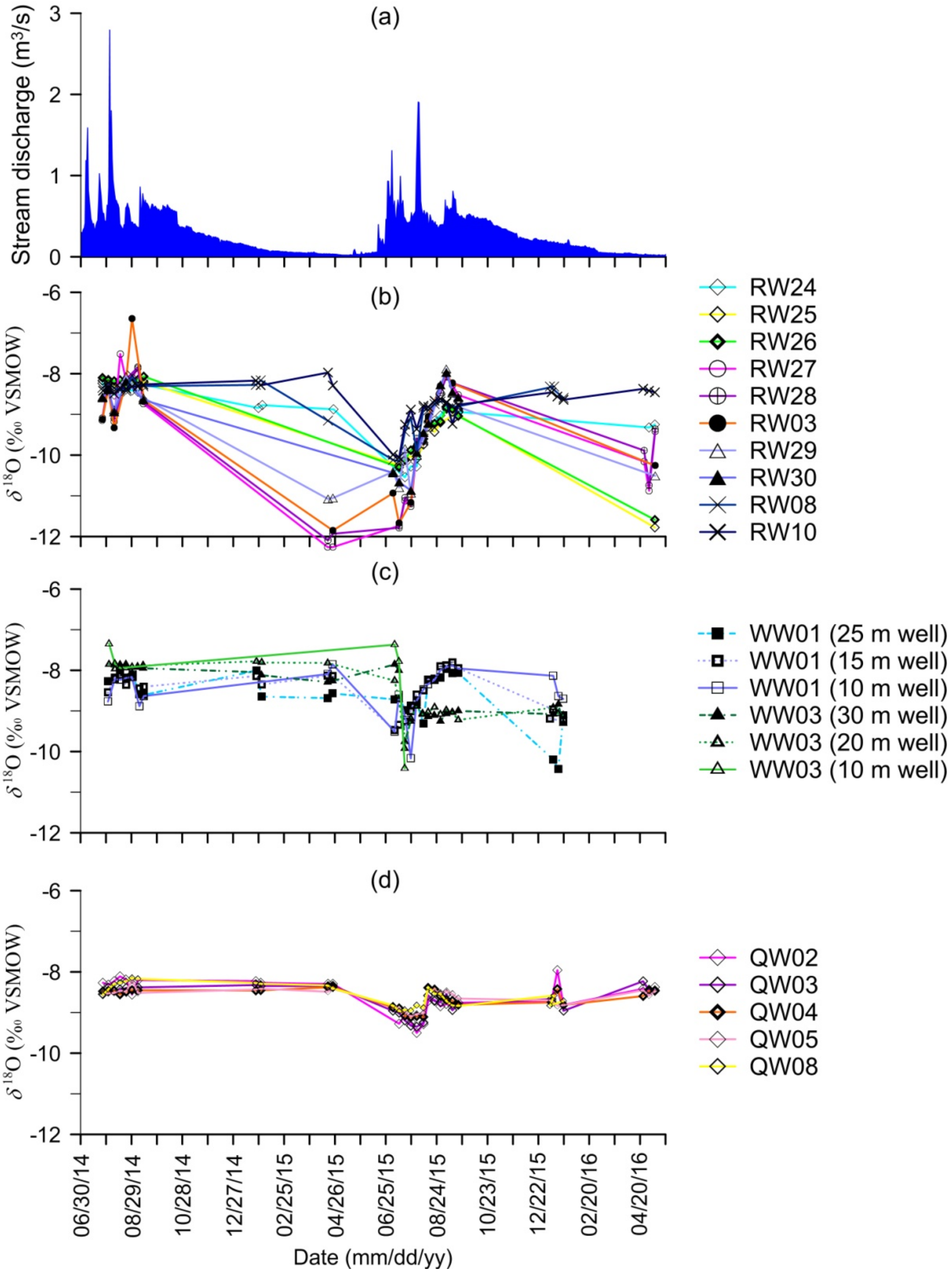
Comment 1: Legend of Fig.12 should be explained clearly, such as the status of runoff (groundwater, surface water) should be depicted.

Response: We have revised Fig. 12 (as shown below) to make it more clear. Since there are many symbols in the figure, it is somewhat inconvenient and unclear if explain them in figure caption. Thus, we added a legend in Fig.12 to explain the meaning of different symbols used in the figure.



Comment 2: The resolution and framework of Fig. 10 should be improved.

Response: The resolution of Fig.10 is already 600 dpi. However, for comparison, we used the same Y-axis scale for three sub-plots (b), (c) and (d). This is the main reason why five lines in sub-plot (c) are too close to be distinguished clearly. The sub-plot (c) would have been more clear and aesthetic if a smaller scale was used for Y-axis. However, given that this figure is designed to show the difference in spatio-temporal variations of $\delta^{18}O$ between three water pools (i.e., well water, spring and stream), and provide insights on their hydrological connections, this framework can yield more valuable information compared to that with varying scales. For example, as mentioned in the manuscript (P12, L24-25 in the revised manuscript), spring waters showed the smallest variation in $\delta^{18}O$ among three water pools, indicating a weaker linkage with surface water, and probably a larger recharge area or/and a longer residence time (in well-mixed). However, we tried our best to revise this figure to make it more clear as shown in below.



Comment 3: The conclusions need to be improved, the author should tell the most important conclusion by the simple statement at this part.

Response: We have revised the conclusions to focus on the most important things. The revised conclusions are as following:

"Groundwater studies in permafrost area are challenging because of the limited infrastructure and the short field season. These conditions favor the use of geochemical and isotopic tracers in baseflow and perennial springs to supplement hydrogeological data to elucidate recharge conditions and flow paths. By selecting a representative catchment in the headwater regions of the Heihe River, Qinghai-Tibet Plateau as study site, this research employed the groundwater head, temperature, geochemical, and isotopic information to determine the roles of groundwater in permafrost and seasonal frost zone for hydrologically connecting waters originating from glaciers in the high mountains to lower elevation rivers.

Our field measurements show the co-occurrence of supra-, intra- and subpermafrost groundwaters in the headwater regions of the Heihe River. To the best of our knowledge, this is the first report of the occurrence of sub- and intrapermafrost groundwaters in this region. The moraine and fluvio-glacial deposits on the planation surfaces of higher hills, which are commonly distributed in the headwater regions of the Heihe River, provide a major reservoir for the storage and flow of sub- and intrapermafrost groundwater. The subpermafrost groundwater on the planation surface was interconnected to the surface hydrological processes and recharged by suprapermafrost groundwater and glacier and snow meltwater. The results of this study could shed new lights on the understanding of the groundwater flow and its interaction with surface water at other catchment, as well as improve the evaluation and management of water resources in the headwater regions of the Heihe River.

Glacier and snow meltwater were transported from the high mountains to the plain through stream channels, slope surfaces, and supra- and subpermafrost aquifers. The groundwater in the piedmont plain within seasonal frost zone was mainly recharged by the lateral flow from the supra- and subpermafrost aquifers and the seepage of streams, and was discharged as baseflow into the Hulugou stream in the north gorge. A rapid transfer of groundwater from the south top to the north base of the plain occurred during the warm season, while the stored groundwater was slowly released during the cold season. This seasonal variation of the aquifer in water-conduction capacity was interpreted by two mechanisms: (1) surface drainage via the stream channel, analogous to the "fill and spill" mechanism in hillslope hydrology. The *narrowing of aquifer from the wide plain to the gorge led to a relatively high water table near the gorge, preventing it from dropping below the channel bed and maintaining a perennial flow in the downstream. This addresses the rapid transfer of groundwater from the top to the base of the plain and the stable water table in front of the gorge during the warm season; and (2) subsurface drainage to an ephemeral artesian aquifer confined by stream icing and seasonal frost. The stream icing and seasonal frost not only blocked the groundwater discharge, but also changed the bottom of the gorge into a confined aquifer during the cold season, leading to an increase in the downstream groundwater head and a decrease in the hydraulic gradient between the wide plain and the narrow gorge. The second mechanism elucidates the slow release of stored groundwater from the plain and the low baseflow in channel throughout the cold season."*

Comment 4: Page 11, the value of δ^2H and $\delta^{18}O$ indicate that suprapermafrost groundwater had experienced strong evaporation, but the hydrogeochemistry also suggest the suprapermafrost groundwater has rapid flow. It should be explained more clearly.

Response: We have revised this part as suggested to express it more clearly. The revised statement is as following:

"The low TDS, Cl^- and Na^- concentrations and the HCO_3-Ca water type suggest that suprapermafrost groundwater had experienced insufficient water-mineral interaction, probably caused by a relatively short residence time or flow path. This is further supported by the highest ^{14}C activity in the suprapermafrost groundwater among all samples (Table 2), which is 96.34 pmC, and by a 15.11 TU ^3H concentration which is close to the atmospheric value and an indicator of modern water (Zhai et al., 2013). Though occurrance on a relatively flat planation surface, the suprapermafrost groundwater was actually easy to drain because the planation surface adjoins the lower slopes in three directions. In addition, the suprapermafrost aquifer is fairly thin and rich in organic matter with high permeability. Therefore, the suprapermafrost groundwater may have a high renewal rate. The enriched ^2H and ^{18}O isotopes indicate that suprapermafrost groundwater had also experienced a certain degree of evaporation (Figure 8). These two conclusions are not contradictory to each other given the high local evaporation and shallow suprapermafrost groundwater depth. The shallow groundwater depth may also result in very short flowpaths for the majority of the waters and relatively short contact time for chemical reactions

between the water and the soils (Frey et al., 2007; Stotler et al., 2009; Vonk et al., 2015).”

Comment 5: The English of the whole manuscript need to be improved.

Response: We have tried our best to edit the English and we have also asked the professional English editing service to polish the English writing.

Hydrological connectivity from glaciers to rivers in the Qinghai-Tibet Plateau: roles of suprapermafrost and subpermafrost groundwater

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Abstract. The roles of ~~subsurface~~ groundwater flow in the hydrological cycle within the alpine area characterized by permafrost and/or seasonal frost are poorly known. ~~We~~ This study explored~~studied~~ the role of permafrost in controlling groundwater flow and the hydrological connections between glaciers in high mountain and river in the low plain with hydraulic head, temperature, geochemical~~,~~ and isotopic data~~. The study area was~~ at a – representative catchment in the headwater region of the Heihe River~~ in the~~, northeastern Qinghai-Tibet Plateau. The results show ~~The~~ that the groundwater in the high mountains mainly occurred~~s~~ as suprapermafrost groundwater, while~~and~~ in the moraine and fluvio-glacial deposits on the planation surfaces of higher hills, suprapermafrost, intrapermafrost~~,~~ and subpermafrost groundwater co-occurred. Glacier and snow-meltwater were~~are~~ transported from the high mountains to the plain through stream channels, slope surfaces, and supra- and subpermafrost aquifers. Groundwater in the Quaternary aquifer ~~under~~ in the piedmont plain was~~is~~ recharged by the lateral inflow from permafrost ~~groundwaters~~ areas and the stream infiltration~~ of streams~~, and was~~is~~ discharged as baseflow to the stream in the north. Groundwater maintained stream flow over the cold season and significantly contributed to the stream flow during the ~~rainy~~ warm season. ~~^{3}H and ^{14}C data indicated that the age of supra- and sub-permafrost groundwater, and groundwater in Quaternary aquifer of seasonal frost zone, ranges from 30-60 years.~~ Two ~~proposed~~ mechanisms are proposed to contribute to seasonal variation of the aquifer water-conduction capacity: (1) surface drainage through the stream channel during the ~~high flow~~warm period, and (2) subsurface drainage to an artesian aquifer confined by stream icing and seasonal frost during the cold season.

1. Introduction

~~The role of p~~Permafrost plays an important role in groundwater flow~~ systems~~ ~~is important in the~~and thus hydrological cycles of cold regions (Walvoord et al., 2012). This is especially true for the mountainous headwaters of large rivers. In these areas interactive processes between permafrost and groundwater influence water resource management, engineering construction, biogeochemical cycling, and downstream water supply and conservation (Cheng and Jin, 2013). Study of groundwater in permafrost areas has been prompted by the need for water supplies, problems associated with groundwater in mining, and construction of buildings, highways, railways, airfields and pipelines. The ice features of permafrost areas and geological mapping are also of great interest (Woo, 2012).

In permafrost-dominated watersheds, hydrogeological regimes are primarily controlled by the distribution of frozen ground and taliks, as well as the freeze-thaw cycle of ~~aquifers~~ active layer (White et al., 2007). Freezing alters the intrinsic behavior of aquifers because ground ice occupies interstitial voids and reduces the permeability of the water storage matrix (Woo, 2012). Thawing alters hydraulic connections between ~~different~~different water pools (Carey and Woo, 2000), further affecting ~~The freeze-thaw process of the active layer affects the~~ groundwater flow path and its interaction with surface water~~.~~ ~~Permafrost greatly affects base flows in the thawing season and groundwater and surface water interactions in permafrost regions~~ (e.g. Bense and Person, 2008; Carey and Quinton, 2005; Woo et al., 2008; Zhang et al., 2013). For example, ~~G~~groundwater-surface water interactions in Alaska were~~are~~ more commonly found in areas of discontinuous permafrost where hydraulic connections were~~are~~ spatially and temporally variable (e.g. Anderson et al., 2013; Minsley et al., 2012; Walvoord et al., 2012).~~ Hydraulic connections are altered as a result of permafrost freeze and thaw (Carey and Woo, 2000).~~ At high latitudes, permafrost distribution may affect lake density in addition to surface flow (Anderson et al., 2013). In areas of continuous permafrost, subpermafrost groundwater is often isolated from the surface, and there are unique mechanisms in thermokarst lake dynamics such as lateral expansion and breaching (Jones et al., 2011; Plug et al., 2008). Permafrost is now warming and thawing in many ~~areas~~ regions of ~~Alaska~~ the world (e.g. Anderson et al., 2013), and connections between permafrost degradation and local hydrologic changes have been established (e.g. O'Donnell et al., 2012; Yoshikawa and Hinzman, 2003).

~~Fundamental knowledge of groundwater systems in areas of permafrost is often lacking (!!! INVALID CITATION !!! (Kane et al., 2013)).~~ Groundwater behavior in permafrost-dominated areas ~~is understudied but~~ ~~will~~ is becoming~~e~~ more important as permafrost, an effective barrier to recharge, continues to degrade~~. Altering the proportion of groundwater to total discharge will shift the composition of biogeochemical exports~~ (Walvoord and Striegl, 2007). However, ~~P~~permafrost hydrogeology studies have been limited to research on groundwater chemistry and modeling, mostly in northern latitude regions such as Alaska (USA), Canada, Siberia, Fennoscandia~~,~~ and Antarctica (e.g. Bense et al., 2009; Carey and Quinton, 2005; Evans et al., 2015; Ge et al., 2011; Woo et al., 2008). Fundamental knowledge gaps of groundwater systems in areas of permafrost ~~is often lacking~~still exist (Kane et al., 2013). Linkage between groundwater circulation and discharge has not been found in field studies, but simulations have shown a possible connection between changes in climate, groundwater movement, and increases in the winter low flows of northern Eurasian and northwestern North American rivers (Smith et al., 1991; Walvoord and Striegl, 2007). The quantitative substantiation of this linkage is challenging because hydrogeological~~;~~ and permafrost information is ~~lacking~~ scarce in remote areas and ~~also due to the complexities of~~ regional-scale permafrost-hydrology interactions are complicated. Lack of ~~typical~~ hydrogeological~~;~~ information such as hydraulic head data, detailed hydrostratigraphy, and groundwater age data, impedes development of detailed models (Walvoord et al., 2012). Thus, a~~n initial conceptual~~ thorough understanding of groundwater flow systems in permafrost ~~regimes~~ regions is a prerequisite ~~essential~~ for constructing advanced numerical modeling to quantitatively ~~analyze~~ characterize groundwater flow and its interaction with surface water.

Because of the limited infrastructure and short field seasons~~ in remote areas~~, geochemical and isotope tracers in samples from baseflow discharge and springs have been used to study recharge conditions and flow paths of groundwater in remote permafrost regions. For example, Stotler et al. (2009) investigated the role of permafrost in ~~influencing~~ deep flow system evolution, fluid movement and chemical evolution using hydrogeochemistry and ~~H~~ ^{2}H and ^{18}O~~O~~ isotopes. Anderson et al. (2013) investigated the causes of lake area changes in Yukon Flats, a region of discontinuous permafrost in Alaska, with ^{2}H and ^{18}O isotopes and found that about 5% of lake water ~~comes~~ came from snowmelt and/or permafrost thaw~~ with H and O isotopes~~. ~~Utting et al. (2013) used~~ Using stable isotopes (~~δ~~^{18}O, ^{2}H~~δD~~ and ~~δ~~^{13}C$_{DIC}$) and noble gases, Utting et al. (2013) ~~to~~ explored groundwater recharge and flow from permafrost watersheds in the western Arctic of Canada. Geochemical and isotopic data have been proved useful in delineating the groundwater system and identifying flow paths in ~~the~~ permafrost zone. However, the related research was mainly limited to arctic and subarctic river basins~~to Canadian and Fennoscandian Shield groundwaters, Alaska, and other part of the USA~~world.

To better understand the effects of permafrost on groundwater flow and its interactions with surface water in mid-low latitude, high altitude mountain areas, we selected the Hulugou catchment, a representative catchment~~–~~ ~~study site~~ in the headwater region of the Heihe ~~Basin~~River~~, as study site. This area region~~ which is covered by large areas of continuous and discontinuous permafrost and seasonal frost, as study site. The Heihe River is the ~~2nd~~ second largest inland river ~~of~~ in China with a drainage area of ~150,000 km^2 (Figure 1(a)). It provides water for domestic use, agriculture, and industry in the Qinghai, Gansu and Inner Mongolia Provinces of northwestern China. The hydraulic head and temperature data obtained from newly drilled wells as well as geochemical and isotope information were combined~~ and used~~ to: 1) trace the recharge and flow paths of groundwater; and 2) investigate the control of permafrost and seasonal frost distribution and ~~its~~ their freeze-thaw processes on groundwater dynamics and ~~its~~ groundwater-surface water interaction~~ with surface water~~. It should be noted that ~~M~~moraine and fluvio-glacial deposits are widely distributed on the planation surfaces of the higher hills in the headwater region of the Heihe River (Figure 1(a)). However, their significance for controlling groundwater recharge and flow has not been studied. This is the first report on the occurrence of subpermafrost and intrapermafrost groundwater in the planation surface~~in this region~~ areas and on their hydraulic connectivity with groundwater in the seasonal frost zone and ~~river~~streams~~ in the headwater regions of the Heihe River~~. Our ~~research~~ results ~~will~~ provide~~increase~~ ~~understanding of~~new insights into the hydrological function of planation surface area~~s~~ ~~that~~ as~~provide~~ a major reservoir for the storage and flow of groundwater ~~and rivers~~ in permafrost regions.

2. Study area and background

2.1 General setting

The Hulugou catchment has a drainage area of 23.1 km^2 and is located within Qilian Mountains in the northeastern Qinghai-Tibet ~~plateau~~Plateau, between 38°12'14"N and 38°16'23"N latitude and 99°50'37"E and 99°53'54"E longitude

(Figure 1(b)). The elevation of the Hulugou catchment ~~elevation~~ ranges ~~from~~ between 2960 ~~to~~ and 4820 m, increasing from north to south. The slope ranges from 0° ~~and~~ to 85°.

The catchment has a continental semi-arid climate characterized by warm, rainy summers and cold, dry winters. From the plain to the high mountains, the mean annual precipitation ranges from 400~~–~~ to 600 mm, approximately 70% of which occurs during July–September (Figure 2). In the high mountains with elevations from ~3800 to 4800 m, most precipitation falls as snow. ~~Snow may fall in summer, but it typically melts within one to three days.~~ The annual potential ~~E~~evaporation ~~ranges from 376 to 650 mm per year~~is 1102 mm. The mean annual temperature is −~~-~~3.9 °C, and the minimum and maximum temperatures are −~~-~~25.2 °C and 25.8 °C, respectively. The daily precipitation and temperatures in the plain from 2014 through 2016 are shown in Figure 2.

The catchment geomorphology is composed of high mountains, erosion hills, ~~and~~ a piedmont sloping plain, and a narrow gorge. High mountains are located in the southern part of the catchment, and this area contains five alpine glaciers, two ice lakes, and a range of classic glacial features such as U-shaped valleys, cirques, horn peaks, arêtes, moraines and talus slopes. The five glaciers have a total area of 0.827 km^2 (Li et al., 2014). The erosion hills are in the north, northeast and northwest of the catchment, with the planation surfaces on the top of the higher hills (3400−3800 m) (Xu et al., 1989). The planation surfaces are underlain by permafrost, with typical permafrost-related features such as thermokarst ponds, frost mounds, permafrost bogs, and permafrost plateaus. Cracks, terraces and landslides caused by active layer detachment slides are common on the upper slopes. The sloping plain is composed of several partially superimposed alluvial-pluvial fans. It is funnel-shaped, surrounded by the high mountains and hills, and ~~having~~ connecting to ~~a~~the narrow gorge at the base, which leads into the Heihe River (Figure 1(c)). ~~There is a distinct break in the slope between the plain and the mountains.~~ The plain dips slightly toward the Heihe River with 2−3 degree slopes.

The ~~Heihe River~~Hulugou stream is fed by the east ~~tributary~~ and west tributary in front of the narrow ~~valley~~ gorge (Figure 1(b)). Both tributaries and their branches originated from the high mountains ~~and~~ are all ephemeral streams and fed mainly by ~~glacial~~ glacier and snow meltwater, ice lakes, and springs. From headwaters to the plain, they receive runoff from subcatchments which are derived from precipitation, and this increases the volume of water flow. ~~The tributaries and their branches are all ephemeral streams.~~ They are intermittently dry throughout the cold season (from October to May) ~~cold season~~. Only the main stream in the narrow gorge is perennial, though it is ~~ice~~ ice-covered during winter.

2.2 Hydrogeology

Bedrock in the high mountains comprises lower Ordovician metamorphic ~~rock~~ and volcanic rock, including interbedded meta-sandstone and slate ~~with local intermediate basic volcanic and green basal with local crystalline limestone~~ (Xu et al., 1989). Late Quaternary moraine deposits, derived primarily from these formations, are located at the front of glaciers within cirques (Figure 1(c)). The moraine is 5−30 m thick and consists of non-sorted, angular gravels and boulders. Scree deposits are also common in the high mountain area, and generally located at the ~~base~~ foot of steep rock slopes or valley walls.

Bedrock in the erosion hills is ~~comprised~~ composed of shales with limestone and sandstone (Xu et al., 1989). The slopes are generally covered with weathered residues of 0.5−3 m thickness but can also have local areas of exposed bedrock, talus material, and silt deposits. The top of the higher hills, recognized as planation surfaces, are covered with middle and upper Pleistocene moraine and fluvio-glacial deposits from several meters to tens of meters thick (Cao, 1977). Thin mud deposits are also found here, especially in thermokarst ponds, permafrost bogs, and permafrost plateaus.

The surface geology in the piedmont sloping plain is primarily upper Pleistocene fluvio-glacial deposits ~~(Xu et al., 1989)~~, which are mainly composed of poorly-sorted, subangular, mud-bearing pebble gravels with erratic boulders. The underlying strata are glacial moraine and fluvio-glacial deposits of the middle and lower Pleistocene series and conglomerates and sandstones from the Cretaceous (Xu et al., 1989). The Holocene alluvial-proluvial deposits are only found on the bottom of the narrow ~~defile~~gorge ~~of the Hulugou stream gorge~~. Near the outlet of the Hulugou catchment, the upper Quaternary alluvial-proluvial deposits occur on the first to third terraces of the Heihe River.

The groundwater flows correspond to the topography, with a flow trend from south to north. According to previous regional hydrogeological investigations (1:200,000) (Cao, 1977), permafrost in the head~~-~~water regions of the Heihe River mainly occurs in areas exceeding 3600 m a.s.l., and the groundwater in permafrost region was conjectured to be suprapermafrost groundwater. Neither subpermafrost nor intrapermafrost groundwater has been reported. Our field investigation demonstrates that permafrost can be found at as low as 3500 m a.s.l. in shady slopes. We found springs or seeps at the lower margin of the cirques containing moraine and scree deposits and at the upper slopes of the hills with fluvio-glacial deposits on the top planation surfaces. Groundwater in the seasonal frost ~~region~~ zone primarily occurred in fluvio-glacial deposits of the sloping piedmont plain, as well as in the mountain scree deposits~~,~~ and slope deposits of the hills~~, and fluvio-glacial deposits of the sloping piedmont plain~~.

3. Materials and methods

3.1 Field measurement

Four cluster wells, WW01, 02, 03 and 04, were installed in July and August~~,~~ 2014, for groundwater monitoring and sampling (locations shown in Figure 1(b)). Each cluster ~~well~~ included 3−4 wells with different interval screen depths. The screened intervals were 5, 10, 15 and 25 m underground for cluster WW01, and 5, 10, 20 and 30 m underground for clusters WW02 and WW03, and 1.5, 12 and 24.3 m underground for cluster WW04. No water was found in wells within the WW02 cluster. Cluster wells WW01, 02 and 03 were located in the piedmont sloping plain dominated by seasonal frost, at elevations of 3144, 3250 and 3297 m, respectively. Cluster WW04 was located in a planation surface dominated by thermokarst ponds, frost mounds, and permafrost bogs, at an elevation of 3501 m.

During installation of each cluster well, temperature loggers (HOBO U20-001-02 temperature logger; Onset, Bourne, MA, USA) were buried in sediments at depths of 0.5, 1, 1.5, 2, 3, 5, 10, 15 ~~-~~(or 20) and 25 ~~-~~(or 30) m ~~below the~~ underground

~~surface~~ to monitor ~~the~~ ground temperature ~~profile with time~~. The ground temperature was recorded at an interval of 15 min. Both groundwater table~~, –~~ (if available) in the cluster wells~~,~~ and ~~river~~ stream stage were measured using electronic pressure sensors (HOBO U20-001-02 water level logger; Onset, Bourne, MA, USA). The sensor for ~~river~~ stream water pressure measurement was installed in a stilling well to exclude waves and turbulence. Atmospheric pressure was measured simultaneously using a barometric pressure sensor (S-BPB-CM50; Onset, Bourne, MA, USA), so that differential pressure between water ~~pressure~~ and atmospheric pressure could be calculated and then converted to the water table. The data was recorded every 15 min to be consistent with ground temperature measurements.

Five weather stations have been maintained by Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences since 2004 within the Hulugou catchment. These stations collect air temperature, humidity, precipitation, and wind speed data at 30 min intervals (Chen et al., 2014). Data from the station~~s~~ on the sloping plain and the one~~station~~ near cluster WW04 (~200 m away; similar elevation) were collected in this study.

3.2 Water sampling and analysis

For ion and isotope analysis, groundwater samples were collected from ~~the~~ 12 wells between 2014~~–~~ and 2016, and stream water samples were collected from 12 sites that were approximately evenly distributed from upstream to downstream between 2011 and 2016 (Figure 1(b)). ~~Sample sites are shown in Figure 1(b).~~ Both types of samples were collected at 7- to ~~14~~ 14-day intervals during the ~~thaw~~ warm season from June to September, but less frequently during the cold season. They were collected 3–~~-~~4 times in each of January and April. In addition to the 12 regularly sampled wells, groundwater was also ~~occasionally~~ irregularly sampled from 7 springs and 18 shallow wells with depth ~~less than~~ $<$3 m ~~in depth~~. Glacier meltwater was collected at 13 periglacial sites at elevations from 4261 to 4432 m between 2013 and 2015. Weekly precipitation (rainfall or/and snowmelt) was sampled from 3 sites that were distributed at about 200 m elevation intervals between 2012 and 2015.

~~Seven water sample subsets were collected from each site and filtered with 0.22 μm membranes in the field into polythene bottles that were thoroughly pre-washed with deionized water.~~ When groundwater was collected from wells, appropriate well purging was done using a peristaltic pump before sampling. At all sampling times, pH, electric conductivity (EC), temperature, and dissolved oxygen concentration were measured in ~~the~~ field using a portable Hatch ~~Ec~~ EC and pH meter (HACH HQ40d), and alkalinity was determined on the sampling day using the Gran titration method (Gran, 1952). Seven water sample subsets were collected from each site and filtered with 0.22 μm membranes in the field into polythene bottles that were thoroughly pre-washed with deionized water. Samples for cation and minor element analysis were acidified with ultrapure HNO_3 to pH=2. All samples were wrapped with parafilm and stored at 4 ^{o}C before being transported to the laboratory ~~for ion and isotope analysis~~.

All samples were analyzed for major ions, minor elements (Fe, Si and Sr), ^{18}O and ^{2}H isotopic compositions, and ^{13}C isotopic compositions of DIC at the Laboratory of Basin Hydrology and Wetland Eco-restoration, China University of

Geosciences (Wuhan). Thirteen groundwater and spring samples were analyzed for ^{3}H concentrations and 7 were analyzed for ^{14}C activity. Anions (SO_4^{2-}, Cl^-~~, -~~ and NO_3^-) were determined using ion chromatography (IC; DX-120, Dionex, USA), ~~whereas~~ while cations (Ca^{2+}, Mg^{2+}, K^+~~, +~~ and Na^+) and some minor elements (Fe, Si~~,~~ and Sr) were determined by inductively coupled plasma-atomic emission spectrometry (ICP-AES; IRIS INTRE II XSP)~~ at the Laboratory of Basin Hydrology and Wetland Eco-restoration, China University of Geosciences (Wuhan)~~ within 14 days after sampling. Ionic balance errors were < 5% for 84% of the samples and between 5.1%−8% for the remaining samples.

Isotopic compositions of ^{18}O and ^{2}H were analyzed using an ultra-high precision isotopic water analyzer (L2130-I, Picarro, USA)~~ at the Laboratory of Basin Hydrology and Wetland Eco-restoration, China University of Geosciences (Wuhan)~~, and were expressed in δ per milliliter relative to the V-SMOW (Vienna Standard Mean Ocean Water), with precision of 0.025‰ and 0.1‰, respectively. The ^{3}H concentration was determined by the solid polymer electrolysis enrichment method with a tritium enrichment factor of 10 using an LSC-LB1 Liquid Scintillation Counter (Quantulus 1220™). The detection limit for the tritium measurement was approximately ±1 TU. The ^{3}H values were reported in tritium units (TU).

The δ^{13}C value of DIC in water samples was measured using a wavelength scanning cavity ring-down spectroscopy (WS-CRDS; G2131-I, Picarro, USA), and reported as per milliliter relative to V-PDB. The analytical precision for $\delta^{13}C_{\cancel{(}DIC\cancel{)}}$ was 0.1‰. For measuring ^{14}C, water samples were treated first with 85% phosphoric acid and filtered to remove weathering carbonates. CO_2 was purified and collected with a cryotrap, and then reduced to graphite using the Zn/Fe method. Finally, ^{14}C activity was determined using an accelerator mass spectrometry (AMS; 3 MV, Tandetron) at the Xi'an AMS Center, China. ^{14}C activity was reported as percent modern carbon (pmC) and the analytical precision was 2‰.

3.3 Sediment sampling and analysis

Sediment samples were collected at 30~~ cm~~ to 100 cm depth intervals~~ along the profile~~ when drilling the deepest borehole within each cluster. The subset for stable isotopic analyses was placed in an 8-mL borosilicate glass vial sealed with a Teflon-lined screw cap and parafilm, and stored at -20 °C. After being transported to the laboratory, water was extracted from the sediment samples using cryogenic vacuum distillation technique and then measured for δ^{18}O and δ^2H (Smith et al., 1991; Sternberg et al., 1986). The measuring instrument, method and precision were the same as ~~that~~ those noted above.

3.4 ^{14}C age model

Along the groundwater flow path, the ^{14}C gained in soils is often diluted by geochemical reactions such as carbonate dissolution, exchange with the aquifer matrix, and biochemical reactions. Therefore, when using the decay of $^{14}C_{DIC}$ as a measure of groundwater age, the dilution by non-atmospheric sources must first be corrected. Accounting for the dilution of ^{14}C caused by geochemical reaction, groundwater age is calculated using the following decay equations (Clark and Fritz, 1997):

$$t = 8267 \times \ln\left(\frac{q \times {}^{14}\mathrm{C}_0}{{}^{14}\mathrm{C}}\right) \tag{1}$$

where t is the groundwater age in years BP, ^{14}C is the measured ^{14}C activity, $^{14}C_0$ is the modern ^{14}C activity in the soil derived from DIC and q is the dilution factor~~ or fraction~~.

Several models have been proposed to obtain the dilution factor (e.g. Mook, 1980; Pearson and Hanshaw, 1970; Tamers, 1975; Vogel, 1970, 1967; Vogel and Ehhalt, 1963). In this study, a δ^{13}C-mixing model modified by Clark and Fritz (1997) from the Pearson model (Pearson and Hanshaw, 1970) was applied to correct the ^{14}C dilution by carbonate dissolution. This model is based on variations in ^{13}C abundance, which differs significantly between the soil-derived DIC and carbonate minerals in the aquifer and is thus a good tracer of DIC evolution in groundwaters. ~~Any~~ The processes that add~~s~~, remove,~~s~~ or exchange~~s~~ carbon from the DIC pool and ~~which~~ thereby alter~~s~~ the ^{14}C ~~concentrations will also affect~~and ~~the~~ ^{13}C concentrations will be accounted by the dilution factor q~~(Clark and Fritz, 1997)~~,~~.~~ ~~Therefore, the q~~which can be obtained from a ^{13}C mass balance:

$$q = \left(\frac{\delta^{13}C_{DIC} - \delta^{13}C_{carb}}{\delta^{13}C_{rech} - \delta^{13}C_{carb}}\right) \tag{2}$$

where $\delta^{13}C_{DIC}$ is the measured δ^{13}C in groundwater, $\delta^{13}C_{carb}$ is the δ^{13}C of the calcite being dissolved (usually close to 0‰), and $\delta^{13}C_{rech}$ is the initial δ^{13}C of DIC in the infiltrating groundwater. The $\delta^{13}C_{rech}$ was taken −18‰ as suggested by Han et al. (2011) for north China.

4. Results

4.1 Sediments

Well logs for cluster~~ wells~~s WW01−03 indicate~~d~~ that the sediments in the seasonal frost area are mainly composed of sandy gravels which are highly permeable~~ in the seasonal frost area~~ (Figure 3). A silt clay layer with thickness between 3−~~-~~6 m was found at all three sites and ~~this may~~ might extend throughout the sloping plain. The underlying bedrock was not revealed by the deepest boreholes at ~~the~~ cluster~~ well~~s WW01 and WW02, indicating that unconsolidated sediments are thicker than 25 m and 30 m at the two sites~~, respectively~~. At cluster ~~well~~ WW03, weathered sandstone was found at 22 m depth, indicating decreased thickness of unconsolidated sediments at the top of the sloping ~~the alluvial-pluvial fans~~plain. These data suggest that alluvial-pluvial deposits might accumulate on a slightly sloping shallow saucer-shaped basin, being the thickest at the center of the plain and becoming thinner towards its edges (Figure 1(c)).

The sediments at cluster WW04 consist of a top clay layer to the depth of 2 m, icy sandy gravel from 2−20 m, and ice-free sandy gravel at 20−25 m depth. There was a 0.2 m thick sandy clay layer at the depth of 12 m which was also ice free.

4.2 Groundwater depth

No ~~liquid~~ water was found in any wells within cluster WW02 throughout the years, ~~and~~ in the 5 m and 10 m deep wells within cluster WW03 ~~at~~ during ~~low flow time period~~cold season ~~in winter~~, and in the 12 m deep well within cluster WW04 at most times. Figure 4 shows the variation of groundwater depth over time from 2014 to 2016 in the wells with groundwater. The groundwater depth in the 20 m and 30 m wells within cluster WW03 fluctuated between 13–~~ m and~~ 18 m below ground during the warm, rainy season from mid-June to late October~~. Conversely,~~, and ~~the groundwater depth~~ declined and ~~was~~ became stable in the cold, rainless season. The water table in the 20 m well was close to that in the 30 m well from late June to late July and~~always~~ higher than that ~~in the 25 m well~~ for the rest of the time~~, but~~. ~~t~~The difference of water table between two wells ranged from ~ 4 m in the cold season to ~~less than~~< 1 m in the warm season. ~~From late June to late July, the water table in the 20 m well was similar to that in the 30 m well.~~ For cluster WW01, ~~T~~the groundwater depth in the 5 m well was comparatively stable with values between 4 and 5 m throughout the whole year, and that~~,~~ in the 10 m, 15 m and 25 m wells ~~within cluster WW01~~ was ~~shallow (~~4−6 m below ground~~)~~ in the warm season~~, and~~ but dropped dramatically to 5−19 m below ground in the cold season. Although the groundwater ~~table~~ depth differed greatly between the ~~two~~ cold and warm seasons, it was relatively stable ~~within~~ during each of the two~~either~~ seasons. ~~In contrast, the water table in 5 m well was comparatively stable throughout the whole year, ranging only from 4 m to 5 m in depth. This water table was very close to, also followed the same seasonal variation trend with, the level of the adjacent Hulugou stream.~~ ~~Similarly~~Similar to the cluster WW03, the water table in the shallower well was always higher than that in the deeper well within cluster WW01, but the difference was much smaller during the warm season than the cold season.

The water table depth ~~ranged from 0 to 1.5 m below ground surface at~~ in the 1.5 m well ~~within the active layer of permafrost zone~~ at cluster WW04 ~~during the warm season~~ was close to the ground surface from June to September and decreased to 1.5 m below ground from October to December.~~ and the water froze in winter.~~ The groundwater depth in the 24.3 m well at cluster WW04 varied between 20.3 and 23.5 m below ground.~~The water table was observed in summer in the 24.3 m well at cluster WW04 and water depth varied between 20.3 and 23.5 m. It This water table was difficult to be monitored automatically in winter because the water was too shallow to cover the pressure sensor.~~

4.3 Ground temperature

The profiles in Figure 5 show the inter-monthly variation of ground temperature over a year from September 2014 to August 2015 at each cluster. The upper part of the profiles was ~~obviously~~ influenced by seasonal heating and cooling from the land surface, showing significant seasonal changes in temperature. The temperature decreased at a gradually reduced rate with depth in the warm season and this was reversed in the cold season~~.~~, ~~This~~which ~~is~~ was presented as right-concave ~~profile~~ and left-concave profiles in temperature vs. depth graph, respectively. Two types of profiles converged at a critical depth where seasonal variation in temperature disappeared. The critical depth was about 7.5 m, 10 m and 12 m below ~~the~~ ground ~~surface~~ at the clusters WW03, 02 and 01, respectively, much deeper than that (only ~ 2 m) at cluster WW04.

However, a slightly dynamic variation ~~of~~ in temperature ~~could~~was still ~~be~~ observed below the critical depths at clusters WW01 and WW03. ~~It~~ This ~~is~~ was probably ~~due to~~caused by the groundwater recharge or discharge processes, which is supported by comparing the temperature profiles among~~comparison with the results at~~ clusters ~~WW02~~ WW01, 02, 03 and ~~WW~~04. ~~This~~ The dynamic variation in temperature was not found at depths between 10 m and 30 m at cluster WW02 where groundwater depth exceeded 30 m, nor at depths between 2 m and 20 m at cluster WW04 where temperature remained almost constant ~~around~~ ~ 0 °C and thus groundwater was frozen ~~all~~ throughout the year~~ at these depths~~. A slightly seasonal variation in temperature was observed below 20 m at cluster WW04~~.~~ –with ~~T~~the pattern~~ of the variation was~~ similar to that in the upper part of the profiles, i.e., increased temperatures in summer and decreased temperatures in winter.

The ground temperature profiles in the warm season did not intersect with the 0 °C isotherm at the clusters WW01−03 (Figure 5), confirming that the three clusters are in a seasonal frost ~~region~~zone. The seasonal frozen depth was about ~~7.5~~2 m and ~~10~~ 2.5 m at clusters ~~WW02~~ WW03 and ~~WW03~~WW02, shallower than that (~~12~~ 3 m) at cluster WW01. The active layer was 2 m thick at cluster WW04.

4.4 Hydrogeochemistry

~~Chemical compositions are listed in Table 2.~~ The chemical compositions including major ions, minor elements (Si and Sr) and TDS for different types of water were listed in Table 2. The ~~river~~stream water concentrations had the seasonal variation. They exhibited ~~The~~ the lowest values ~~in river waters samples from east tributary were located~~ within the periglacial and permafrost zone, and increased ~~in the waters samples from east and west tributaries located~~ within the seasonal frost zone,~~.~~ ~~The values~~and further increased ~~in the river water~~ at the catchment outlet. ~~On a seasonal basis, river water concentrations had larger geochemical variations compared to groundwater.~~ Except for NO_3^- and SO_4^{2-}, other major ions and minor elements (Si, Sr) concentrations as well as ~~EC and~~ TDS~~ concentrations~~ were similar between ~~river~~ stream water at the catchment outlet and groundwater in winter (Table 2 and Figure 6). The spring waters exhibited minor changes ~~of~~ in geochemistry ~~between the seasons~~over time.

The groundwaters sampled from the seasonal frost ~~region~~ zone of the sloping plain (clusters WW01 and 03) were $HCO_3 \cdot SO_4$-Ca·Mg and $HCO_3 \cdot SO_4$-Mg·Ca types, being ~~neutral to~~ slightly alkaline with pH between 7.64 and 8.74. The ~~By comparison, s~~samples at cluster WW01 had higher ~~levels of~~ major ions, Si~~ and~~ , Sr, and TDS concentrations than those at cluster WW03 (Table 1 and Figure 6 and 7). The Ca^{2+}, Mg^{2+}, NO_3^-, SO_4^{2-}, Sr and TDS concentrations in groundwater ~~aquifers~~ at relatively shallow depths (≤~~<~~ ~~20~~ 15 m) were generally higher than those ~~levels~~ in deeper parts of the aquifer (> ~~25~~ 15 m) at cluster WW01~~ and 03 (Table 1 and Figure 7)~~, whereas Na^+ and K^+ were higher in the deeper parts~~ of the aquifer~~ (Table 1 and Figure 7). Among the groundwaters at cluster WW03, the Ca^{2+}, Mg^{2+}, NO_3^-, SO_4^{2-}, Sr and TDS concentrations in the 20 m well ~~are~~were highest, followed by those in the 30 m well, and then lowest in the 10 m well. The other parameters (Mg^{2+}, Cl^-, HCO_3^-~~,~~ and Si~~ and Sr~~ concentrations) were similar at different depths within ~~the~~ clusters WW01 or WW03.

At cluster WW04, ~~T~~the chemical type was HCO_3-Ca for ~~suprapermafrost~~ groundwater ~~(~~in the 1.5 m well~~ at cluster~~

~~WW04)~~, $HCO_3 \cdot SO_4$-Mg·Ca for ~~subpermafrost (~~groundwater in the 24.3 m well~~ at cluster WW04)~~ and HCO_3-Ca·Na·Mg for ~~intrapermafrost~~ groundwater ~~(~~in the 12 m well~~ at cluster WW04)~~. Among the stream water~~ samples~~, thermokarst water~~,~~ and groundwaters~~ in three wells~~, the groundwater in the 12 m well~~ the groundwater in the 12 m well (intrapermafrost groundwater)~~ had the highest Ca^{2+}, Mg^{2+}, K^+, Na^+, Si, Sr, Cl^-, HCO_3^- and TDS concentrations and the lowest SO_4^{2-} and NO_3^- concentrations. The groundwater in the 24.3 m well had the higher K^+, Na^+, Mg^{2+}, Sr, Cl^-, SO_4^{2-}~~ and~~, NO_3^- and TDS~~concentrations~~ concentrations but lower Ca^{2+} and HCO_3^- concentrations than in the 1.5 m well.~~ However, T~~T~~he relative concentrations of Mg^{2+} and SO_4^{2-} showed little difference associated with depth.~~ ~~sThe supra- and subpermafrost groundwaters had similar TDS values and chemical compositions.~~ The groundwater in permafrost ~~region~~zone generally had lower~~The~~ SO_4^{2-}, Mg^{2+} and TDS concentrations~~ and major ions concentrations~~ but higher Cl^- and K^+ concentrations ~~except for Na^+ were lower~~ than ~~those~~ groundwaters ~~from~~ in the seasonal frost ~~region~~zone. Other chemical parameters were similar between the groundwaters ~~in~~within the two ~~region~~zones. ~~The relative concentrations of Mg^{2+} and SO_4^{2-} showed little difference associated with depth.~~

4.5 Stable isotopes

A local meteoric water line (LMWL) ~~drawn through~~fitted to the ^{2}H and ^{18}O isotopic compositions of precipitation at the study area is $\delta^2H = 8.5\,\delta^{18}O + 22.6$ (r^2=0.9886; n=120) (Figure 8)~~. This, is~~ similar to ~~the line~~that ($\delta^2H = 8.3\,\delta^{18}O + 17.1$) reported by Tong *et al*. (2016) at a weather station near the Hulugou ~~stream~~catchment outlet. The δ^{18}O of glacier meltwater samples was between −10‰ and −7.6‰~~, respectively~~, while the δ^2H was between −60‰ and −35‰~~, respectively~~. The stream waters had δ^{18}O values ~~compostions and δ^2H of river stream waters ranged~~ between −12.3‰ and −6.7‰, and ~~−~~ δ^2H ~~compostion~~values between −88.5‰ and −31.6‰, respectively~~ (Figures 8 and 9)~~, most of which ~~. Most stream water samples exhibited isotopic values that~~ overlapped with ~~the samples~~those of groundwaters from the seasonal frost zone (Figure 8).

~~The δ^2H and δ^{18}O of~~The water or/and ice extracted from sediment cores at depths < 5 m below ground at cluster WW04 ~~were~~ exhibited the relatively ~~positive at shallow depths (<5 m belowground)~~enriched ^{2}H and δ^{18}O, with compositions between −50‰ and −10‰ and ~~δ^{18}O, with values between −50‰−10‰ ~ and −10‰−50‰ for δ^2H and~~ between −8‰ and −2‰ ~~~ −8‰ for δ^{18}O~~, respectively (Figure 9). All samples from these depths ~~fell~~ fell below the LMWL~~,~~ and could be statistically defined by the regression line~~:~~ $\delta^2H = 6.17\,\delta^{18}O + 2.99$ (r^2=0.98, n=35) with the slope less than that of LMWL (Figure 8)~~. The 6.17 slope of this line is less than that of the LMWL~~, indicating the occurrence of evaporation ~~inthat the water/ice experienced evaporation (Clark and Fritz, 1997)~~. ~~In By contrast~~comparison, the δ^2H and δ^{18}O of extracted water/ice ~~extracted from sediment cores~~ at depths between 5 m and 20 m were relatively ~~negative~~depleted, with average values of −50‰ ~~for δ^2H~~ and −9.5‰ ~~for δ^{18}O~~, respectively (Figure 9), which were ~~values~~ similar to those of glacier meltwater. Most of the samples at these depths ~~fell~~ fell on the LMWL~~ in the δ^2H vs. δ^{18}O plot~~, indicating a precipitation origin without significant evaporation ~~(Clark and Fritz, 1997)~~(Figure 8). ~~Below~~ At the depth >20 m, ~~however,~~ the δ^2H and δ^{18}O isotopes~~ values of extracted water/ice extracted from cores were~~became enriched again in the extracted water/ice, with δ^2H

~~compostions~~values between −55‰ and −25‰ and δ^{18}O ~~compostion~~values between −8 ‰ and −2‰. These samples ~~,~~ ~~whichgreater and~~ fell on a line with a slope of 5.1.

The change of δ^2H and δ^{18}O in groundwaters with depth at cluster WW04 was similar to that in extracted water/ice from sediments. The δ^2H and δ^{18}O ~~compostions~~ were most enriched in the groundwater ~~in~~from the 1.5m well, less enriched in the groundwater from the 24.3 m well, and most depleted in the groundwater from the 12 m well (Figure 8). All groundwater samples at cluster WW04 fell below the LMWL and the δ^2H and δ^{18}O values of groundwater from the 12 m well were similar to th~~at~~ose of the glacier meltwater.

~~Groundwater in the 1.5 m well of cluster WW04 had the most positive δ^2H and δ^{18}O values and fell below the LMWL in the δ^2H vs. δ^{18}O plot (Figure 8) (Clark and Fritz, 1997). The groundwater samples collected from the 12 m well showed the most negative δ^2H and δ^{18}O values and were similar to the glacier meltwater samples in the δ^2H vs. δ^{18}O plot. The samples from 24.3 m well had intermediate δ^2H and δ^{18}O values between glacier meltwaters and the groundwaters from 1.5 m well in the δ^2H vs. δ^{18}O plot.~~

~~In the δ^2H vs. δ^{18}O plots, t~~The groundwater samples collected from clusters WW01 and WW03 fell along the LMWL~~,~~ and their δ^{18}O and δ^2H values ~~compostions were~~ were similar to th~~at~~ose in the glacier meltwater ~~samples and mountain precipitation samples. They were significantly depleted in ^{2}H and ^{18}O compared to rainfall occurring on the plain~~ (Figure 8). ~~These groundwater samples had similar isotopic values and locations in the plot to the stream samples (Figure 8). By comparison, t~~The ~~samples~~ groundwater~~s~~ samples at cluster WW01 ~~showed~~ exhibited more negative δ^2H and δ^{18}O values ~~at cluster WW01~~ than those at cluster WW03. ~~A general depletion of~~The δ^2H and δ^{18}O ~~compostions are~~were close at different depths from late July to October, but had a general depletion trend ~~at~~ with depth ~~of groundwater was observed~~ at both clusters for the rest of the year (Figure 10). ~~However, a discrepancy or reversal of this general depletion happened frequently because the groundwater showed significant variation in δ^2H and δ^{18}O and the variation differed at different depths (Figure 10).These groundwater samples had similar isotopic values and locations in the plot to the stream samples (Figure 8).~~ Both magnitude and seasonal variation of δ^{18}O and δ^2H ~~compositions~~ were similar between the groundwater and~~ose of river~~stream waters. However, ~~When comparing with groundwater from clusters WW01 and WW03 and stream water,~~ spring water showed much smaller variation in δ^{18}O and δ^2H compared to the groundwater and stream water~~, indicating a weaker linkage with surface water, and probably a larger recharge area or/and a longer residence time (in well-mixed)~~.

4.6 Radioactive isotopes and groundwater age

The ^{3}H concentrations were 15.11 TU in the groundwater from the 1.5m well~~in the groundwater sample~~ at cluster WW04, between 16.20 ~~to~~ and 24.18 TU in the groundwater at clusters WW01 and WW03, and between 13.61 ~~to~~ and 43.59 TU ~~in for~~in the springs ~~of~~ in the sloping plain (Table 2). Except for one spring sample (QW05), the ^{3}H concentrations of all samples were < 30 TU, indicating that the groundwater was ~~derived~~ recharged ~~from~~by recent precipitation and some “bomb” related ^{3}H is possibly presented~~ (Table 2)~~ (Zhai et al., 2013). Along with flow path, the δ^{13}C~~-~~$_{DIC}$ in groundwaters increased from the permafrost zone with values between −~~-~~13.6‰ and −~~-~~16.77~~–~~‰ to the ~~higher locations~~top of the sloping plain~~seasonal frost zone~~ with values ~~around~~ ~ −~~-~~8.79‰, and further to the base of the sloping plain~~lower locations of the seasonal frost zone~~ with values ~~around~~ ~ −~~-~~5.09‰ (Table 2). Opposite to ^{13}C~~-~~$_{DIC}$ trend, ~~The~~ the ^{14}C activity decreased ~~in~~ from permafrost ~~groundwater~~zone~~ varied~~ with values ~~from~~ between ~~35.51~~76.43 ~~to~~ and 96.34 pmC~~ (Table 2). Groundwater samples from cluster WW04 had much~~ to the top of the sloping plain with values ~51 pmC, and further to the base of the sloping plain with values ~ 44 pmC (Table 2).~~ higher ^{14}C values than values in groundwater and spring samples from the sloping plain, showing a general increasing trend from the permafrost zone to higher locations of the seasonal frost zone, and further to the lower elevation groundwaters. Except for the 24.3 m well within cluster WW04, the corrected ^{14}C ages of all samples were negative, indicating that they were derived from modern precipitation (Clark and Fritz, 1997).~~ The ~~sample~~ groundwater ~~from~~in the 24.3 m well ~~within~~ at cluster WW04~~, with the δ^{13}C of −16.77‰,~~ had a relatively old corrected ^{14}C age of 1627 yr. The other groundwaters exhibited negative corrected ^{14}C ages, indicating that they were derived from modern precipitation (Clark and Fritz, 1997).

5. Discussion

5.1 Exchange and pathways of groundwater in the permafrost ~~region~~zone

The groundwater in the 1.5 m well at cluster WW04 occurred within the active layer and thus was recognized as suprapermafrost groundwater, which was previously reported in the study area (Cao, 1977). Within the permafrost layer with a thickness of 20 m (2−22 m below ground), the groundwater was found in a talik at the depths between 12 and 12.5 m (in the 12 m well). It was considered as intrapermafrost groundwater. The underlying subpermafrost groundwater in the 24.3 m well was observed in the field, which was further evidenced by the slightly increased temperature and the distinct hydrogeochemistry. The intra- and subpermafrost groundwater had not been reported before this study.

5.1.1 Suprapermafrost groundwater

~~The low TDS, Cl^- and Na^- concentrations and the HCO_3-Ca water type suggest that suprapermafrost groundwater had experienced insufficient water-mineral interaction, probably caused by a relatively short residence time. This is supported by the highest ^{14}C activity in the suprapermafrost groundwater among all samples (Table 2), which is 96.34 pmC and close to the atmospheric value (Clark and Fritz, 1997), and a 15.11 TU ^{3}H concentration, which is an indicator of modern water (Zhai et al., 2013). Though occurring on a relatively flat planation surface, the suprapermafrost groundwater is actually easy to drain because the planation surface adjoins the lower slopes in three directions (see below). Add to that the fact that suprapermafrost aquifer is fairly thin whereas rich in organic matter with high permeability, one can understand why it may have a high renewal rate. However, the enriched ^{2}H and ^{18}O isotopes, along with samples' position relative to the LMWL in~~

~~the δ^{2}H vs. δ^{18}O plot, indicate that suprapermafrost groundwater had also experienced a certain degree of evaporation (Figure 8). These two conclusions are not in conflict when considering the high local evaporation (376–650 mm/yr) and shallow suprapermafrost groundwater depth (0–1.5 m below ground). The high groundwater table may also result in very shallow flowpaths for the majority of the water and few possibilities for chemical reactions between the discharging water and the deep mineral soil (Frey et al., 2007; Stotler et al., 2009; Vonk et al., 2015).~~ ~~Though the δ^{2}H and δ^{18}O values indicate that suprapermafrost groundwater had experienced strong evaporation (Figure 8), it was still a HCO_3-Ca type in hydrogeochemistry, with low concentrations of TDS, Cl^- and Na^+. This suggests that the suprapermafrost groundwater has a short flow path or rapid flow resulting in a relatively short residence time and relatively weak water-rock interaction. This is supported by the highest ^{14}C activity in the suprapermafrost groundwater among all samples, which was 96.34 pmC and close to the atmospheric value (Clark and Fritz, 1997), and a 15.11 TU ^{3}H concentration, which is an indicator of modern water (Zhai et al., 2013).~~ The δ^{2}H and δ^{18}O values~~H and O isotopic data~~, ^{3}H concentration~~tent~~ and shallow groundwater depth~~These data~~ suggest that suprapermafrost groundwater ~~is~~ was mainly recharged from recent local precipitation via vertical seepage. The widespread thermokarst ponds and organic cover with high porosity favor water ~~entry~~ enter into the suprapermafrost reservoir. The δ^{2}H and δ^{18}O ~~compostion~~ values at the intersect between the evaporation line of suprapermafrost groundwater~~s~~ and LMWL were similar to those ~~in~~of glacier/snow meltwater, suggesting that glacier/snow meltwater was another recharge source (Figure 8). ~~This result was further confirmed by stable isotopic data, which showed that the regression line through suprapermafrost groundwater samples intersects the LMWL near the precipitation samples.~~ Given that cluster WW04 is located on the lowest of three ladder-like terraces, the suprapermafrost ~~reservoir~~ groundwater may also be recharged by the lateral flow from the aquifer located on ~~from~~ a higher terrace. ~~As indicated by the δ^{2}H vs. δ^{18}O plot, the lateral recharge should mainly be from the suprapermafrost aquifer located on a higher terrace (Figure 8).~~

The terrace on which cluster WW04 is~~was~~ located adjoins two opposite hill slopes ~~created by streams cutting~~ to the west and east, respectively, and a hill slope connecting to the north plain (Figure 1(c)). At the shoulder of the three slopes, the moraine and fluvio-glacial sediments ~~, arch over the slope, become~~ become thinner, and finally end at the upper slope. Thus, except for ~~the portion that is discharged as~~ evapotranspiration, much of the suprapermafrost groundwater ~~flows~~ flowed to the adjacent slopes covered by thin weathered residues~~.~~ , ~~Because these slopes are covered by weathered residues only 0–3 m thick, and with many local areas of exposed bedrock and silt deposits (Xu et al., 1989), the suprapermafrost groundwater~~and ~~is~~ was mainly discharged ~~directly~~ into streams as baseflow, or onto the surface as seeps and springs and from there into streams. This not only explains why many springs and seeps ~~are~~ were found on the upper slopes of the hills whose upper planation surfaces ~~are~~ were covered with moraine and fluvio-glacial sediments~~. It is~~, but also was one of ~~a~~ major reasons why streams increased progressively in volume from headwaters to the sloping plain. Where weathered residues are continuous along the slope and have a coarse grain size, the suprapermafrost groundwater can be discharged into these residues, then flow through them to the talus fan at the base of the hill and, finally, drain into the aquifers ~~on~~ in the sloping plain. Our ~~study~~ field investigation demonstrated that another discharge way of suprapermafrost groundwater ~~is~~ was leakage to the subpermafrost aquifer through sinkholes created by thawing and collapse of the permafrost (Figure 11).

The low TDS, Cl^- and Na^- concentrations and the HCO_3-Ca water type suggest that suprapermafrost groundwater had experienced insufficient water-mineral interaction, probably caused by a relatively short residence time or flow path. This is further supported by the highest ^{14}C activity in the suprapermafrost groundwater among all samples (Table 2), which is 96.34 pmC, and by a 15.11 TU ^{3}H concentration which is close to the atmospheric value~~by~~ and~~–~~ an indicator of modern water (Zhai et al., 2013). Though occurring on a relatively flat planation surface, the suprapermafrost groundwater was actually easy to drain because the planation surface adjoins the lower slopes in three directions. In addition, the suprapermafrost aquifer is fairly thin and rich in organic matter with high permeability. Therefore, the suprapermafrost groundwater may have a high renewal rate. The enriched ^{2}H and ^{18}O isotopes indicate that suprapermafrost groundwater had also experienced a certain degree of evaporation (Figure 8). These two conclusions are not contradictory to each other given the high local evaporation and shallow suprapermafrost groundwater depth. The shallow groundwater depth may also result in very short flowpaths for the majority of the waters and relatively short contact time for chemical reactions between the water and the soils (Frey et al., 2007; Stotler et al., 2009; Vonk et al., 2015).

~~As occurring in the active layer, The the amount~~The recharge of suprapermafrost groundwater ~~in the active layer –~~varied seasonally. It ~~is~~ mainly occurred~~recharged~~ during the warm season because glacier melting and precipitation ~~are~~ were ~~mainly~~ concentrated ~~occur~~ during this period. Meanwhile, the active layer ~~undergoes~~ underwent thawing. Recharge ~~is~~ was limited in the cold season because recharge sources ~~are~~ were frozen and active layer freezing ~~obstructs~~ obstructed infiltration (Woo, 2012). The discharge of suprapermafrost groundwater ~~shows~~ exhibited a corresponding seasonal cycle. An examination of groundwater depth and temperature data indicates that the storage of suprapermafrost groundwater also ~~varies~~ varied significantly throughout the warm seasons. This ~~is~~ was not only a result of variation in the thawed depth of the active layer, but ~~is~~ also related to the frequent conversion of recharge-discharge interrelationship. During the late spring when ~~the~~ active layer ~~is~~ was beginning to thaw and the storage capacity of suprapermafrost reservoir ~~is~~ was still small, the water table ~~is~~ was close to the surface ~~and~~ though the recharge ~~is~~ was limited. In the summer, though the seasonal thaw ~~descended~~moved downward and thus the storage capacity of suprapermafrost reservoir increased, the groundwater ~~can~~ r~~ise~~ose further and ~~move~~ exfiltrated over the land surface to support bogs and thermokarst ponds~~. At the same time, the seasonal thaw moves downward and the storage capacity of the suprapermafrost reservoir is increased~~. This is because ~~that~~ the ~~level of~~ recharge ~~is~~ was so intensive ~~and~~ that it ~~exceeds~~ exceeded the discharge capacity of the aquifer. ~~In October, t~~The water table began to ~~decrease~~ decline in October and dropped to 1.2 m below ground by December~~ caused by a reverse of the recharge-discharge interrelationships. The surface water retreated to the subsurface~~, leading to drying of the bogs and thermokarst ponds. ~~We suppose that Tthe water table decline~~ This was caused by a reverse of the recharge-discharge interrelationships~~ between surface water and groundwater due to the existence of permafrost.~~ : ~~B~~by late October, glaciers ~~that are a major recharge source of suprapermafrost groundwater~~ were frozen~~.~~ and ~~A~~a~~nother major water source,~~ local precipitation~~,~~ was also minimal~~. B~~, but the discharge passages of suprapermafrost aquifer, located on hill slopes at relatively lower altitudes, remained unfrozen. Consequently, the discharge ~~of suprapermafrost groundwater,~~ exceeded the recharge during this period, ~~which~~ result~~ed~~ing in the drainage of suprapermafrost groundwater~~,~~ and decline ~~of~~ in the water table~~, and drying of bogs~~

~~and ponds~~.

5.1.2 Subpermafrost groundwater

~~Our results demonstrate that subpermafrost groundwater has patterns similar to suprapermafrost groundwater regarding either stable and radioactive isotopes and hydrogeochemistry or temporal variations of in groundwater temperature (Table 1 and 2; Figure 5). This suggests that the subpermafrost groundwater on the planation surface is strongly closely linked to surface hydrological processes. The ground temperature in the subpermafrost aquifer exhibits a slight seasonal variation consistent with air temperature. It increases in summer and decreases in winter. These results indicate the existence of an efficient passage allowing water to flow through permafrost from superficial water pools such as suprapermafrost aquifer, streams, or and thermokarst ponds to the subpermafrost aquifer. Our field investigation reveals that the An opposite seasonal variation in water was observed in subpermafrost groundwater compared to suprapermafrost water, rising in winter and declining in summer (Figure 4). This indicates suprapermafrost groundwater discharge to subpermafrost via passages such as sinkholes. There are widely distributed sinkholes resulting from thawing and collapse of permafrost that could serve as this kind of passages (Figure 11(a)), through which the suprapermafrost groundwater and thermokarst pond water rapidly recharge the subpermafrost groundwater. This is confirmed by the depleted δ^{13}C and relatively high DOC concentrations in subpermafrost groundwater.~~

The recharge from superficial water pools such as suprapermafrost aquifer and thermokarst ponds to the subpermafrost aquifer was suggested by the similar seasonal change in temperature between the supra- and subpermafrost groundwaters, although the amplitude of temperature change in subpermafrost groundwater was much smaller (Figure 5). Our field investigation revealed that the sinkholes resulting from thawing and collapse of permafrost serve as passages between supra- and subpermafrost aquifers (Figure 11a). However, the recharge amount from suprapermafrost aquifer should be limited since the subpermafrost groundwater had different geochemical characteristics, more depleted ^{2}H and ^{18}O isotopes and older ^{14}C age in comparison with suprapermafrost groundwater.

The weaker evaporation and stronger water-rock interaction for subpermafrost groundwater, inferred by more depleted ^{2}H and ^{18}O compositions and higher TDS and major ion concentrations than in suprapermafrost groundwater, suggest a second recharge source. This source should occur in a colder environment and thus be depleted in isotope composition, and experience a longer flow path and residence time for chemical reactions. On the δ^{2}H vs. δ^{18}O plot, the subpermafrost groundwaters fell between meltwater and suprapermafrost groundwater samples, suggesting that this second recharge source was glacier and snow meltwater (Figure 8).

~~However, the weaker evaporation and stronger water-rock interaction for subpermafrost groundwater, inferred by~~ ~~more depleted δ^{2}H and δ^{18}O compositions and~~ but relatively ~~larger TDS and major ion concentrations compared to those~~than ~~in suprapermafrost groundwater, suggest a second recharge source~~ (Figure 7 and and 8). ~~This source could~~ should ~~occur in a colder environment and thus be depleted in isotope composition~~, ~~and take a longer flow path and residence time in the~~

~~recharging process. On the $\delta^{2}H$ vs. $\delta^{18}O$ plot, the subpermafrost groundwater falls between meltwater samples and suprapermafrost groundwater samples, suggesting that this second recharge source is glacier and snow meltwater(Figure 8).~~ ~~negative~~values~~As described above, to the south,T~~ ~~the terrace on which cluster WW04 is located adjoins two higher terraces that are composed of thick moraine and fluvio-glacial deposits. Further south are moraine sediments in cirques and a glacier. This means that Tt~~The thick unconsolidated sediment, consisting of highly permeable ~~boulders and gravels~~moraine and fluvio-glacial sediments, is continuously deposited from the front of glacier to the lowest terrace on the top of the hill, and thus ~~existence of~~ a continuous, slightly sloping subpermafrost porous~~e~~ aquifer is expected. Thus, we hypothesize that glacier meltwater recharged~~s~~~~ding~~ ~~of the~~to the subpermafrost aquifer~~ occurs~~ mainly at localized water bodies such as glacier-fed headwater streams and lakes on the moraines~~, where surface water percolates through thawed stream bank and lake bed into the gravel and boulder deposits,~~ and then travel~~sed~~ for a long horizontal distance in the aquifer to ~~down into the subpermafrost aquifer and, finally, to the aquifer on~~ the lowest terrace where the cluster WW04 is located.~~through a long flow path.~~

~~Groundwater depth data show that t~~Although the subpermafrost aquifer underlies the 20 m thick permafrost, the water table below the bottom of permafrost indicated that the subpermafrost groundwater was unconfined~~though table is always below the bottom of overlying permafrost~~, ~~(Figure 4 and 5). The well log also records a relatively dry sediment layer at depths between 12 m and 12.5 m. The occurrence of this kind of groundwater that is in the confining aquifer but without additional pressure~~which is an indicator of poor recharge or/and good discharge of groundwater (Zhang et al., 2011). As the hydrogeological setting is relatively favorable for the recharge of subpermafrost groundwater in ~~summer~~warm season, it must have a comparable discharge capacity. ~~This capacity is related to aquifer permeability. Our data on~~The sediments and ground temperatures data show that the subpermafrost aquifer ~~underlied the 20 m thick permafrost~~ is mainly composed of unconsolidated sandy gravels and pebbles with high permeability~~the permafrost on the planation surface is thin, and thus the subpermafrost groundwater is mainly stored in unconsolidated material that is composed of gravels and pebbles with high permeability~~ (Figure 3 and 5)~~. These would~~, facilitating ~~permit~~ fast flow and thus ~~facilitate~~ groundwater discharge. In addition, the interface between unconsolidated sediments and underlying bedrock may also serve as an efficient passage for subpermafrost groundwater discharge (Woo, 2012).

There is a distinct break in sediment composition and thickness between the planation surface and the adjacent three hill slopes. With the thinning of the moraine and fluvio-glacial sediments, the subpermafrost ~~pore~~ porous aquifer disappears over the impermeable bedrock or ~~at the~~ thin residues ~~of~~ at the upper slopes. Thus, like the suprapermafrost groundwater, the subpermafrost groundwater was ~~is~~ mainly discharged directly into streams as baseflow, or onto ~~the~~ surface as seeps and springs at the upper portions of the hill slopes and then into streams. This is probably why several ground and spring icings can be found on the slopes during cold seasons (Figure 11~~(~~b~~)~~).

The recharge and discharge of the ~~S~~subpermafrost groundwater mainly occurred ~~is also recharged mostly~~ in the warm season, ~~whereas~~ while ~~recharge~~ they ~~is~~ were limited in the cold season. ~~because the sources are frozen. A similar pattern was seen for the discharge of subpermafrost groundwater.~~ However, the starting time of discharge ~~is~~ was earlier than the recharge time whereas the end times ~~are~~ were reversed due to the altitude difference between recharge sources and discharge exports. This would ~~decrease~~ reduce subpermafrost groundwater storage in ~~the~~ early autumn and later spring and ~~help explain~~illuminate why the subpermafrost groundwater table ~~declines~~ declined significantly in ~~winter~~cold season.

5.1.3 Intrapermafrost groundwater

~~Monitoring data of the 12 m well within cluster WW04 demonstrates the occurrence of intrapermafrost groundwater in a talik. However, t~~The ground temperatures in the talik ~~at the depths~~where intrapermafrost groundwater occurred ~~are~~ were similar to those ~~of~~ in the adjacent~~neighboring upper and lower~~ permafrost, being ~ 0 °C throughout the year (Figure 5). Thus, the localized presence of this unfrozen cold groundwater ~~is~~ may be related to its high mineralization (~ 1059 mg/L in TDS). ~~Hydrochemical and isotopic data further indicate that it is a closed talik.~~ The ~~EC,~~ TDS and concentrations of major cations, minor elements (Si and Sr), HCO_3^- and Cl^- in intrapermafrost groundwater ~~are~~ were much higher than in ~~subpermafrost~~ sub- and suprapermafrost groundwater and thermokarst pond water (Figure 7-b), excluding the mixture of these ~~open~~ water sources. On the other hand, the intrapermafrost groundwater ~~is~~ was depleted in ^{2}H and ^{18}O ~~depleted~~ and ~~falls~~ fell near the LMWL on the δ^2H vs. δ^{18}O plot (Figure 8), indicating a modern meteoric water origin without significant evaporation ~~(Clark and Fritz, 1997)~~. These results suggest that ~~the higher TDS and ions in~~ intrapermafrost groundwater ~~are a result of~~experienced a long-term water-rock interaction~~s~~ in a closed environment. The well logs show~~ed~~ that this talik ~~is~~ was rich in organic matter. Given the very low SO_4^{2-} ~~relative concentration~~ (4.1 mg/L) and much higher HCO_3^- concentration (833.6 mg/L) in the intrapermafrost groundwater, sulfurization may have occurred in the reservoir (Domenico and Schwartz, 1998). ~~This~~ The hydrochemical and isotopic data ~~provides additional evidence~~prove that this ~~hydrochemical~~ talik ~~is~~ was closed and ~~possesses~~ possessed strong reducibility, and also~~. The data also~~ suggest that the intrapermafrost groundwater ~~has~~ had a poor hydraulic connection with ~~suprapermafrost~~ supra- and subpermafrost groundwaters.

5.2 Exchange and pathways of groundwater in seasonal frost ~~region~~zone

5.2.1 Groundwater at the top of the piedmont sloping plain

The water table ~~in the 20 m well~~ was always higher in the 20 m well than ~~that~~ in the 30 m well within cluster WW03 and ~~the table~~it in both wells fluctuated ~~greatly~~ in response to heavy rainfall events and stream discharge pulses during the warm season. This suggests~~indicates~~ that the groundwater at the top of the piedmont sloping plain was~~is~~ recharged ~~mainly from~~by ~~rainfall or~~ local stream infiltration since the deep water table excluded the possibility of vertical rainfall infiltration. This was confirmed by the concave upward profiles of temperature~~s~~ at cluster WW03 in the warm season (Figure 5). However, ~~this is not supported by~~ the δ^2H and δ^{18}O values of groundwater~~, which~~ were relatively constant over time and showed little response to rainfall or stream discharge pulses (Figure 10-c), indicating that the isotopic signals might be diluted by lateral inflows from high mountain and hill areas to the groundwater at the top of the plain.

~~This means that t The groundwater depth at cluster WW02 was > 30 m and we can use its ground temperature profiles as references that are not affected by groundwater flow. In comparison, the upper part (< 6 m in depth) of all profiles at cluster WW03 had a similar pattern (Figure 5), excluding the possibility of rainfall or stream infiltration which would have shifted the profile to the right on the depth vs. temperature plot during the warm season. Conversely, temperature profiles shifted to the left at 6–16 m depths in September and October 2014 and August 2015, and at 6–28 m depths in July 2015, indicating the presence of colder lateral inflows (Figure 5). The groundwater is significantly depleted in ^{2}H and ^{18}O compared with rainfall occurring in the plain (Figure 8), indicating its recharge sources were generated in a colder environment.~~

The combined groundwater ~~level~~table, temperature, and hydrogeochemical and isotopic data suggest~~ed~~ that three sources may contribute to the lateral inflows~~ to the groundwater at the top of the plain~~. Two sources may be suprapermafrost and subpermafrost groundwater occurred in deposits on the planation surfaces of the higher hills which connect to the southeast top of the piedmont sloping plain. ~~, which~~As discussed above, they discharged onto hill slopes as seeps and springs and flowed down the slopes as surface runoff or ~~discharged into and can also~~ flowed through the weathered slope residues as subsurface runoff and~~. The water then flowed into the talus fans at the base of the hill~~, ~~and~~ finally moved as ~~a~~ lateral flow into the aquifer at the top of the sloping plain. The third source ~~is~~ was the suprapermafrost groundwater and surface runoff generated in the bedrock mountains which are connected to the south top of the piedmont sloping plain. In the bedrock mountains, ~~In the bedrock outcrop area, only~~ suprapermafrost groundwater ~~occurs~~ occurred only within the surficial ~~surface~~ fissures and weathered zones, and the amounts ~~are~~ were limited~~–~~ (Cao, 1977), whereas surface runoff~~. In fact, Bbedrock areas mountains were~~ was assumed to be~~ the key areas of surface runoff yield~~ abundant due to ~~their~~ the steep slopes and low permeability of the area (Chen et al., 2014). Much of this shallow subsurface and surface runoff ~~flows~~ flowed into streams while~~ much runoff~~ some of it may flow~~s~~ through talus fans at the base of mountains and, finally into the aquifer at the top of the sloping plain. The limited storage and rapid flow of this recharge source result~~s~~ed in significant responses of water table at the top of the plain~~a significant water table response, at the top of the plain,~~ to heavy rainfall events~~. T~~, while the mixture of runoff generated at different altitudes ~~minimizes~~ minimized the fluctuation of δ^{2}H and δ^{18}O ~~compositions~~values in groundwater~~ in δ^{2}H and δ^{18}O~~.

~~Ground temperature and water table results demonstrate that t~~The lateral inflows into the plain ~~occurs~~ occurred mainly during~~ rainy~~ warm season indicated by ground temperature and water table data~~ and when the active layer thaws in the mountains~~. As ~~T~~talus consists of gravel and boulders that are more permeable than mud-bearing pebble gravels in the plain (Xu et al., 1989)~~ and~~, the lateral flow from the mountains may accumulate at the top of the plain, leading to the increase in~~. Thus,~~ the water table~~ there rises~~rose, and thus ~~the~~ decreased difference in water table~~phreatic surface~~ between ~~mountain base~~the talus of the mountain and the top of the plain~~ becomes became minor~~gentle. As a result, the aquifer at the top of the plain ~~is~~ was ~~also~~ dominated by lateral flow with~~that has had~~ a small vertical component. ~~This means little difference in hydraulic head between shallow and deep groundwater. It~~It ~~would explain~~ addresses the distinct peaks in the water table ~~level~~ several days after heavy rainfall events and small difference in groundwater hydraulic head between the 20 m and 30 m wells within cluster WW03 during the ~~rainy~~ warm season (Figure 4). Over the cold season from November to June, the lateral inflow decreased and even~~finally~~ ceased ~~completely. T~~, but the groundwater stored during the ~~rainy~~ warm season was still released slowly to the base of the plain. As a consequence, the water table at the top of the plain declined dramatically and ~~thus~~ the phreatic surface between mountain ~~base~~ foot talus and the top of the plain became steeper. Therefore, the groundwater flow had~~s~~ a larger vertical downward component, ~~which~~ explain~~s~~ing the increased ~~why the~~ difference in water head between the 20 m and 30 m wells within cluster WW03 ~~increased~~ ~~in~~during the cold season (Figure 4). The lateral recharge from ~~sub~~permafrost groundwater was probably continuous ~~to~~ until ~~mid winter, as inferred by the slight shift of ground temperature profiles to the right in 15–28 m depth from~~ October as suggested by water table change~~to December 2014 (Figure 5)~~. ~~A depleted trend in δ^2H and δ^{18}O of groundwater during the cold season also provides evidence for this speculation (Figure 10 c).~~ The ~~change~~ switch of the water table dynamic in cluster WW03 from falling to rising in ~~April~~ May~~2015 may~~ marked the beginning of lateral recharge in a new annual cycle. This is consistent in time with the thaw of the active layer indicated by ground temperature ~~results~~ data at cluster WW04 (Figure 5).

5.2.2 Groundwater at the base of the piedmont sloping plain

The almost invariable groundwater table at cluster WW01 during either warm or cold season was typical characteristics of groundwater in discharge area. Along the flow path from cluster WW03 to WW01~~ locations~~, major ions and TDS concentrations increased, and the enrichment of ^{2}H and ^{18}O isotopes ~~of~~in groundwater was expected (Clark and Fritz, 1997). However, the groundwater had more negative δ^2H and δ^{18}O values at cluster WW01 than ~~that~~ at cluster WW03 (Figure 8), which suggests the mix of an isotopically depleted water source when groundwater flowed through the plain. The local rainfall infiltration can be excluded according to the recent research on water balance in the plain, which reported that the thick vadose zone and high transpiration prevented precipitation from entering the aquifer (Chen et al., 2014). From June to September when the stream water was fed by isotopically depleted glacier meltwater and thus had more negative δ^2H and δ^{18}O values, groundwater exhibited the similar depleted trend in ^{2}H and ^{18}O~~value~~, strongly suggesting the recharge of stream infiltration to the groundwater (Figure 8 and 10). The recharge of this "new" water source also explains the very young age of groundwater at cluster WW01 inferred by ^{3}H concentration (Table 2).

~~Compared to the cluster WW03, the fluctuation of water tablethe water table fluctuation at cluster WW01 was more gradual, representing typical characteristics of groundwater in the discharge area (Figure 4). The groundwater had more negative δ^2H and δ^{18}O values at cluster WW01 than at cluster WW03 (Figure 8), although groundwater was flowing from cluster WW03 to WW01 and isotopic enrichment of groundwater is expected along the flow path (Clark and Fritz, 1997). This means that an isotopically depleted water source must have recharged the groundwater when it flowed through the plain. The recharge by local rainfall that is isotopically enriched relative to groundwater can be excluded (Yang et al., 2012), so this additional recharge may have beenbe from streams. Streams are fed mainly by isotopically depleted glacier meltwater runoff and precipitation runoff in the high mountains and the water percolates down into the coarse-textured aquifer when~~

~~flowing through the plain. This result is also supported by recent research on water balance in the plain, which reported that the thick vadose zone and high transpiration prevented precipitation from entering the aquifer (Chen et al., 2014). The δ^2H and δ^{18}O values of groundwater at cluster WW01, which were intermediate between the values of groundwater samples at cluster WW03 and stream water samples, also support this explanation (Figure 8 and 10). The δ^2H and δ^{18}O values of groundwater at cluster WW01 are closer to those of stream water during high flow periods (Figure 10), indicating a larger contribution to the aquifer from stream leakage. The ground temperature profiles at cluster WW01, which shifted to the right below 12 m depth in September and October 2014 and July and August 2015 (Figure 5), indicate that river leakage mainly occurred upstream in summer and then flowed toward the base of the plain as lateral inflows. The recharge of this "new" water source also explains the very young age of groundwater at cluster WW01 inferred by ^{3}H concentration and the TDS value similar to that in groundwater at cluster WW03 (Table 2).~~

As ~~previously~~ described above, the piedmont sloping plain is funnel-shaped, with only a narrow gorge at the base leading to the Heihe River. The east and west tributaries~~feeder streams~~ converged into the main Hulugou stream in front of the gorge, which then ~~is~~ was contained within the gorge (Figure 1-b). Since~~Because~~ the gorge is surrounded ~~between~~by hills that are composed of less permeable shales and sandstones~~,~~ ~~(Figure 1-c)~~ and unconsolidated deposits ~~are~~ were only found on the bottom of the gorge, groundwater ~~from the open plain~~ was blocked ~~also converges~~ in front of the gorge with the narrowing of flow cross section~~,~~ and ~~then is~~ discharged mainly as baseflow along the main stream ~~within the gorge~~ or as springs at the ~~base~~ foot of the hills (Figure 1-b). ~~This means that the groundwater in front of the joint of open plain and gorge is blocked, just like and pushed upward similar to the backwater caused by subsurface damming (McClymont et al., 2010).~~ This is similar to the "fill and spill" mechanism in hillslope hydrology (Spence and Woo, 2003; Tromp-van Meerveld and McDonnell, 2006) and ~~helps explain~~ addresses the relatively high and stable~~why the~~ water table in the warm season at cluster WW01~~, near which is located slightly above the junction of open plain and gorge, was relatively high and stable in both rainy and dry seasons~~ (Figure 5). ~~Small differences in water head between the 5 m, 10 m, 15 m and 20 m wells during warm seasons indicates that the aquifer at the base of the plain is also dominated by lateral flow which has a small vertical component (Figure 5).~~ The water table in the 5 m and 10 m wells at WW01 were close to each other and higher than that in the 15 m and 25 m wells in the warm season. This may be related to the continuous clay layer at depth of 13-18 m and suggests two flow paths in the aquifer. Given that the groundwater flow within the gorge was~~is~~ ~~completely~~ consistent ~~in the horizontal direction~~ with the stream flow in the horizontal direction ~~within the gorge~~, the shallow groundwater was ~~should be mainly~~ discharged into the upper portions of the main Hulugou stream, while the deep groundwater ~~is~~ drained~~discharged~~ into the lower portions ~~of the stream~~ (Figure 12).

The discharge of groundwater to the stream was indicated by the similar chemical compositions between the stream water and groundwater ~~D~~during the cold season, ~~groundwater is still discharged mainly as baseflow, but~~ and the discharge process~~situation~~ ~~is~~ was complicated by the development of stream icing and seasonal frost. Our data show~~s~~ that all tributaries were dry throughout the cold season ~~from October to May cold season~~ and river icing was only found in the main Hulugou stream channel within the gorge (Figure 11~~(-b)~~). Icing was initially formed in the upper reaches of the stream channel in early winter, followed by continued thickening and downstream expansion~~ of the icing~~ in winter and early spring. ~~At the same time~~Meanwhile, icing was also formed at the spring near the ~~basin~~plain-hill border. Field investigation in late January, 2015 showed that the upper reaches of the stream channel were completely filled with ice and no water was flowing under ~~the ice~~it. The frozen streambed ~~streambed was probably also frozen, not only blocking groundwater discharge into the stream and but also also~~ exert~~ing~~ed hydrostatic pressure on ~~it~~ the groundwater. ~~Although there is no ground temperature data in the gorge, we can deduce from the data at cluster WW01 that~~ T~~t~~he maximum depth of the seasonal frost in the gorge should be ~~>~~3 m deduced from the temperature data at cluster WW01 (Figure 5). Considering that the main stream ~~is~~ was sustained completely by baseflow in winter, the groundwater depth along stream channel~~s~~ (bottom of the gorge) should be shallow and probably < 1 m. Thus, the ~~the impermeable~~ seasonal freezing would reach the water table~~ rapidly~~ in early winter and also exert~~ed~~ pressure on groundwater, resulting in the confined condition in~~.~~ ~~T~~the unconsolidated sediment aquifer within~~at the bottom of~~ the gorge~~ would then become a confined aquifer in winter~~. When groundwater flow~~s~~ed from the phreatic aquifer in the open plain to this tilted confined aquifer, it would have a larger vertical downward component~~.~~, ~~This would explain~~causing~~ why~~ the larger difference in the water head between the 5 m, 10 m, 15 m and 20 m wells within cluster WW01 ~~became larger~~ in the cold season (Figure 4). At the lower reaches of the stream channel with~~, though~~ water ~~was still~~ flowing under ice, the ~~increased~~ icing constricted the channel cross section and exerted hydrostatic pressure on stream water, also significantly reducing groundwater discharge into the channel (Kane, 1981). This may be another reason responsible for~~why~~ the relatively stable water table at the base of the open plain~~ was relatively high and stable, even~~ in the winter. The~~ great difference in~~ more ~~depleted~~negative δ^2H and δ^{18}O ~~compositions~~values in the stream water compared to ~~between the~~its source groundwater ~~at cluster WW01 and the stream water (Figure 10), which should be derived from the same source because the stream was sustained completely by baseflow,~~ indicates~~d~~ a strong isotopic fractionation between river icing and stream water (Souchez and Jouzel, 1984). ~~The switch of water head dynamics in the deep wells within cluster WW01, from falling to rising in April 2015 (Figure 4), may mark the initial melting of river ice, and the sharp rise in June 2015 may mark the beginning of inflow from upstream to the plain aquifer. The latter is consistent in time with the refilling of dry upstream channels with runoff.~~

5.3 Conceptual model of the groundwater exchange and pathways

Based on the geochemical, thermal, isotopic and hydrological results, a conceptual model of the hydrological connectivity in the mountain-hill-plain complex was developed (Figure 12). Groundwater in the high mountains mainly occurred~~s~~ as suprapermafrost groundwater within either moraine and scree deposits or surficial fissures in bedrock outcrop areas. In the moraine and fluvio-glacial deposits on the planation surfaces of higher hills (about > 3500 m a.s.l.), ~~suprapermafrost~~supra-, ~~intrapermafrost~~intra-, and subpermafrost groundwaters co-occurred. There ~~are~~ were three hydrological passages through which glacier/snow meltwater and precipitation were~~are~~ transported from the high mountains to the plain. The first and fastest one ~~is~~ was the stream channel, which generally originated~~s~~ at the glacier front and ~~is~~ was fed by ~~glacial~~ glacier and snow meltwater in its head. Then it ~~moves~~ was recharged by overland flow and suprapermafrost groundwater over its course from the mountains to the piedmont sloping plain, and also probably by subpermafrost groundwater at the ~~base~~ foot of hill slopes. The stream ~~percolates~~ percolated partly down into the aquifers when flowing through the open plain, and ~~then~~ ~~is~~ was recharged by groundwater when flowing through the gorge ~~at the north end of the plain~~. This passage ~~is~~ was available only during the warm season and ~~it~~ drie~~s~~d up during the cold season. The second passage ~~is~~ was the slope surface and suprapermafrost aquifer, which collected precipitation over a large area, ~~and~~ then transport much of it as overland flow and suprapermafrost groundwater into talus fans at the ~~base~~ foot of mountains or hills, and finally into the aquifer at the top of the plain. Where the moraine and scree deposits in high mountains adjoin the moraine and fluvio-glacial deposits on higher hills, the glacier and snow meltwater may also be transported through this passage after flowing through moraine and scree deposits ~~into the suprapermafrost reservoir~~ at the lower margin of cirques. This passage ~~is~~ was also seasonal. The third passage ~~is~~ was the subpermafrost aquifer occurring on the planation surface, through which the recharged glacier/snow~~conducts~~ meltwater that percolated down ~~percolating down~~ over the moraines within cirques flowed to the hill slopes, and finally into the aquifer at the top of the plain ~~via a variety of pathways~~. The water within the second passage ~~is~~ also added into this passage through supra- and subpermafrost connections on the planation surface. ~~This~~ The third passage ~~is~~ was the slowest one, but also the only one that ~~is~~~~was~~~~may be~~was available during cold season.

The ~~Quaternary~~ porous aquifer ~~under~~ in the piedmont plain ~~is~~ was mainly recharged by the lateral flow from the south mountains and hills and ~~also by~~ the seepage of streams ~~when they flow through the open plain~~, and discharged mainly as baseflow to the stream in the north gorge. The water table dynamics ~~at the top of the plain~~ at the top of the plain ~~are~~ were characterized by sharp rises and recessions in response to heavy rainfall events but a gradual decline during the cold season ~~at the top of the plain~~, while ~~. Water table dynamics~~~~that~~those at the base of the plain exhibited ~~are characterized by~~ a stable condition confined to a narrow range. This behavior ~~indicates~~ indicates a rapid transfer of groundwater from the south top to the north base of the plain during the ~~high-flow~~warm ~~period~~ season and a slow release of stored groundwater during the ~~low-flow period~~cold season~~.~~. ~~It~~It suggests that the groundwater ~~under~~ in the plain not only contributed significantly to stream flow during the warm season, but also maintain~~s~~ed stream flow over the cold season~~, but also contributes significantly to stream flow during the rainy season~~. We propose ~~–~~ two mechanisms involved in the significant seasonal variation of the aquifer in water-conduction capacity~~.~~, ~~These~~ ~~They~~which ~~are~~were surface drainage through the stream channel and subsurface drainage to an artesian aquifer confined by stream icing and seasonal frost (Figure 12). The first mechanism ~~is~~ was similar to “fill and spill” in hillslope hydrology (Spence and Woo, 2003; Tromp-van Meerveld and McDonnell, 2006) and ~~involves~~ involved the funnel-shaped distribution of unconsolidated permeable deposits ~~on~~ in the plain. When groundwater flowed ~~moving~~ from the wide plain to the gorge, the cross section narrowed down ~~of groundwater flow becomes narrow~~, ~~resulting in~~leading to a decrease in ~~reduced~~ transmissivity~~, increased flow resistance,~~ ~~–~~ and an uplifted water table. This ~~ensures~~ kept ~~that~~ the water table in front of the gorge ~~never~~ from drop~~s~~ping below the channel bed ~~and~~, thus maintaining continuous~~ly~~ flowing~~s~~ in the downstream channel ~~continuously flows~~ throughout the year. On the other hand, ~~T~~the unchecked surface drainage through the stream channel ~~prevents~~ prevented the water table from rising too high after storms in the rainy season. This mechanism explains the rapid transfer of groundwater from the top to the base of the plain and the stable water table in front of the gorge during the ~~high-flow period~~warm season. The second mechanism ~~works~~ worked only during the cold season, when the stream icing and seasonal frost ~~converts~~ converted the aquifer~~the bottom of~~ in the gorge from unconfined to ~~into~~ a confined ~~aquifer~~condition. The rise of the downstream groundwater head ~~reduces~~ reduced the hydraulic gradient between the wide plain and the gorge, resulting in decreased discharge~~ and reduced transmissivity~~. In addition, the increased icing ~~constricts~~ constricted the channel cross section while the descending frost reduce~~s~~d the effective thickness of saturated soil, ~~and~~ significantly ~~reduces~~ decreasing groundwater discharge into the channel. This mechanism ~~explains~~ illuminated the slow release of stored groundwater from the plain and thus the gradual decline of the water table at the top of the plain during the ~~low-flow period~~cold season.

6. Conclusions

~~Knowledge of groundwater systems in permafrost areas is often meagre (Kane et al., 2013). Groundwater studies in permafrost are challenging given the limited infrastructure and the short field season. These conditions favor samples from baseflow discharge and perennial groundwater springs, combined with the use of geochemical and isotope tracers to elucidate recharge conditions and flow paths. We selected a representative catchment in the headwater region of Heihe, Qinghai-Tibet Plateau as a study site. The study used groundwater head, temperature, geochemical, and isotopic information to determine the roles of groundwater within the permafrost zone for hydrologically connecting waters originating from glaciers in the high mountains to lower elevation rivers.~~

~~Previous studies reported that groundwater in the permafrost region occurred only as suprapermafrost groundwater (Cao, 1977). Our field study confirms the co-occurrence of supra-, intra- and subpermafrost groundwater. The suprapermafrost groundwater is mainly recharged by local precipitation and glacier meltwater, and discharged into streams as baseflow, or onto the surface as seeps and springs. An additional discharge route of suprapermafrost groundwater is leakage to the subpermafrost aquifer through sinkholes. The suprapermafrost groundwater generally has a short flow path, leading to a relatively short residence time and weak water-rock interactions. Recharge mostly occurs during warm seasons since the source waters (glacier meltwater and precipitation) are mainly concentrated when the active layer is thawed. Limited recharge occurs in the cold season because the recharge sources and the active layer are frozen. Due to a change in the thawing depth of the active layer and frequent conversion of the recharge-discharge interrelationship, the storage of suprapermafrost groundwater varies significantly throughout the warm seasons. The subpermafrost groundwater on the planation surface is strongly linked to the surface hydrological processes and it is recharged from suprapermafrost groundwater and glacier and snow meltwater. The chemical and isotopic results indicated that the suprapermafrost groundwater had not flowed through the underlying bedrock and then moved upward to the subpermafrost aquifer after deep circulation along fissures as previous study indicated (Evans et al., 2015). The glacier meltwater recharging the subpermafrost aquifer occurred mainly at localized water bodies. The highly permeable unconsolidated materials in which~~

~~the subpermafrost groundwater is stored facilitate fast groundwater discharge. The subpermafrost groundwater discharges into streams as baseflow or onto the surface as seeps and springs. The subpermafrost groundwater is also recharged mostly in warm seasons, whereas the recharge is very limited in cold seasons. Intrapermafrost groundwater occurs in a closed hydrochemical talik with strong reducing environments and poor hydraulic connections with the suprapermafrost and subpermafrost groundwater.~~

~~The moraine and fluvio-glacial deposits on the planation surfaces of the higher hills are commonly distributed in the head water regions of the Heihe River. These deposits provide another major reservoir for the storage and flow of groundwater in the permafrost region. This is the first report on the occurrence of subpermafrost and intrapermafrost groundwater in the head water regions of the Heihe River.~~

~~The groundwater under the piedmont plain within the seasonal frost zone is mainly recharged by lateral flow from the south mountains and hills and the seepage of streams, and is discharged as baseflow into the stream in the north gorge. A rapid transfer of groundwater from the south top to the north base of the plain occurs during the high-flow period whereas stored groundwater is slowly released during the low-flow period. The seasonal variation of the aquifer in water conduction capacity was interpreted by two mechanisms: (1) surface drainage via the stream channel, similar to "fill and spill" mechanism in hillslope hydrology. The narrowed cross section of groundwater flow from the wide plain to the gorge led to an increase in the water table, preventing the water table upstream from the gorge from dropping below the channel bed and maintaining the continuous flow in the downstream channel throughout the year. This explains the rapid transfer of groundwater from the top to the base of the plain and the stable water table in front of the gorge during the high-flow period; and (2) subsurface drainage to an artesian aquifer confined by stream icing and seasonal frost. When the stream icing and seasonal frost changes the bottom of the gorge into a confined aquifer during the cold season, downstream groundwater head rises and the hydraulic gradient between the wide plain and the narrow gorge is reduced. In addition, increased icing constricts the channel cross section, significantly reducing groundwater discharge into the river channel. The second mechanism proposed here explains the slow release of stored groundwater from the plain and thus the gradual decline of the water table at the top of the plain during the low-flow period. This expanded the existing "fill and spill" mode for catchment and hillslope hydrology.~~

Groundwater studies in permafrost area are challenging ~~given~~because of the limited infrastructure and the short field season. These conditions favor the use of geochemical and isotop~~e~~ic tracers in ~~samples from~~ baseflow ~~discharge~~ and perennial ~~groundwater~~ springs to supplement~~, combined with~~ hydrogeological data ~~the use of geochemical and isotope tracers~~ to elucidate recharge conditions and flow paths. ~~We~~ By select~~ed~~ing a representative catchment in the headwater regions of the Heihe River, Qinghai-Tibet Plateau as study site~~. The study used~~, this research employed the groundwater head, temperature, geochemical, and isotopic information to determine the roles of groundwater –in permafrost and seasonal frost zone for hydrologically connecting waters originating from glaciers in the high mountains to lower elevation rivers.

Our field measurements ~~confirm~~shows the co-occurrence of supra-, intra- and subpermafrost groundwaters in the headwater regions of the Heihe River. To ~~our~~the best of our knowledge, this is the first report ~~on~~of the occurrence of sub~~permafrost-~~ and intrapermafrost groundwaters in this region. The moraine and fluvio-glacial deposits on the planation surfaces of higher hills, which ~~were~~are commonly distributed in the headwater regions of the Heihe River, provide a major reservoir for the storage and flow of sub~~permafrost-~~ and intrapermafrost groundwater. The subpermafrost groundwater on the planation surface ~~is~~was~~is~~was interconnected to the surface hydrological processes and recharged by suprapermafrost groundwater and glacier and snow meltwater. The results of ~~the~~ this study could shed new lights on the understanding of the groundwater flow and its interaction with surface water at other catchment, as well as improve the evaluation and management of water resources in the headwater regions of the Heihe River.

Glacier and snow meltwater ~~are~~were~~are~~were transported from the high mountains to the plain through stream channels, slope surfaces, and~~, slope surfaces, and~~ supra~~permafrost aquifers-~~ and subpermafrost aquifers. The groundwater ~~under~~in the piedmont plain within seasonal frost zone ~~is~~was mainly recharged by the lateral flow from the supra- and subpermafrost aquifers~~south mountains and hills~~ and ~~by~~ the seepage of streams, and was discharged as baseflow into the Hulugou stream in the north gorge. A rapid transfer of groundwater from the south top to the north base of the plain occurred during the warm season~~high flow period~~, while the stored groundwater was slowly released during the cold season~~ low flow period~~. This seasonal variation of the aquifer in water-conduction capacity ~~is~~was interpreted by two mechanisms: (1) surface drainage via the stream channel, analogous to the "fill and spill" mechanism in hillslope hydrology. The narrowing of aquifer from the wide plain to the gorge l~~eads~~ed to a relatively high water table near the gorge, preventing it from dropping below the channel bed and maintaining a perennial flow in the downstream. This ~~also explains~~addresses the rapid transfer of groundwater from the top to the base of the plain and the stable water table in front of the gorge during the ~~high flow period~~warm season; and (2) subsurface drainage to an ephemeral artesian aquifer confined by stream icing and seasonal frost. The stream icing and seasonal frost not only blocked~~ed~~ the groundwater discharge, but also changed~~sd~~ the bottom of the gorge into a confined aquifer during the cold season, leading to an increase in the downstream groundwater head ~~rises~~ and a decrease in the hydraulic gradient between the wide plain and the narrow gorge~~ is reduced. In addition, increased icing constricts the channel cross section, significantly reducing groundwater discharge into the stream channel.~~ The second mechanism elucidates ~~proposed here explains~~ the slow release of stored groundwater from the plain and the low baseflow in channel throughout~~during~~ the cold season~~ low flow period~~.

Acknowledgements

This research was financially supported by the National Natural Science Foundations of China (~~NSFC~~ No. 91325101~~, and~~ 91125009, and 41521001)~~ and the Grant for Innovative Research Groups of the National Natural Science Foundation of China (No. 41521001)~~.

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Figure captions:

Figure 1. (a) Location of the head~~-~~water regions of the Heihe River~~ Basin~~ and the distribution of ~~Quaternary ~~unconsolidated deposits within the~~ upper Heihe River Basin~~ regions~~;~~, (b) a map of the Hulugou ~~Catchment ~~catchment ~~study area ~~showing monitoring and sampling sites~~;~~, and (c) a geological cross section.

Figure 2. (a) Precipitation ~~recorded at an elevation of 3649 m a.s.l.,~~ and (b) air temperature recorded at an elevation of 3649 m a.s.l. within the Hulugou ~~Catchment ~~catchment from ~~April ~~June 2014 to ~~October ~~April 2016~~5~~.

Figure 3. The well log of the sediments for cluster~~ well~~s WW01, WW02 and WW03 within the seasonal frost zone, and cluster WW04 within the permafrost zone.

Figure 4. ~~Water table depth in the cluster wells WW03 at the up-gradient recharge zone and WW01 at the down-gradient discharge zone within the seasonal frost zone, and in the cluster well WW04 within permafrost zone.~~ Time series of water table depth in the wells at cluster WW01, WW02 and WW04.

Figure 5. Temperature envelopes in the sediments at ~~locations ~~clusters~~of~~ WW01, WW02 and WW03 within the seasonal frost zone, and cluster WW04 within the permafrost zone.

Figure 6. The piper diagram for groundwater~~s~~, ~~river ~~stream water~~s~~, ~~rain ~~precipitation and glacier and snow meltwater~~snow-melting waters~~ in the study area. "H" refers to ~~summer ~~high flows in warm season; "L" refers to ~~winter ~~low flows in cold season.

Figure 7. (a) Groundwater chemistry at different depths of ~~various ~~the two cluster~~ well~~s within the seasonal frost zone~~ (a)~~, and (b) chemistry of groundwater, ~~river ~~stream water and thermokarst pond water within the permafrost zone~~ (b)~~. WW01, WW03 and WW04 are symbols for cluster~~ well~~s. The number in brackets means the specific screen depth of ~~cluster ~~wells. Note the log scale on the y-axis.

Figure 8. The δ^{18}O and δ^{2}~~D~~H relationship ~~in ~~for different water types collected from September 2014 to August 2015, as well as~~and~~ ~~in~~ for ~~permafrost sediments from September 2014 to August 2015.~~water/ice extracted from sediment cores at cluster WW04.

Figure 9. The ~~change of~~variation of δ^{18}O and δ^{2}H~~D~~ in water/ice extracted from sediment cores ~~compositions along~~with depth ~~of iced sediments below ground surface ~~at cluster WW04~~within permafrost zone~~.

Figure 10. Time series of the Hulugou stream discharge (a), and ~~and ~~δ^{18}O in stream water (b), well water (c) and spring water (d).~~Heihe River flux (a), and the δ^{18}O and δD values change with time in river waters (b), well waters (c), and spring waters (d) from June 2014 to May 2016.~~

Figure 11. Pictures showing~~:~~ (a) sinkholes in the permafrost zone, and (b)~~Photos of sinkholes widely developed within permafrsot zone (a), and~~ ~~river ~~stream icing within the gorge (left) and spring icing on the hill slope (right) during cold season~~(right) at the study site in winter (b)~~.

Figure 12. Conceptual model of groundwater exchange and pathways~~ groundwater flow system~~ in the Hulugou catchment~~at the study site~~.

Table 1. Mean values~~,~~ and standard deviations (± SD) of major ions, Si and Sr, and TDS concentrations in groundwater and stream water (in mg/L) within permafrost and seasonal frost zones. Number of samples used to calculate is also shown. All samples were collected ~~and number of samples used to determine chemical concentrations in different types of waters from July to September, and~~ from January 2014 to September ~~in 2014~~ 2015. "H" refers to ~~summer~~ high flows in warm season; "L" refers to ~~winter~~ low flows in cold season. "n.s." means that no samples were collected.

~~Water type~~Sampling information		Number of ~~S~~samples ~~number~~		Ca^{2+}		Mg^{2+}		Na^{+}		K^{+}		Sr		Si	
Water type & ~~Location~~location	Sample ~~No~~site~~.~~	H	L	H	L	H	L	H	L	H	L	H	L	H	L
Stream water; East tributary, periglacial ~~and permafrost~~ zone	RW27	18	2	28.5±3.9	11.3±2.7	15.6±2.3	5.3±1.3	1.6±0.4	0.9±0.1	0.5±0.1	0.3±0.1	0.2±0.0	0.1±0.0	0.9±0.1	0.2±0.0
	RW28	15	2	27.9±2.7	16.5±9.1	15.2±1.5	8.4±4.2	1.6±0.5	1.3±0.5	0.5±0.2	0.4±0.1	0.2±0.0	0.1±0.0	0.9±0.1	0.3±0.3
	RW03	15	0	27.3±2.6	n.s.	14.5±1.7	n.s.	1.5±0.4	n.s.	0.4±0.1	n.s.	0.2±0.0	n.s.	0.8±0.1	n.s.
Stream water; East tributary, seasonal frost zone	RW29	17	2	34.0±7.3	19.3±13.3	20.7±6	14.2±10.0	2.5±1.2	1.8±1.4	0.6±0.1	0.4±0.2	0.2±0.1	0.1±0.1	1.2±0.3	0.4±0.3
	RW30	15	0	33.6±9.6	n.s.	20.0±6.9	n.s.	2.4±1.3	n.s.	0.5±0.1	n.s.	0.2±0.1	n.s.	1.1±0.2	n.s.
Stream water; West tributary, seasonal frost zone	RW24	19	3	26.1±1.8	32.5±14.4	12.6±1.0	16.7±5.9	1.8±0.3	2.1±0.6	0.6±0.3	0.7±0.4	0.1±0.0	0.2±0.1	1.1±0.1	1.4±1.1
	RW25	19	0	31.2±2.8	n.s.	15.1±1.8	n.s.	2.2±0.4	n.s.	0.6±0.1	n.s.	0.1±0.0	n.s.	1.2±0.1	n.s.
	RW26	19	0	32.3±3.1	n.s.	15.5±1.8	n.s.	2.5±0.5	n.s.	0.7±0.1	n.s.	0.1± 0.0	n.s.	1.2±0.1	n.s.
Stream water; ~~C~~Catchment outlet, seasonal frost zone	RW08	20	3	46.6±8.9	60.2±37.7	28.5±6.3	39.3±23.2	4.9±1.7	9.7±6.9	0.8±0.2	1.2±0.8	0.3±0.1	0.5±0.4	1.6±0.2	1.6±1.2
	RW10	20	4	50.9±6.5	76.7±11.2	31.3±4.6	36.6±4.3	7.3±1.6	26.2±12.2	0.9±0.2	1.6±0.3	0.4±0.1	0.8±0.1	1.8±0.2	2.8±1.3
Spring water; Seasonal frost zone	QW02	19	4	59.3±4.1	51.4±16.1	36.7±1.7	31.5±7.8	14.1±0.8	12.4±3.9	1.4±0.2	1.1±0.6	0.5±0.0	0.5±0.2	2.3±0.2	1.7±1.3
	QW03	20	4	62.7±5.7	48.6±14.1	37.5±2.6	30.3±8.0	16.6±0.4	13.4±6.2	1.4±0.3	1.0±0.5	0.6±0.0	0.5±0.2	2.4±0.3	1.9±1.0
	QW04	20	4	64.5±5.1	48.5±15.3	39.0±2.3	30.4±8.6	18±0.3	13.5±5.5	1.5±0.3	1.1±0.6	0.6±0.0	0.5±0.2	2.4±0.2	1.8±1.2
	QW05	20	4	65.5±7.3	52.9±10.0	39.7±3.2	34.0±5.7	19.1±0.5	16.3±4.2	1.5±0.3	1.2±0.4	0.7± 0.0	0.6±0.1	2.6±0.8	2.0±1.1
	QW08	20	4	58.9±5.5	44.6±15.2	36.2±3.0	28.2±8.2	13±1.3	8.0±2.6	1.1±0.1	0.9±0.5	0.6±0.0	0.5±0.2	2.3±0.2	1.7±1.2
Well water; ~~at p~~Permafrost zone	WW04 (24.3m)	1	0	47.4	n.s.	22.9	n.s.	23.3	n.s.	6.4	n.s.	0.3	n.s.	1.3	n.s.
	WW04 (12m)	0	2	n.s.	204.6±1.4	n.s.	95.9±1.3	n.s.	221.0±10.4	n.s.	9.7±1.8	n.s.	2.7±0.1	n.s.	9.1± 0.2
	WW04 (1.5m)	17	0	72.4±5.7	n.s.	15.4±1.4	n.s.	8.6±2.8	n.s.	4.3±1.3	n.s.	0.3±0.0	n.s.	3.9±0.3	n.s.
Well water ~~at~~; The top of the sloping plain, seasonal frost~~,~~	WW03 (30m)	19	4	55.1±11	33.3±13.2	36.7±6.3	25.2±9.9	17.6±15.1	21.1±10.6	1.6±0.9	1.7±1.0	0.4±0.1	0.3±0.1	1.8±0.1	1.2±1.2
	WW03 (20m)	19	3	60.1±6.9	57.0±9.6	38.8±3.8	35.6±7.2	7.3±2.7	6.7±1.3	1.2±0.4	1.4±0.4	0.4±0.0	0.4±0.1	1.9±0.2	1.9±1.0
	WW03(10m)	6	0	46.5±11.8	n.s.	35.7±13.1	n.s.	9.4±6.8	n.s.	4.7±5	n.s.	0.3±0.1	n.s.	1.9±0.5	n.s.

zone~~upgradient~~													
Well water; The base of the sloping plain, ~~at~~ seasonal frost zone~~,~~ ~~downgradient~~	WW01 (25 m)	19	4	65.3±20.1	31.4±4.3	43.2±10.9	20.7±9.9	24.5±42.5	14.5±7.7	1.7±1.2	1.3±0.8	0.5±0.1	0.2±0.1	2.2±0.3	1.1±1.1
	WW01 (15 m)	19	4	67.1±15.7	70.8±20.1	43.8±9.6	41.8±11.3	13.2±18.1	13.1±7.8	1.4±0.7	1.5±0.7	0.5±0.1	0.5±0.1	2.2±0.3	1.6±0.9
	WW01 (10 m)	19	2	64.9±17.4	80.8±3.6	42.2±11.8	34.4±4.8	8.7±2.2	6.6±1.3	1.3±0.6	0.7±0.2	0.4±0.1	0.4±0.0	2±0.4	0.4±0.2
	WW01 (5 m)	12	0	76.6±8.4	n.s.	48.9±4.8	n.s.	9.0±1.0	n.s.	1±0.1	n.s.	0.5±0.1	n.s.	2.1±0.1	n.s.

Sampling information		Number of samples		SO_4^{2-}		NO_3^-		Cl^-		HCO_3^-		TDS	
Water type & location	**Sample site**	**H**	**L**	**H**	**L**	**H**	**L**	**H**	**L**	**H**	**L**	**H**	**L**
Stream water; East tributary, periglacial zone	RW27	18	2	29.5±11	32.9±13.6	2.2±1.1	1.4±0.6	3.3±0.1	7.3±0.9	105.6±13.2	104.0±4.1	134±16.7	111.5±11.8
	RW28	15	2	31.7±8.3	30.2±11.0	2.5±0.9	1.4±0.2	3.1±0.3	8.1±2.5	102.1±12.9	107.3±5.5	133.6±14.2	120.0±30.1
	RW03	15	0	31.2±8.9	n.s.	2.6±0.9	n.s.	3.3 ± 0.2	n.s.	101.2 ± 12.2	n.s.	131.5 ± 14.4	n.s.
Stream water; East tributary, seasonal frost zone	RW29	17	2	45.3±16.6	57.6±14.2	2.9±1	1.7±0.4	3.4±0.4	6.6±0.0	131.4±29.8	133.6±9.9	175.1±44.9	168.6±44.4
	RW30	15	0	46.8±27.1	n.s.	3±1.2	n.s.	3.3±0.4	n.s.	125.1±33.2	n.s.	172.1± 61.0	n.s.
Stream water; West tributary, seasonal frost zone	RW24	19	3	28.7±8.4	73.3±14.8	2.7±0.6	1.9±0.4	3.5±0.2	3.9±0.2	96±6.9	122.7±5.8	124.2±11.5	192.5±34.0
	RW25	19	0	41.4±10.1	n.s.	3.1±0.7	n.s.	3.7±0.2	n.s.	108.5±11.5	n.s.	151.6 ± 17.6	n.s.
	RW26	19	0	44.7±10.6	n.s.	3.2±0.7	n.s.	3.6±0.3	n.s.	108 ± 9.5	n.s.	156.7 ± 18	n.s.
Stream water; Catchment outlet, seasonal frost zone	RW08	20	3	92±30	207.9±107.0	3.9±1.2	3.1±1.1	3.7±0.4	5.2±0.6	166.3±30	240.0±85.6	263.6±61.2	446.8±218.8
	RW10	20	4	106.4±23.8	246.1±71.0	4±1.1	2.7±0.7	4±0.4	6.9±2.3	178.8±25.7	238.0±4.5	294.4±47.5	516.1±89.7
Spring water; Seasonal frost zone	QW02	19	4	126.1±27.7	162.1±31.1	4.2±1.4	2.8±0.4	4.9±0.5	5.5±0.4	222.3±12.8	230.7±2.6	358±31.4	382.4±22.7
	QW03	20	4	137.3 ±43.6	152.7±26.8	4.1±1.6	2.6±0.7	5±0.7	5.3±0.7	233.1 ± 13.9	238.8±3.4	381.2±50.9	373.4±56.8
	QW04	20	4	150.1±34.1	156.0±20.0	4.2±1.4	2.8±0.4	5.6±0.6	5.4±0.4	237.7±10.7	240.3±4.7	401.9±38	378.2±48.6
	QW05	20	4	150.9±34.2	147.7±39.1	4.2±1.5	5.3±6.6	5.5±0.6	5.3±0.8	243.4±11.2	248.7±5.5	408.4±37.2	387.3±53.8

	QW08	20	4	95.4±33.2	107.5±37.1	4.3±1.8	2.4±1.0	4.4±0.5	4.6±0.7	254.8±14.1	246.1±6.0	340.8±40.3	319.5±61.1
Well water; Permafrost zone	WW04 (24.3m)	1	0	64.7	n.s.	1.5	n.s.	17.6	n.s.	237.5	n.s.	302.9	n.s.
	WW04 (12m)	0	2	n.s.	4.1±0.0	n.s.	0.2±0.2	n.s.	106.4±10.4	n.s.	833.6±30.2	n.s.	1059.3±40.6
	WW04 (1.5m)	17	0	10.2±5.5	n.s.	0.3±1.1	n.s.	6.1±1.1	n.s.	294.3±25.7	n.s.	264.6±18.2	n.s.
Well water; The top of the sloping plain, seasonal frost zone	WW03 (30m)	19	4	115±16.8	74.9±24.6	3.8±1.3	0.1±0.1	4.5±0.9	4.9±0.3	243.8±24.9	282.4±14.7	356.4±29.6	302.6±52.1
	WW03 (20m)	19	3	116.2±31.7	148.8±26.5	4±1.5	2.4±0.4	4±0.5	5.1±0.4	236.1±31.4	250.2±9.0	349.7±41.3	382.3±42.1
	WW03(10m)	6	0	122.4±64.2	n.s.	3.6±0.7	n.s.	5±1.1	n.s.	297.8±136.3	n.s.	409.5±196.4	n.s.
Well water; The base of the sloping plain, seasonal frost zone	WW01 (25 m)	19	4	158.9±51.6	92.4±22.0	4.9±2.4	0.7±0.7	5.2±2.7	5.1±0.4	270.6±43	212.1±32.5	439.2±95.9	272.5±61.0
	WW01 (15 m)	19	4	162.4±33.6	212.3±70.9	5.5±2	2.8±0.9	4.8±1.1	5.0±0.2	255±42.2	287.6±58.4	425.9±78.2	491.3±126.7
	WW01 (10 m)	19	2	150.5±52.6	267.7±26.6	5.3±2.1	2.6±0.2	4.7±0.7	5.1±0.4	243.2±54.6	332.2±2.7	399.4±109.3	564.1±35.9
	WW01 (5 m)	12	0	172.6±33.2	n.s.	6.9±1.2	n.s.	4.5±0.3	n.s.	269.4±23.9	n.s.	454.3 ± 58	n.s.

Table 2. ^{3}H, ^{13}C and ^{14}C isotopic composition of groundwater samples and ^{14}C ages corrected using the ~~^{13}C~~ δ^{13}C-mixing model modified by Clark and Fritz (1997). "n.d." means not determined and "n.c." means not calculated.

Sample site	^{3}H (TU)	δ^{13}C (‰)		^{14}C activity (pmC)		Uncorrected ^{14}C Age		Corrected ^{14}C age	
		δ^{13}C	Error (1σ)	^{14}C activity	Error (1σ)	Age (year)	Error (1σ)	q	Age (year)
WW04 (24.3 m well)	n.d.	-16.77	0.51	76.43	0.32	2159	34	0.90	1637
WW04 (1.5 m well)	15.11	-13.60	0.57	96.34	0.31	299	26	0.76	-2009 (modern)
WW03 (30 m well)	19.38	-8.79	0.57	51.77	0.22	5288	33	0.49	-483 (modern)
WW03 (20 m well)	16.22	n.d.	n.d.	n.d.	n.d.	n.c.	n.c.	n.c.	n.c.
QWIP01 (spring)	20.69	-8.31	0.61	35.51	0.17	8317	39	0.46	2170
QWIP02 (spring)	17.33	-8.05	0.55	49.60	0.20	5632	32	0.45	-856 (modern)
WW01 (25 m well)	16.95	-5.92	0.53	44.38	0.18	6525	33	0.33	-2477 (modern)
WW01 (15 m well)	24.18	n.d.	n.d.	n.d.	n.d.	n.c.	n.c.	n.c.	n.c.
WW01 (10 m well)	16.20	n.d.	n.d.	n.d.	n.d.	n.c.	n.c.	n.c.	n.c.
QW02 (spring)	27.83	n.d.	n.d.	n.d.	n.d.	n.c.	n.c.	n.c.	n.c.
QW03 (spring)	13.84	n.d.	n.d.	n.d.	n.d.	n.c.	n.c.	n.c.	n.c.
QW05 (spring)	43.59	n.d.	n.d.	n.d.	n.d.	n.c.	n.c.	n.c.	n.c.
QW04 (spring)	13.61	-5.09	0.70	43.05	0.19	6770	34	0.28	-3475(modern)
QW08 (spring)	18.58	n.d.	n.d.	n.d.	n.d.	n.c.	n.c.	n.c.	n.c.

~~n.d. means not determined and n.c. means not calculated.~~

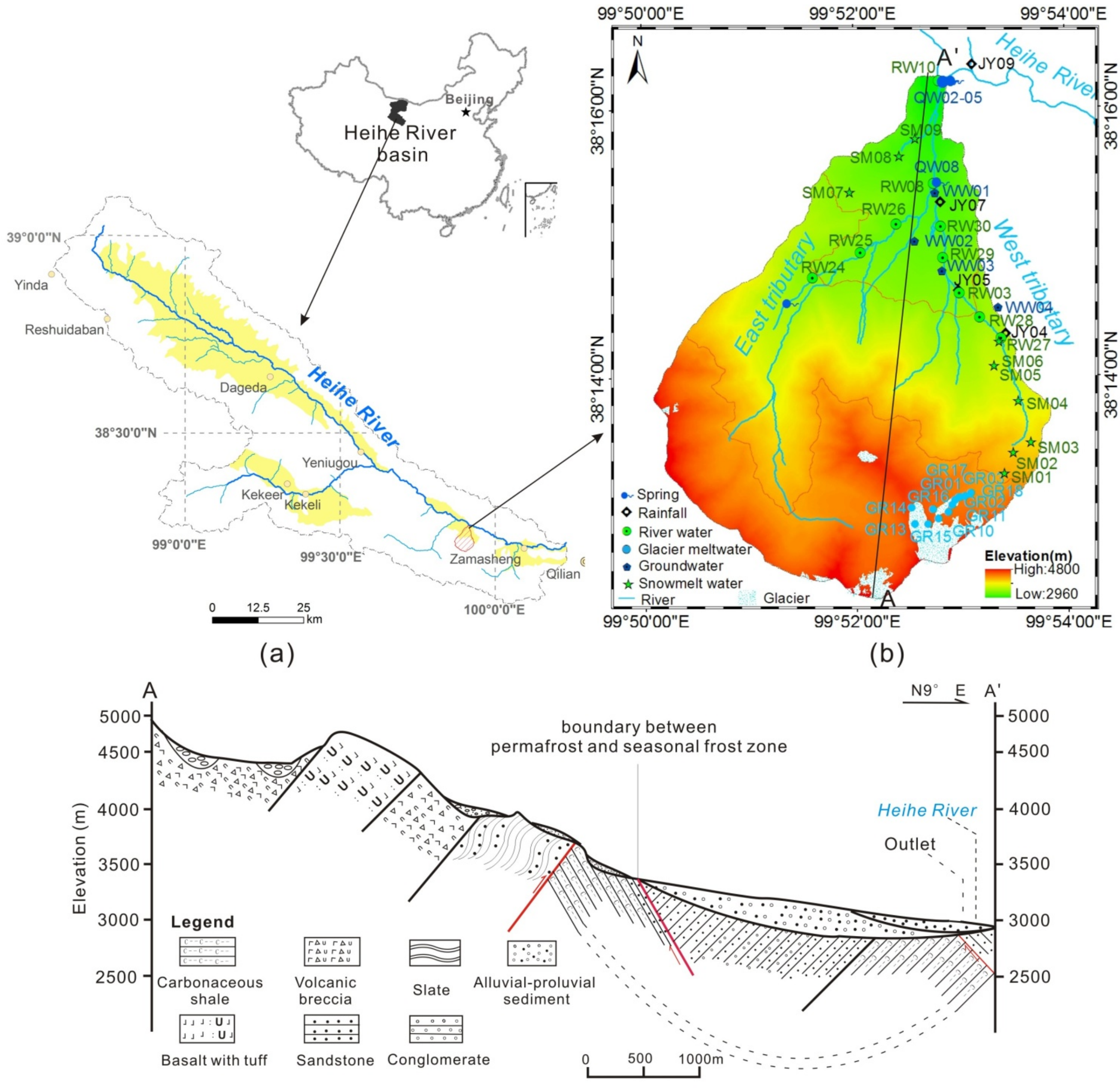

Figure 1. (a) Location of the headwater regions of the Heihe River and the distribution of unconsolidated deposits within the regions, (b) a map of the Hulugou catchment showing monitoring and sampling sites, and (c) a geological cross section.

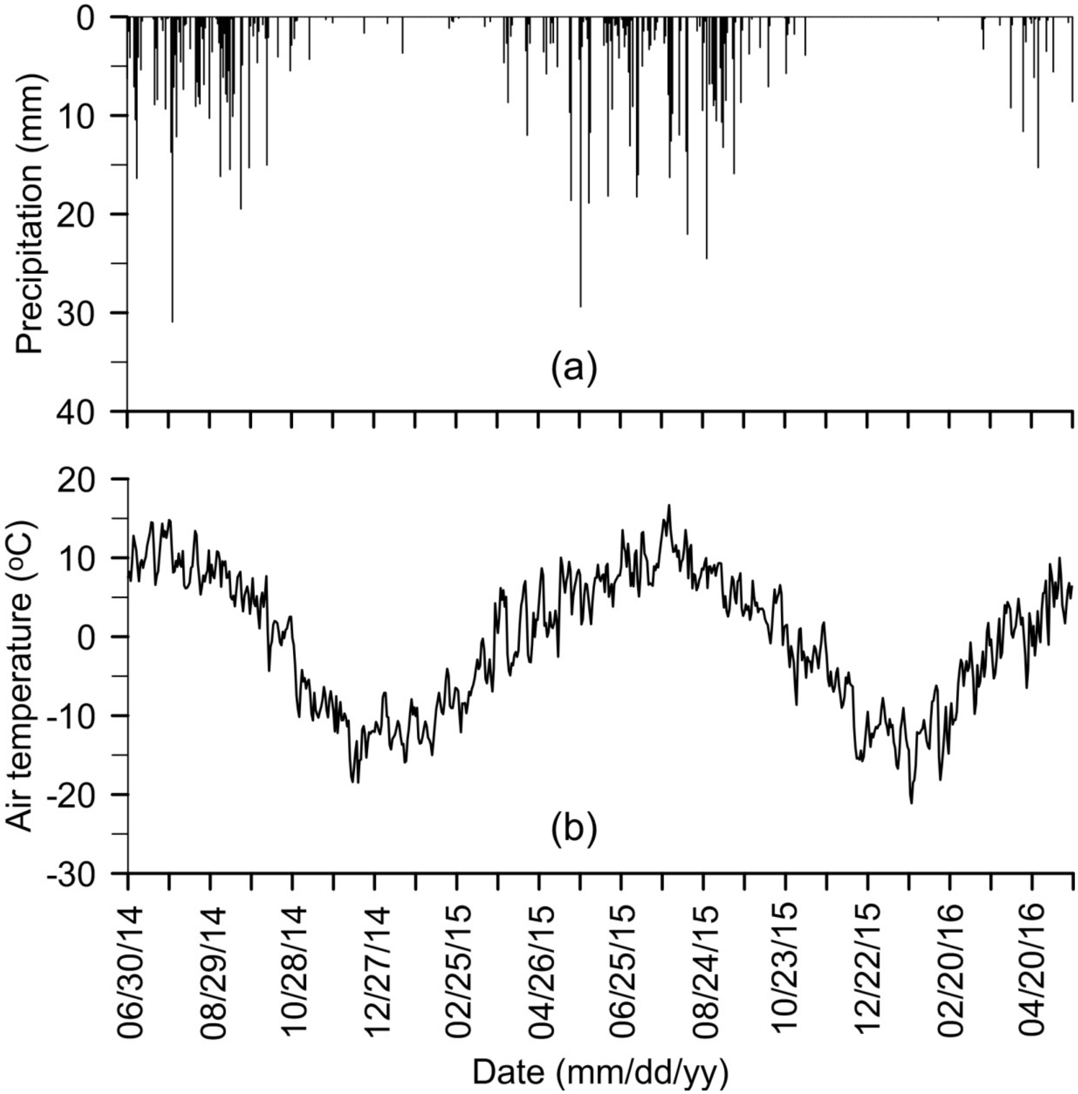

Figure 2. (a) Precipitation and (b) air temperature recorded at an elevation of 3649 m a.s.l. within the Hulugou catchment from June 2014 to April 2016.

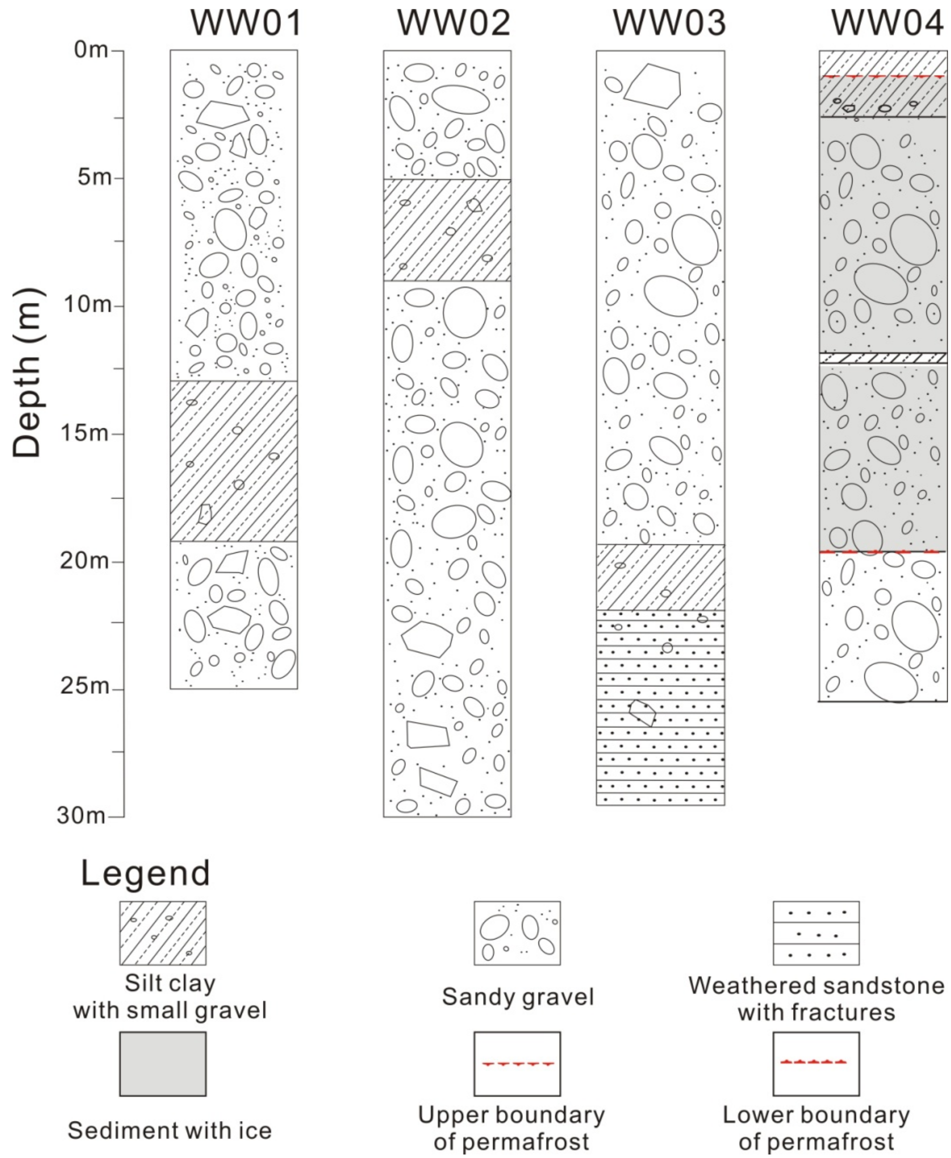

Figure 3. The well log of the sediments for clusters WW01, WW02 and WW03 within the seasonal frost zone, and cluster WW04 within the permafrost zone.

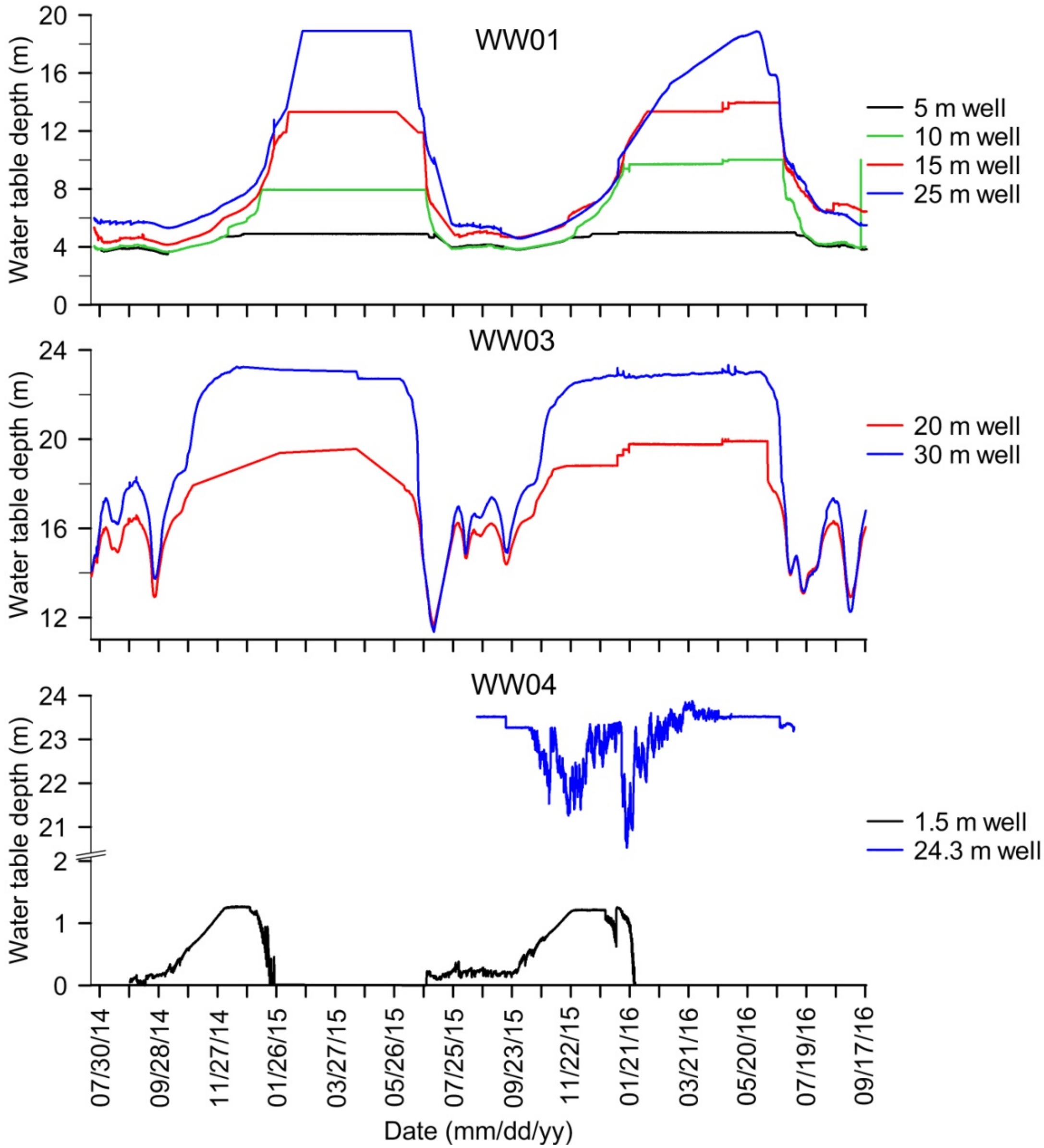

Figure 4. Time series of water table depth in the wells at cluster WW01, WW02 and WW04.

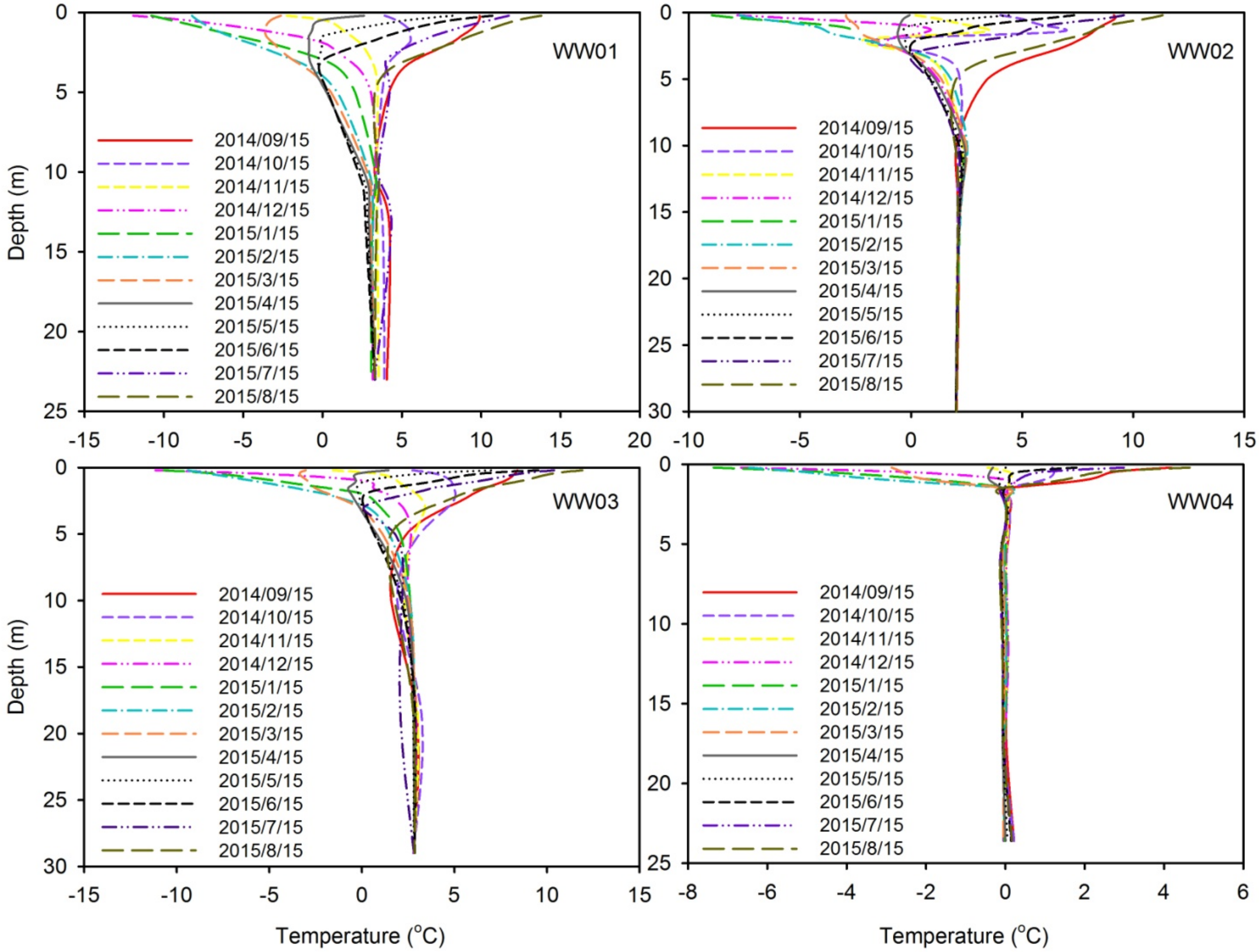

Figure 5. Temperature envelopes in the sediments at clusters WW01, WW02 and WW03 within the seasonal frost zone, and cluster WW04 within the permafrost zone.

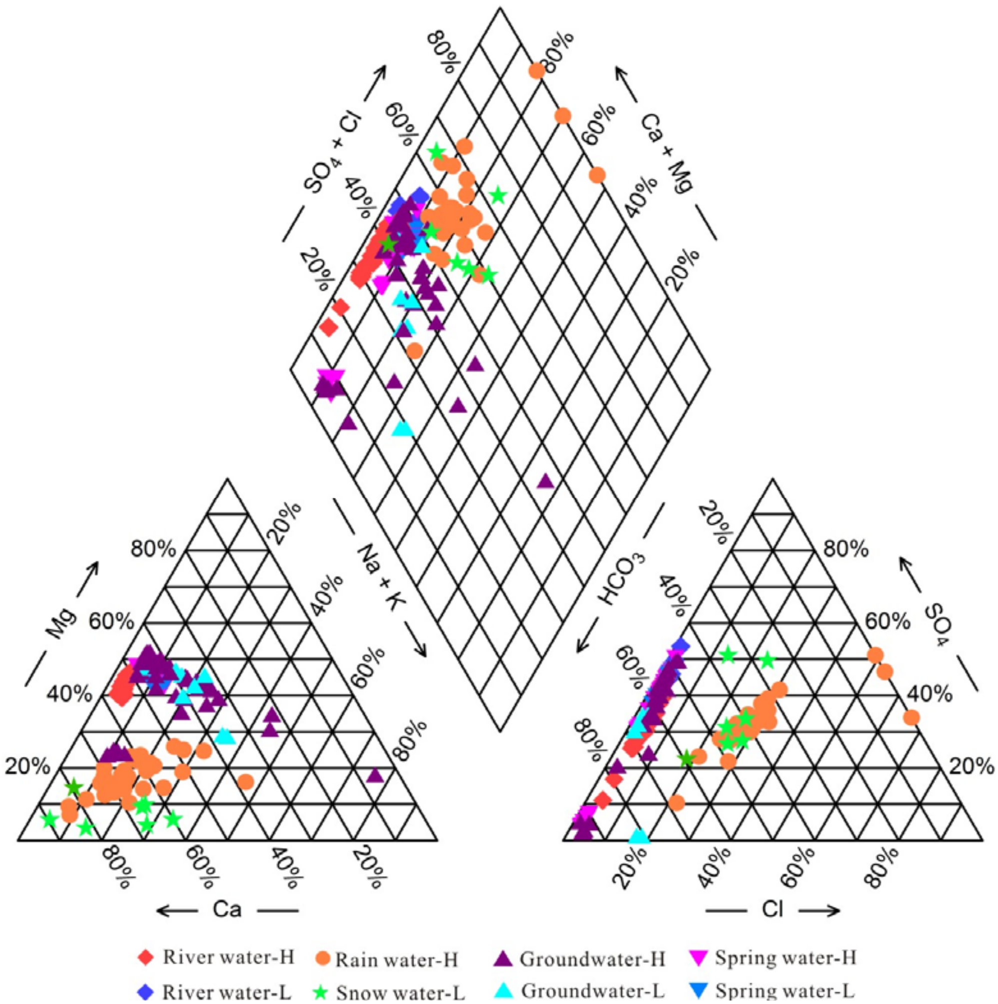

Figure 6. The piper diagram for groundwater, stream water, precipitation and glacier and snow meltwater in the study area. "H" refers to high flows in warm season; "L" refers to low flows in cold season.

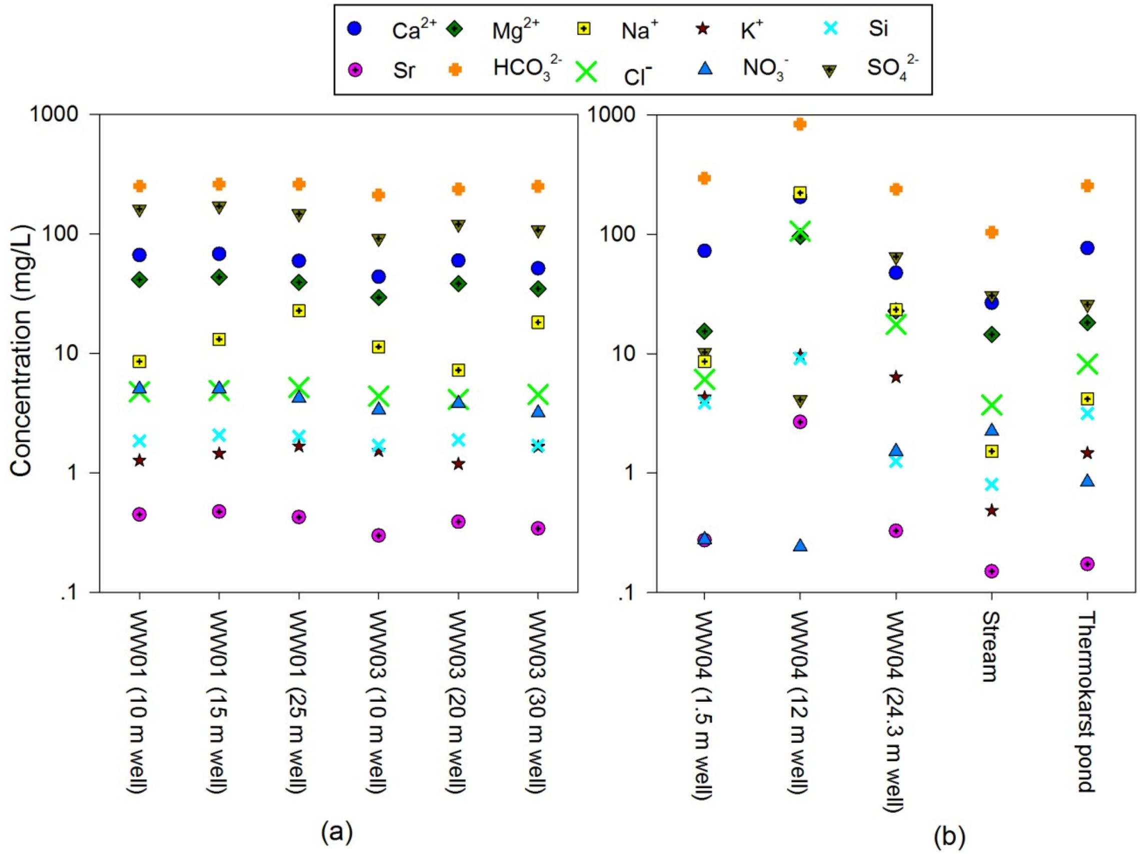

Figure 7. (a) Groundwater chemistry at different depths of the two clusters within the seasonal frost zone, and (b) chemistry of groundwater, stream water and thermokarst pond water within the permafrost zone. WW01, WW03 and WW04 are symbols for clusters. The number in brackets means the specific screen depth of wells. Note the log scale on the y-axis.

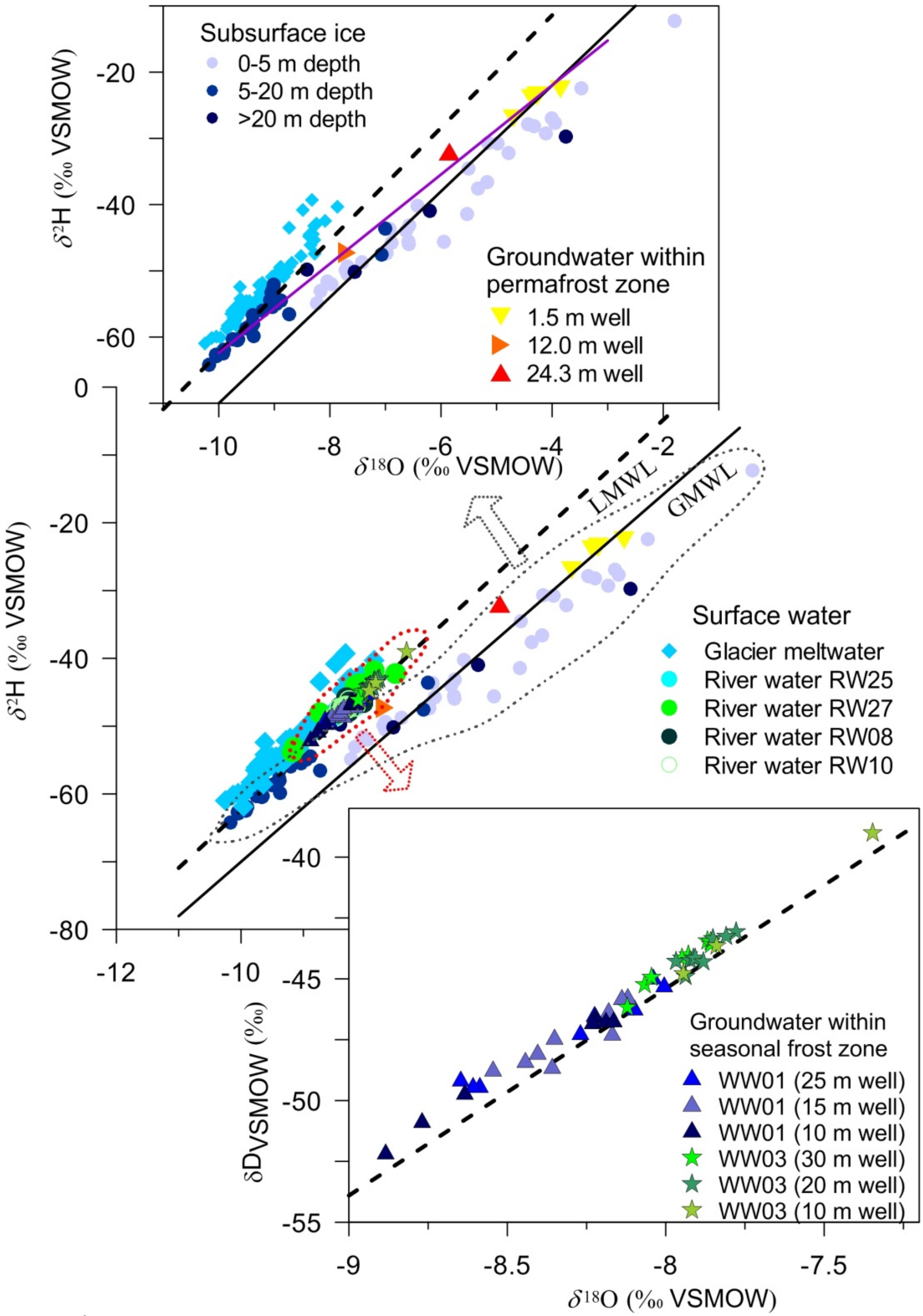

Figure 8. The δ^{18}O and δ^{2}H relationship for different water types collected from September 2014 to August 2015, as well as for water/ice extracted from sediment cores at cluster WW04.

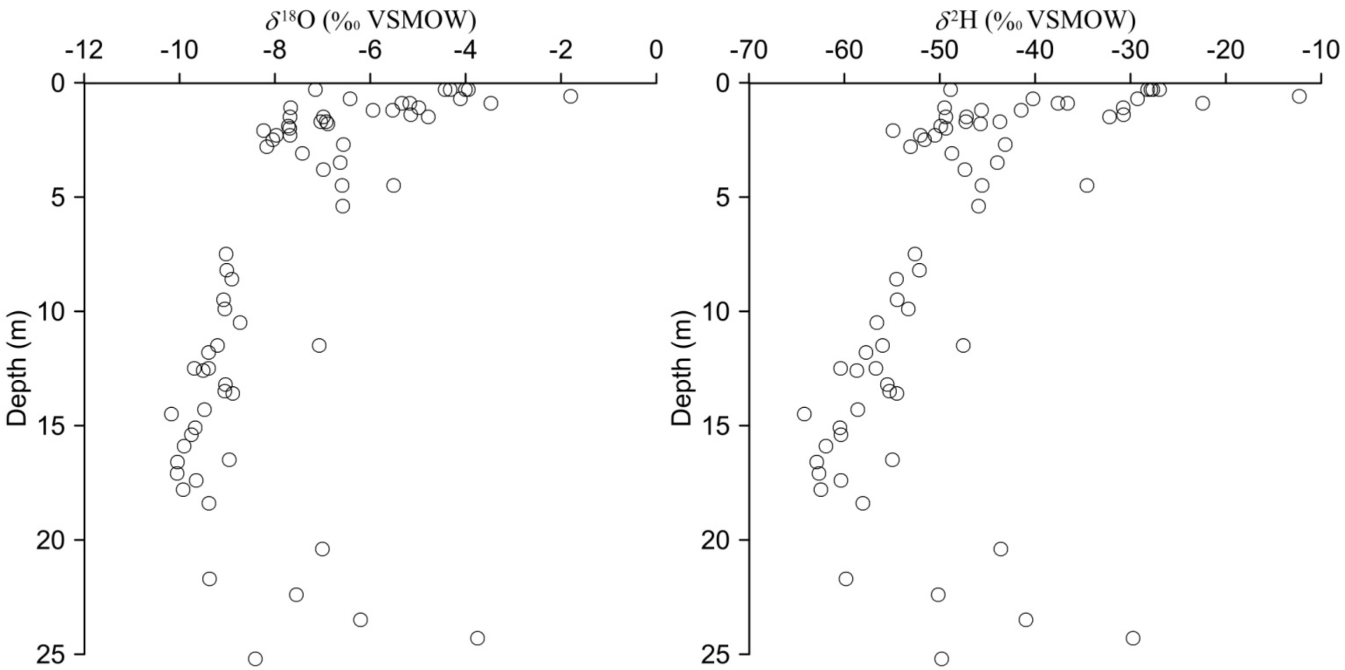

Figure 9. The variation of $\delta^{18}O$ and $\delta^{2}H$ in water/ice extracted from sediment cores with depth at cluster WW04.

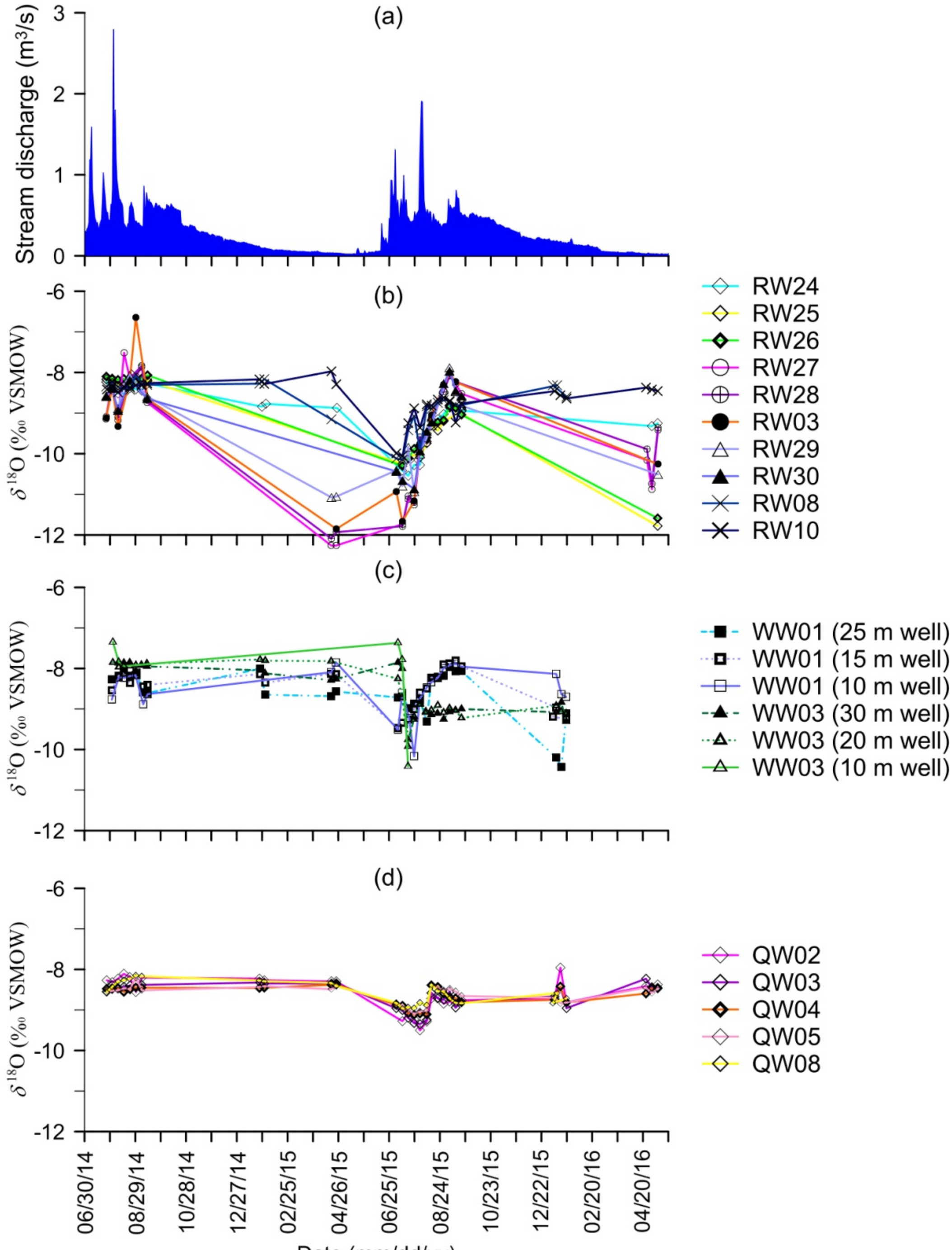

Figure 10. Time series of the Hulugou stream discharge (a), and $\delta^{18}O$ in stream water (b), well water (c) and spring water (d).

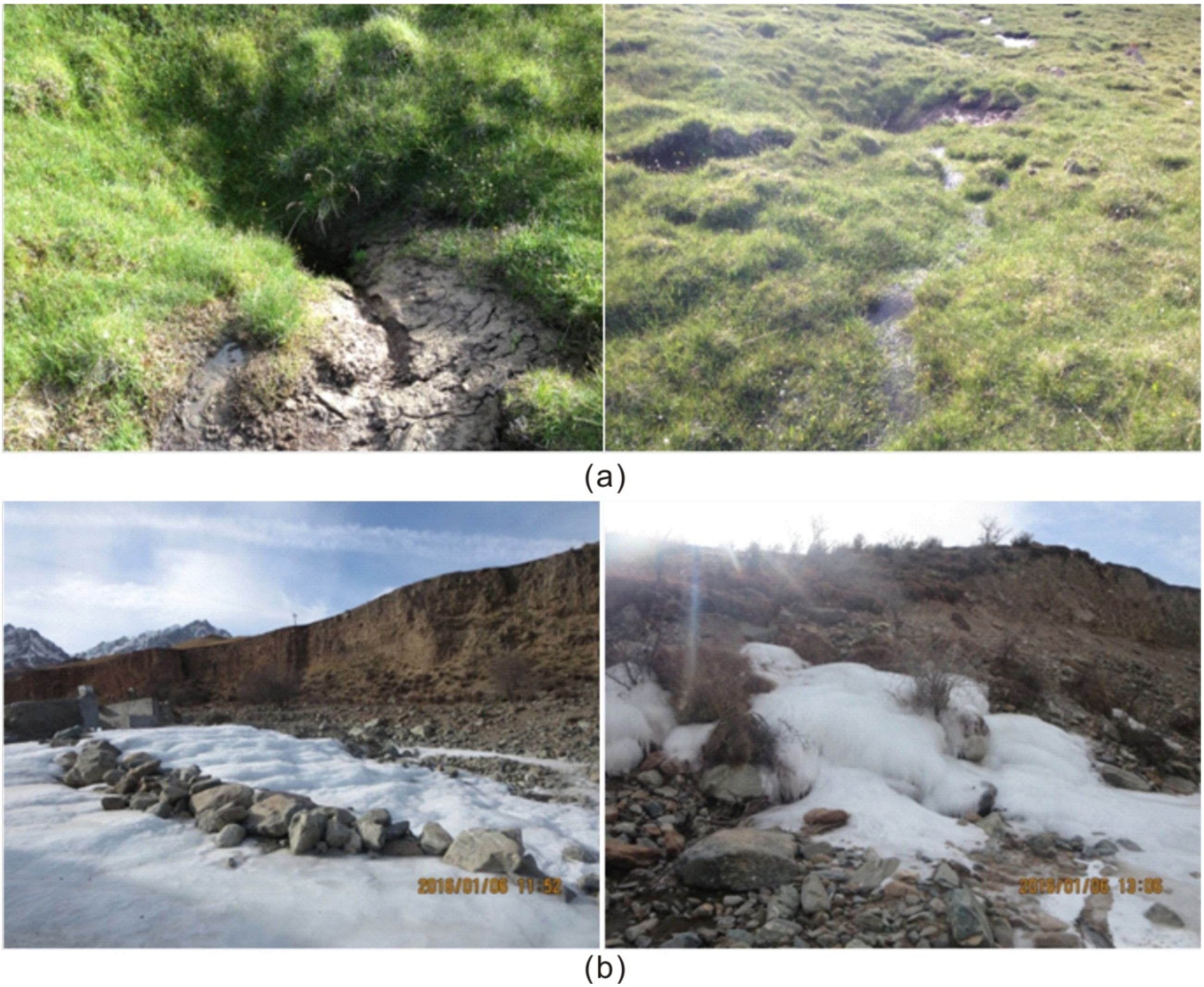

Figure 11. Pictures showing (a) sinkholes in the permafrost zone, and (b) stream icing within the gorge (left) and spring icing on the hill slope (right) during cold season.

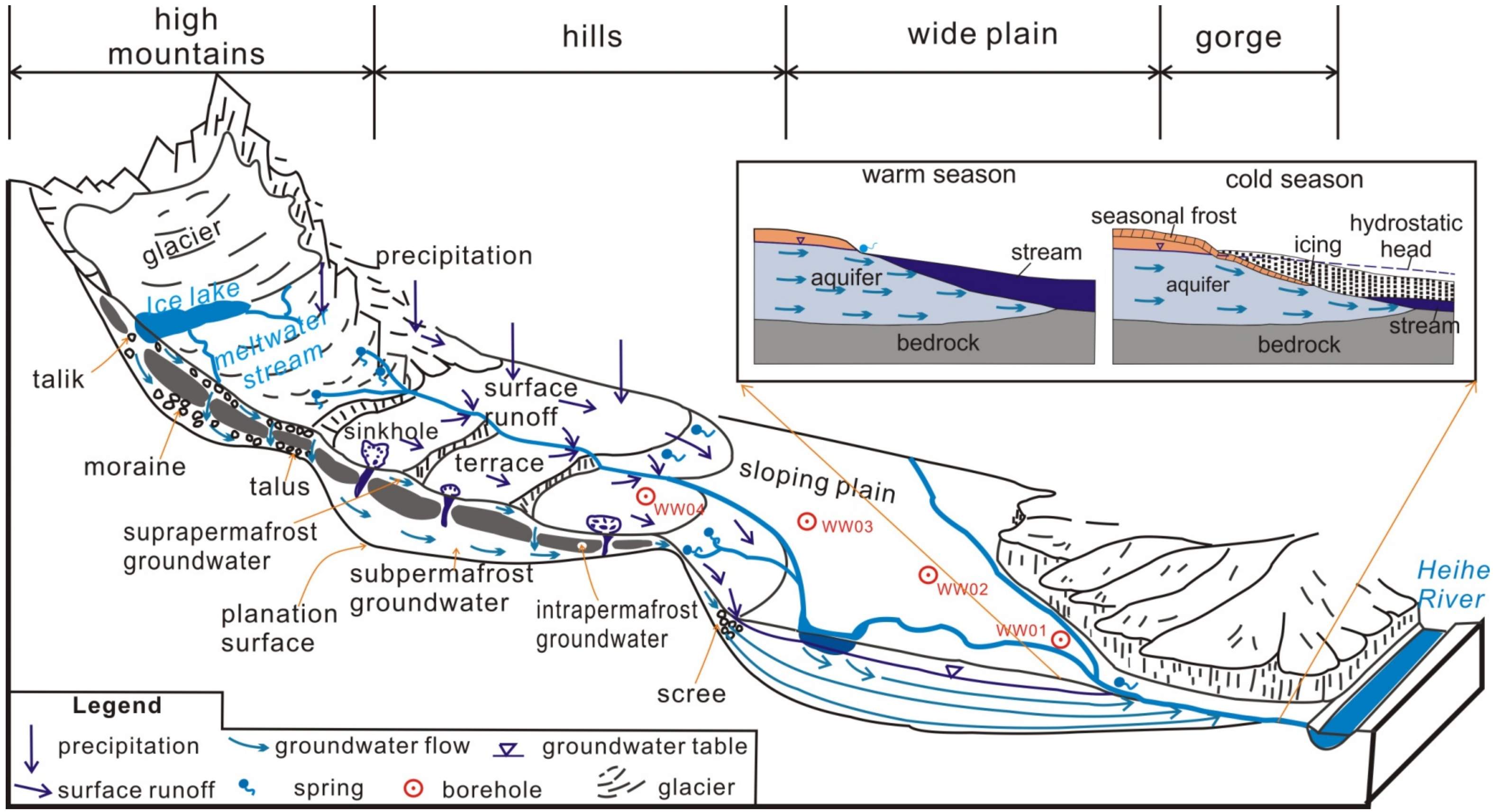

Figure 12. Conceptual model of groundwater exchange and pathways in the Hulugou catchment.