Links between seasonal suprapermafrost groundwater, the hydrothermal change of the active layer, and river runoff in alpine permafrost watersheds

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Abstract. The seasonal dynamic of the suprapermafrost groundwater significantly affects the runoff generation and confluence in permafrost basins and is a leading issue that must urgently be addressed in hydrological research in cold and alpine regions. In this study, the seasonal dynamic process of the suprapermafrost groundwater level (SGL), vertical gradient changes of soil temperature (ST), ~~and~~ moisture content in the active layer (AL), and river level changes were ~~systematically~~ analyzed at four permafrost watersheds in the Qinghai–Tibet Plateau using comparative analysis and the nonlinear correlation evaluation method. ~~How~~ The impact of freeze–thaw processes ~~impact~~ on seasonal SGL~~,~~ and the links between SGL and surface runoff~~,~~ were also ~~discussed~~investigated. The SGL process in a hydrological year can be divided into four periods: (A) a rapid falling period (October–middle November), (B) a stable low-water period (late November–May), (C) a rapid rising period (approximately June), and (D) a stable high-water period (July–September), which synchronously respond to seasonal variations in soil moisture and temperature in the AL. The characteristics and causes of SGL changes significantly varied ~~significantly~~ during these four ~~different~~ periods. The freeze–thaw process of the AL ~~has crucial~~regulated ~~regulatory effects on~~ SGL and surface runoff in permafrost watersheds. During p~~P~~eriod A, with rapid AL freezing, the ST had a dominant impact on the SGL;~~.~~ ~~I~~in p~~P~~eriod B, the AL was entirely frozen ~~because of~~due to the stably low ST, ~~and~~ while the SGL dropped to the lowest level with small changes. During p~~P~~eriod C, ST in the deep soil layers of ~~the active layer~~AL (below 50 cm depth) significantly impacted the SGL (nonlinear correlation coefficient R^2>0.74, P <0.05), whereas the SGL change in the shallow soil layer (0–50 cm depth) ~~had~~ showed a closer ~~relationship~~ association with soil moisture content. Rainfall was the major cause for the stable high SGL during p~~P~~eriod D. In addition, the SGLs in p~~P~~eriods C and D were closely linked to the retreat and flood processes of river runoff. The SGL contributed approximately 57.0–65.8 % of the river runoff changes in p~~P~~eriod D. These findings ~~can provide references for~~will help to facilitate future hydrological research in the permafrost basins and ~~guide~~ the ~~rational~~ development and utilization of water resources in cold and alpine regions.

1 Introduction

The g~~G~~roundwater in permafrost watersheds ~~is always composed of~~comprises suprapermafrost, intrapermafrost, and subpermafrost groundwater (Clark et al., 2001; Mavromatis et al., 2014; Huang et al., 2020). The suprapermafrost groundwater (SG) refers to the groundwater distributed above the permafrost layer~~, ~~;~~and~~ its stable floor is the permafrost table, which ~~is primarily recharged~~ is primarily replenished by rainfall, surface water,~~,~~ and lateral flow in the active layer (AL) (Ma et al., 2017; Tregubov et al., 2022). When the surface soil is frozen, most surface replenishment ~~recharge~~ sources of the SG are cut off, whereas, during the summer thawing season, the SG becomes non-confined water with~~ a~~ a free surface (Qin et al., 2022). SG significantly impacts the regional water cycle and the supply-demand relationship of ecological water in permafrost watersheds (Huang et al., 2020; Gao et al., 2021~~). It~~) and plays a crucial role in regulating land surface processes and hydrology in cold regions (Wellman et al., 2013; Chang et al., 2015; Liu et al., 2021).

The suprapermafrost groundwater level (SGL) maintains a high value during the summer half- of the year ~~because of~~due to the quantity of rainfall and surface water frequently infiltrating into the thawed AL (~~Wei et al., 2021;~~ Tregubov et al., 2021; Wei et al., 2021). The dynamics of the ~~suprapermafrost groundwater level (~~SGL ~~) dynamic is~~are directly affected by rainfall and the surface meltwater supply (Young et al., 2000). ~~Because of~~Due to the impermeability of the permafrost table, SG can flow out of low-lying areas after reaching a particular level or laterally ~~directly~~ supply river runoff or lakes ~~laterally~~ (Krickov et al., 2018; O'Neill et al., 2020; Gao et al., 2021; Qin et al., 2022). In the winter half of the year, with decreasing air temperature and surface soil freezing, most SG ~~turn~~ transforms into ground ice stored in ~~the~~ AL (Xu et al., 2021). ~~As a type of groundwater,~~ SG ~~has a crucial~~significantly impacts~~ on the~~ hydrological processes and water cycles in the permafrost basins through water migration and transformation (Ge et al., 2011; Chen et al., 2018). SG ~~As~~ is one of the primary water sources for lake and river runoffs in a permafrost basin, ~~the SG cannot be disregarded,~~ especially during the summer AL thawing period. In some continuous permafrost basins, such as the source area of the Shule River in the northeastern part of the Qinghai–Tibet Plateau (QTP), SG contributes to over 30 % of the total river runoff (Qin et al., 2022). The SG replenished ~~recharged~~ over 60 mm of water into the ~~thermokarst lake~~Thermokarst Lake in the Beiluhe watershed of the QTP from June 20 to October 26, 2019, when the surface runoff flow into the ~~thermokarst lake~~Thermokarst Lake was only approximately 170 mm (Gao et al., 2021). The effect of frozen SG in the winter ~~half of the year can also not be~~should be considered ~~disregarded because~~ since the ice stored in AL could rapidly thaw ~~in~~ during spring and supply a substantial amount of water to the spring flood. For example, at least one-third of the Shestakovka River spring flood is ~~formed by~~attributed to melted superpermaforst ice (Lebedeva, 2019), and the measured SG contributes to over 60~~ %~~% of the total discharge in the Ugol'naya-Dionisiya River at the beginning of the warm season (Tregubov et al., 2021). In addition, SG is a major source of baseflow in cold river basins. ~~Simulation analysis shows that t~~The SG contribution ~~of SG~~ to base flow is over 90~~ %~~% in the continuous permafrost region of the Yukon River Basin around the Arctic (Walvoord et al., 2012).

Permafrost thaw is closely linked to soil moisture and temperature (Schuur and Abbott, 2011). The dynamics of SGL are closely ~~related to~~associated with ~~the~~ seasonal hydrothermal changes and freeze–thaw processes of AL. ~~With the~~

~~freezing–thawing–refreezing of the AL, t~~The SGL ~~correspondingly~~ has a correspondingly distinct response to -the freezing–thawing–refreezing of AL (Renzheng and Juan, 2019), ~~which is~~ a significant hydrological characteristic that differs from that in non-frozen soil regions (Wei et al., 2018). Previous studies ~~regarding~~ on seasonal SG have primarily focused on the characteristics of SGL change in different freeze–thaw stages of AL in basins of the high latitudes of the Northern Hemisphere and QTP (Chang et al., 2015; Throckmorton et al., 2016; O'Connor et al., 2019; Wei et al., 2021) and the impact factors of SG variation, including the climate (such as rainfall and air temperature (Dugan et al., 2009; Zhang et al., 2021), geological conditions (Woo and Xia, 1995; Sjöberg et al., 2013), soil properties (Raudina et al., 2018)~~,~~ and vegetation types (Koch et al., 2022), as well as the slope and aspect of the permafrost watershed (~~Wei et al., 2021;~~ Tregubov et al., 2021; Wei et al., 2021). O'Connor et al. (2019) ~~found~~ have previously reported that the SGL ~~in the~~during early summer (June) ~~in~~ was lower than that ~~in the late~~during late summer (August) in an Arctic watershed. Chang et al. (2015) and Gao et al. (2021) reported that SGL ~~significant~~significantly ~~rises~~ rose during the AL thawing period during ~~in~~ summer, ~~while it will falls back~~ and ~~was~~ rapidly fell~~restored~~ ~~after~~ following land surface freezing in autumn and early-winter in the source region of the Yangtze River. These studies ~~have~~ recognized the significant impact of seasonal SG on the ecology and ~~the~~ interaction between surface water and groundwater in cold regions, which ~~have~~ further highlighted the necessity of ~~conducting a~~ systematic ~~study~~ investigations into~~on~~ the seasonal changes of SG in the Qinghai Tibet Plateau, as an important cold region ~~in the world~~.

Changes in ~~A~~air temperature ~~change~~ directly ~~affects~~affect the thickness and the freeze-thaw process of AL, as well as the water-resisting effect of permafrost (Chang et al., 2015). That ~~It, in turn,~~ ~~causes~~ further initiate~~s~~s the replenishment process and dynamic changes of SGL (O'Connor et al., 2019; Wei et al., 2021). Precipitation is the ~~main~~ primary water source of SG. Especially in the thawing period, rainfall ~~directly~~ dominates the SGL variation (Dugan et al., 2009; Zhang et al., 2021). In addition, the SGL ~~always~~ varies in permafrost regions with different vegetation and soils~~, because of~~due to ~~the varied~~ differences in migration rates and infiltration amounts of surface water to SG. For example, the hydrograph of SGL in alpine meadows ~~is~~ significantly diff~~erent~~ers from that of alpine grasslands and bare land during the same rainfall events. In non-vegetation regions, SGL peaks and rapidly responds ~~faster~~ to rainfall ~~and has the highest peak~~ (Koch et al., 2022). In addition, the SG depth ~~also~~ varies in different land cover ~~of a~~of specific region~~s,~~; for instance, ~~such as~~ the SG depth in the swamp meadow of the Yellow River source is 0.1-–0.8 meters, ~~while~~ 0.8-–2 meters in the alpine grassland~~,~~ and 2-–8 meters in the desertification grassland (Wenbing et al., 2003). Moreover, ~~it is evident that there are~~ significant differences have been reported in the interactive transport between SG and river runoff under different topographies, especially under different slope aspects. Wei et al. (2018, 2021) ~~reported that SG has~~observed a lower terrain migration trend for SG ~~in~~ during the thawing season ~~,~~ and ~~they propose~~proposed ~~a hypothesis~~ that ~~the~~ SG ~~maybe~~ flows into and ~~recharge~~ replenish ~~the~~ nearby rivers or Thermokarst Lakes ~~thermkarst lakes~~. Renzheng~~.~~ (2019) reported that a ~~few~~ small amount of water could infiltrate ~~into~~ AL ~~in~~ during the initial freeze period of surface soil, ~~which leads to~~thereby lowering SGL ~~comparing~~compared ~~to~~ with river levels (RL); therefore, ~~, thus the~~ SG would be resupplied by ~~the~~ nearby rivers. However, these findings lack supporting analysis based on field observation data. It is therefore necessary to conduct a detailed study ~~of~~ on the “SG-~~river level~~RL” dynamic to clarify its linkage ~~with~~ to topography changes.

~~Existing~~ Data from previous studies have expanded our~~enhanced the~~ understanding of SG~~,~~, the ~~and its~~ effect of which has improved the development of permafrost hydrology. It is necessary to systematically ~~reveal~~ investigate the linkage between ~~the~~ seasonal hydrothermal changes of AL, SG,~~,~~ and surface runoff. This unclear linkage, which has been regarded as a “black box” in hydrological analyses and simulations (Yongjian et al., 2017), is a bottleneck problem in permafrost hydrological studies (Ge et al., 2011; Lafrenière et al., 2019). Identifying seasonal variations in SG and its hydrological linkages based on systematic ~~experimental~~ observations is essential in cold regions, especially in the context of climate warming.

To ~~further~~ better understand the dynamic rules and driving factors of SG, this study selected continuous permafrost watersheds in different locations of the QTP to ~~explore~~ address two ~~scientific problems~~challenges: (1) the seasonal dynamic pattern and spatial differentiation law of SG and (2) the influence of the AL freeze–thaw process on the dynamic changes in SG and river runoff in permafrost watersheds. Based on field observations, this study ~~attempted to~~ revealed the seasonal variation patterns of SG~~, aiming~~ to provide ~~scientific and~~ theoretical support ~~for~~ and facilitate regional water cycle research in permafrost regions.

2 Study area and materials

2.1 Selected research stations

~~Due to t~~The long-term cold climate and special geological tectonic movements~~,~~ contribute to the special -development process and distribution characteristics of the permafrost ~~on~~ in ~~the~~ QTP ~~has a special development process and distribution characteristics~~ (Cheng et al., 2019). With the rising temperatures, the permafrost area in the plateau has decreased to 1.06 million km^2 (or 40% of the total area of the QTP), ~~but it~~yet remains the largest and highest permafrost region in the middle and low latitudes ~~of the world~~ (Zhao et al., 2020). The climate ~~on~~ in the QTP has become warmer and wetter, with the warming rate almost twice the global average (Zhao et al., 2020). With permafrost ~~the~~ degradation~~n of permafrost~~, the permafrost ~~thickness has become~~has become thinner and some island permafrost ~~have~~has also begun to thaw, making groundwater dynamic gradually active. There is a large amount of groundwater in the QTP, ~~and~~ while several ~~many~~ areas are affected by permafrost and AL change. ~~Large~~A large proportion of groundwater burial is shallow, and the thickness of the aquifer is relatively thin (<3 m) (Cheng and Jin, 2013).

Four permafrost stations were selected in this study ~~(~~, namely HLG, SL, MD, and FHS~~)~~, at different locations on the QTP (Fig. 1) ~~to conduct~~for ~~a~~ comparative analysis of the meteorological and hydrothermal changes in AL and river runoff. The HLG ~~experimental station~~ and SL experimental stations are located in the headwater regions of the Heihe and Shule Rivers in the Qilian Mountains of the northeastern QTP, respectively, ~~and~~ while the MD and FHS stations are in the headwater regions of the Yellow and Yangtze Rivers in the hinterland of the QTP, respectively. The mean annual precipitation at these four stations ranges from 100– to 400 mm. Stations HLG and SL in the Qilian Mountains have higher annual precipitation than stations stations FHS and MD. The annual precipitation at the HLG station is the highest (403.4 mm), whereas that at the MD station is 133.7 mm. The mean annual temperature in the four stations ranges from –5.2 ℃ (FHS) to 2 ℃ (MD), and while thetheir ground temperature ranges from –1.7 ℃ (FHS) to 0.3 ℃ (HLG). The maximum AL thawing depth at the research sites changes from 1.5 m at the FHS observation station to 2.5 m at the HLG station in summer. The primary vegetation types on the underlying surfaces of the stations are alpine meadows, alpine grasslands, , and swamp meadows (Table 1).

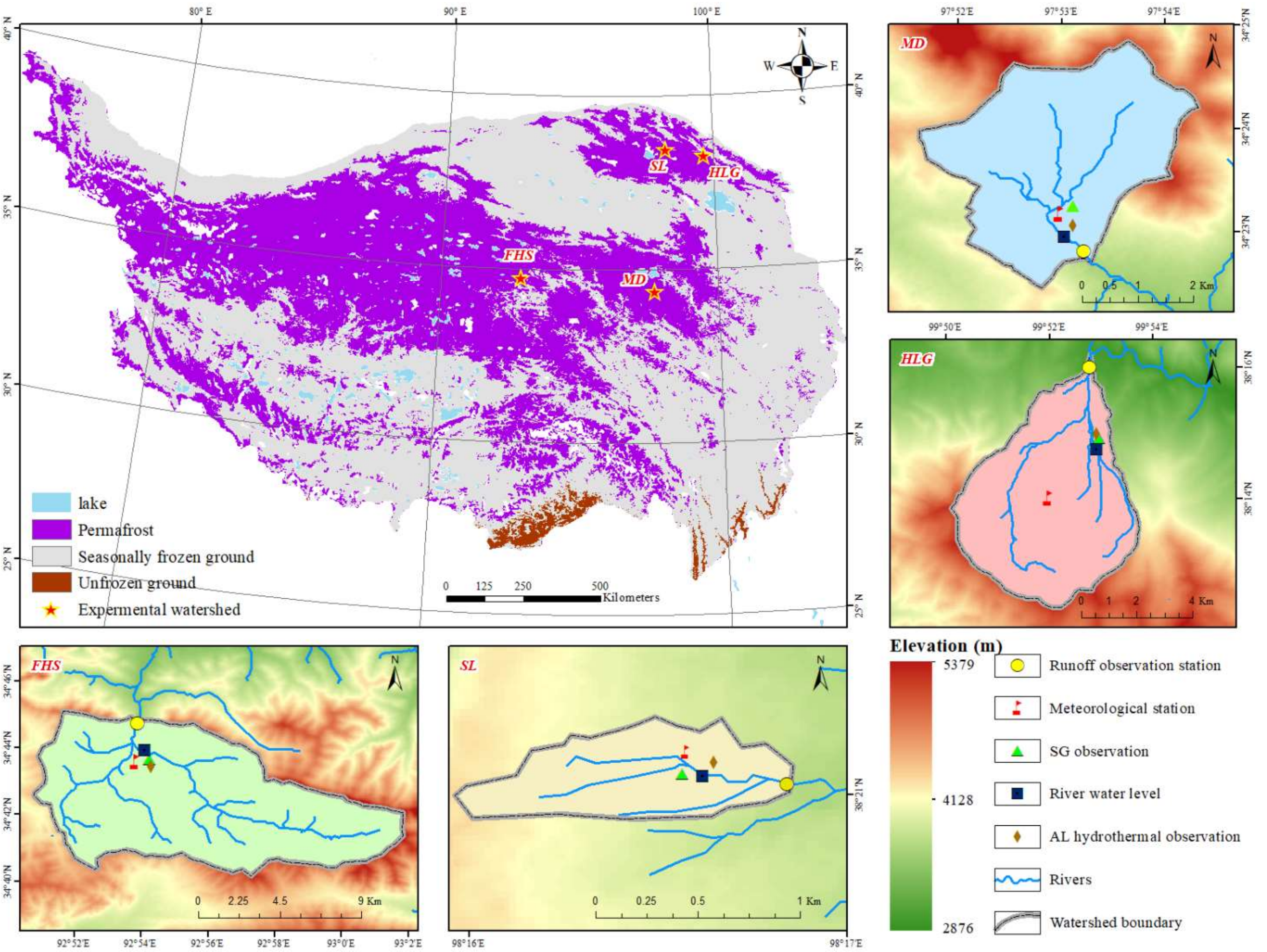


Figure 1: Permafrost distribution and locations of the four SG observation stations in the QTP.

Table 1. The parameter characteristics in the four experimental watersheds of the Qinghai-Tibet plateau.

	P (mm)	Ta (℃)	Tg (℃)	Hmax (m)	vegetation type
HLG	403.4	-3.1	-0.3	2.5	Alpine grassland
SL	350.2	-3.5	-0.5	2.0	Alpine meadow
MD	133.7	-2.0	-1.0	1.8	Swamp meadow
FHS	290.9	-5.2	-1.7	1.5	Alpine meadow

Note: P is the annual precipitation, Ta is the annual mean air temperature, Tg is the annual mean ground temperature, and Hmax is the maximum yearly depth of AL.

The AL thickness of the four experimental watersheds ~~them~~ is influenced by ~~the~~ vegetation coverage and slope orientation. In areas with poor vegetation coverage and sunny slopes, the total thickness of the permafrost layer does not exceed 100 m; conversely, ~~.~~ ~~i~~In areas with well-developed vegetation and shady slopes, the maximum thickness of the permafrost layer can reach ~~about~~ 300 m, while the permafrost layer on the riverbed is the thinnest (~~e.g. it generally~~ lower than 50 m in FHS). In addition, AL and deeper permafrost ~~layer~~layers contain abundant ground ice, ~~and~~ the thawing and freezing of ~~ground ice~~which ~~in AL~~ can significantly affect SVMC change. The selected watersheds are commonly located in ~~relative~~relatively open terrain with wide and shallow ~~valley~~valleys, ~~and~~with ~~the~~ mean annual river discharge of ~~them are~~ 0.12 × 10^8 km^3 (HLG), 0.2 × 10^8 km^3 (FHS), 0.4 × 10^8 km^3 (MD), and 1.0 × 10^8 km^3 (SL)~~, respectively~~. Over 80% of the RL is concentrated in the summer ~~half year~~. Storage time of groundwater, especially ~~the~~ SG, in the experimental watersheds is relatively short and relies heavily on the supply of precipitation. SG is ~~always~~ discharged ~~through~~by converging into adjacent rivers. The active period of groundwater is ~~mainly during~~ June–~~-~~October;~~, and~~ the SG around the river has been stored for a long time. Affected by the river water, there ~~is still~~remains a high SG level in November, with sufficient ~~recharge~~ replenishment and more active movement of groundwater. ~~In~~ During summer, groundwater replenishes the river water, while in ~~later~~ autumn and early winter, the RL is above the SGL, leading to the replenishment of SG ~~recharging back~~ from river water ~~to SG~~.

2.2 Experimental data

This study was primarily based on soil temperature (ST) and soil volumetric moisture content (SVMC) measured at different depths of AL, as well as the SGL data at the four permafrost stations (Fig. 1). The analysis of ST, SVMC,~~,~~ and SGL was conducted in a hydrological year (from 1st of October ~~1~~ to 30th of September ~~30~~)~~, and~~ and the time scale was daily. The~~se~~ data were obtained from the field observation stations of the Chinese Academy of Sciences, along with ~~and from~~ existing literature (Chang et al., 2015; Wei et al., 2018; Qin et al., 2022). The daily data of ~~the river level (~~RL~~L)~~ during the wet season (in summer) and water recession period (in autumn) in SL and FHS watersheds was also measured and compared with SGL to analyze the “SGL-RL” dynamic relationship. Daily rainfall data for the same hydrological year were obtained from automatic rain and snow gauges (T-200B) (30 min) at the permafrost stations and national weather stations (http://data.cma.cn/) in the study areas.

2.3 Observation of soil hydrothermal change and SGL

ST and SVMC at different AL depths were the two major soil hydrothermal parameters used in this study. In SL and HLG stations, ST and SVMC ~~they~~ were continuously measured using HydraProbe Lite sensors with an accuracy of 0.3 °C and ±1.0 ~~%~~%. The ST in the MD and FHS stations were measured ~~by~~ using S-TMB-M006 sensors with an accuracy of 0.2 °C~~,~~ and the SVMC was measured ~~by~~ using S-SMC-M005 sensors with an accuracy of ±3.0 ~~%~~%. All sensors are suitable for use at –40 ~~°C –~~ –50 °C. All probes used for measuring the ST and SVMC were buried in the soil from the ground surface (10 cm depth) to the permafrost table. Probes were installed in the soil at depths of 10, 20, 40, 60, 80, 120,~~, and~~ and 160 cm. All instruments were attached to a CR1000 data logger for data acquisition at each station, and recorded data were collected ~~once~~ every 30 min. The ST and SVMC data in the SL, MD, and FHS stations were used to ~~detail analyse~~analyze the hydrothermal change of AL in a hydrological year~~,~~ ~~because~~ since some data of ST and SVMC in the HLG station ~~is~~ was missing due to instrument damage.

The SGLs at the four stations were measured using a HOBO pressure water level logger (U 20-001-04) produced in the United States. The logger, ~~is~~ a built-in pressure water level sensor with a fully enclosed titanium alloy shell, is~~. It is~~ suitable for the automatic observation of groundwater in alpine environments. The measurement accuracy was high, with a resolution of 0.014 kPa (0.14 cm water depth). A water level logger was set in the AL groundwater wells at the four stations~~, and data were automatically collected every 30 min~~;~~.~~ ~~T~~the HOBOware Pro software was used to operate the logger. Using a reference water level, HOBOware Pro automatically converts pressure readings into water level readings, ~~and the~~ providing SGL data for a specific measurement period ~~can be obtained~~. In addition, some data from manually measuring the groundwater level with a ruler were used to compare and correct the HOBO-observed SGL data in different wet and dry periods. Daily SGL was calculated by averaging all corrected water level data obtained every 30 min ~~for each day~~daily.

~~The necessary calibrations of t~~The SGL, SVMC,~~, and~~ and ST sensors were ~~done~~ calibrated prior to~~before~~ field observations~~. The calibration process~~, which included~~s~~ measuring the initial value of the sensors, recording the measurement results,~~, and~~ and ~~then~~ adjusting the measurement results to achieve accurate values. ~~Before install and bury probes, w~~We ~~firstly~~ excavated the original soil in AL layer by layer~~. Then,~~ and buried the probes; ~~were buried and the u~~undisturbed soils were backfilled in different layers. ~~At the beginning~~During the initial days of the SGL, SVMC, and ST sensor ~~working~~function, the data were ~~always~~ influenced by the unstable soil structure~~. So~~ and were therefore ~~the data in the initial period of the sensors installed were~~ excluded from analysis~~in the study~~. ~~Daily,~~Every 30 min ~~of~~ recorded data ~~recorded in a day will be~~was assessed ~~checked~~ to eliminate ~~instantaneous~~ abnormally high or low values, which were interpolated by adjacent data. In addition, typical alpine hillslopes were selected in the central part of the SL and FHS experimental watersheds where the groundwater flow field on the hillslopes was cut by the river (with ground ice exposed at the edge of the riverbed ~~and~~ with an obvious exchange between SG and river runoff), to observe the "SGL-RL" linkage during the AL thawing period.

2.4 Correlation analysis between the SGL and soil hydrothermal parameters in the AL

~~For a detailed study on~~To better investigate seasonal SGL, the tipping points of the SGL data series were analyzed using the Pettitt test (Pettitt, 1979). A contour map was created using SigmaPlot (SigmaPlot 14.0, 2020) software to analyze the ST and SVMC changes at different depths of ~~the~~ AL. To analyze the impact of soil hydrothermal parameters on SGL, the Boltzmann formula was used to perform nonlinear fitting between ST and SGL as well as ~~between~~ SVMC and SGL at different AL depths. The formula was ~~evaluated and judged to be~~ optimum for ~~to~~ nonlinear fitting analysis between SG and hydrothermal variables in AL (Wang et al., 2012; Chang et al., 2015), as confirmed using ~~through~~ the Levenberg–Marquardt method (Bates and Watts, 1988) and Universal Global Optimization algorithm (Benson, 2002). SPSS (SPSS 18.0, 2016) was used to perform nonlinear correlation analysis. The fitting and correlations were evaluated using the coefficient of determination (R^2) and root mean square error (RMSE). The Boltzmann formula is expressed as follows:

$$H = H_0 + \frac{a}{1 + e^{-\left(\frac{T - T_0}{b}\right)}}$$

where H ~~represents~~ is the SGL, and T and T_0 ~~represent~~ are the ST of the target depths and the initial ST during the calculation period at that depth, respectively (unit: °C); H_0 ~~represents~~ is the initial SGL, and a and b are undetermined parameters ~~that are related to~~ associated with soil characteristics at different depths.

3 Seasonal characteristics of SGL, ST~~, and~~ and SVMC

As shown in ~~Figure~~ Fig. 2, the SG data series during ~~a~~ the hydrological year have four ~~obvious~~ tipping points in each ~~one of the four observation~~ stations. The Pettitt test results indicated that the trend of the streamflow series changed on 4th of December~~4 Dec~~, 11th of June,~~11 Jun, and~~ and 5th of July~~5 Jul~~ in the HLG station;~~,~~ 17th of November~~17 Nov~~, 10th, and 25th of ~~,~~ June,~~10 Jun, and 25 Jun~~ in the SL station;~~,~~ 3rd of November~~3 Nov~~, 5th of December~~5 Dec~~, 6th of June,~~6 Jun, and~~ and 10th of July~~10 Jul~~ in the MD station;~~,~~ and~~as well as~~ 29th of October~~29 Oct~~, 20th of November,~~20 Nov~~ 7th, and 26th of June ~~, 7 Jun, and 26 Jun~~ in the FHS station. According to the tip points, which refer to the start or end times of different periods, there are four typical periods of SGL variation throughout the hydrological year at different stations on the QTP~~. The four periods of the SG hydrographs~~, which can be divided as follows: (A) rapid falling period, (B) stable low-water period, (C) rapid rising period,~~, and~~ and (D) stable high-water period. Periods A–D began in mid-autumn (October–early November), early winter (late November–early December), early summer (June),~~,~~ and mid-summer (July), respectively. The specific start and end times of each period, as well as the duration of each period, showed minimal difference among the four stations (Fig. 2).

The ST and SVMC in the AL ~~have~~ showed synchronous responses to seasonal variations in SGL (Figs. 2 and 3). ST rapidly ~~decreases~~ decreased to 0 ℃ ~~zero~~ (rapid freezing) and ~~,~~ stable low temperature below 0 ℃ (frozen stability), rapidly ~~rising~~ increased above 0 ℃ (rapid thawing)~~,~~ and ~~fluctuation~~ fluctuated above 0 ℃ (thawing stability) in Periods A, B, C,~~;~~ and D, respectively. The SVMC also has four corresponding stages, namely~~:~~ rapid reduction, stable low value, rapid rise ~~,~~ and fluctuation with the complete melting of the AL.

To some extent, SVMC could be a dynamic indicator of SGL. According to the vertical variations in seasonal SVMC and SGL at the experimental sites (Fig. 3), summer SGL fluctuates at depths where SVMC has a high value. For example, ~~the~~ summer SGL at the SL site primarily fluctuated at 40–60 cm depths, where the SVMC ~~also has~~had a high value, ~~and~~ while the soil ~~remains~~ remained saturated or nearly saturated for an extended duration. ~~Similar to~~Likewise ~~the SL station~~, the summer SGL at the MD station ~~fluctuates~~ fluctuated in 10–80 cm depths, where the SVMC also maintained a higher value (Fig. 2). Exploring the soil characteristics and SVMC in the AL can ~~indirectly~~ clarify the SGL dynamics in a specific area.

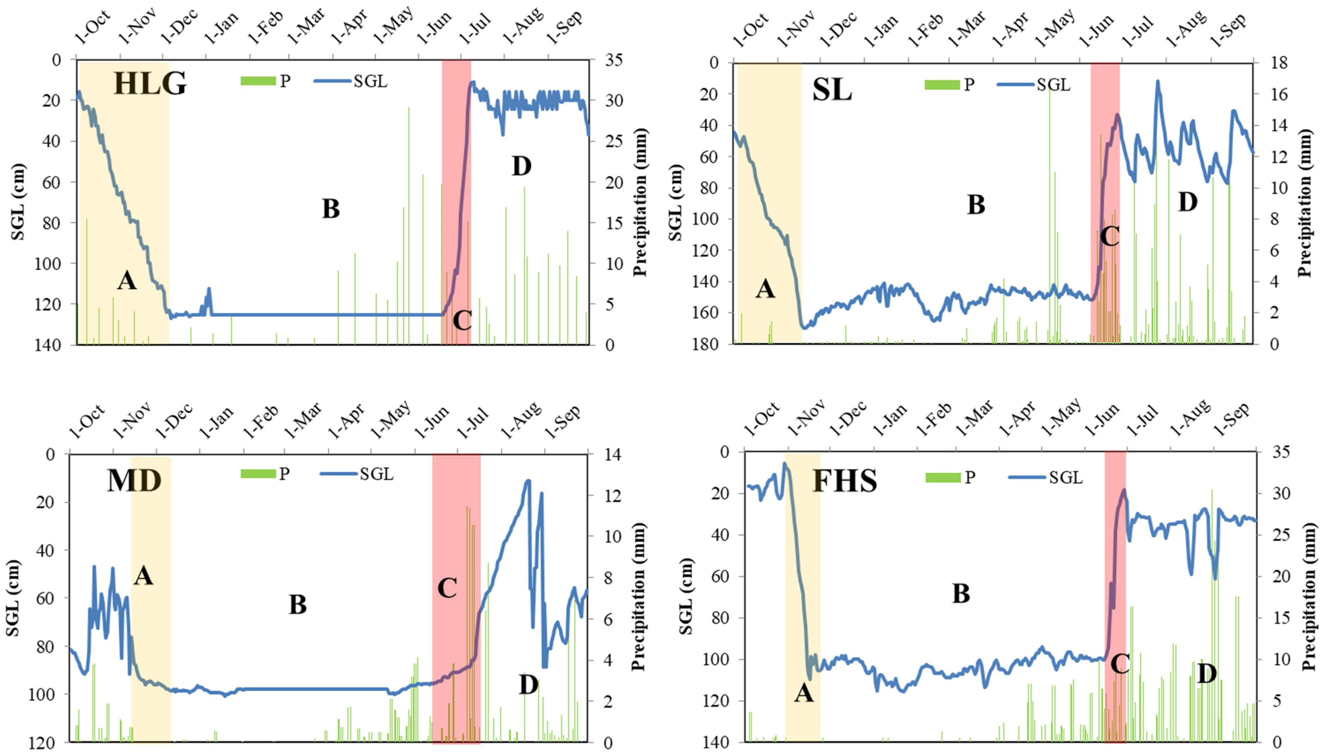


Figure 2: Four major phases of the seasonal suprapermafrost groundwater level (SGL) and the corresponding daily precipitation (P) in different sites of the QTP. A–D refer to the rapid falling period, stable low-water period, rapid rising period~~, and~~ and stable high-water period, respectively.

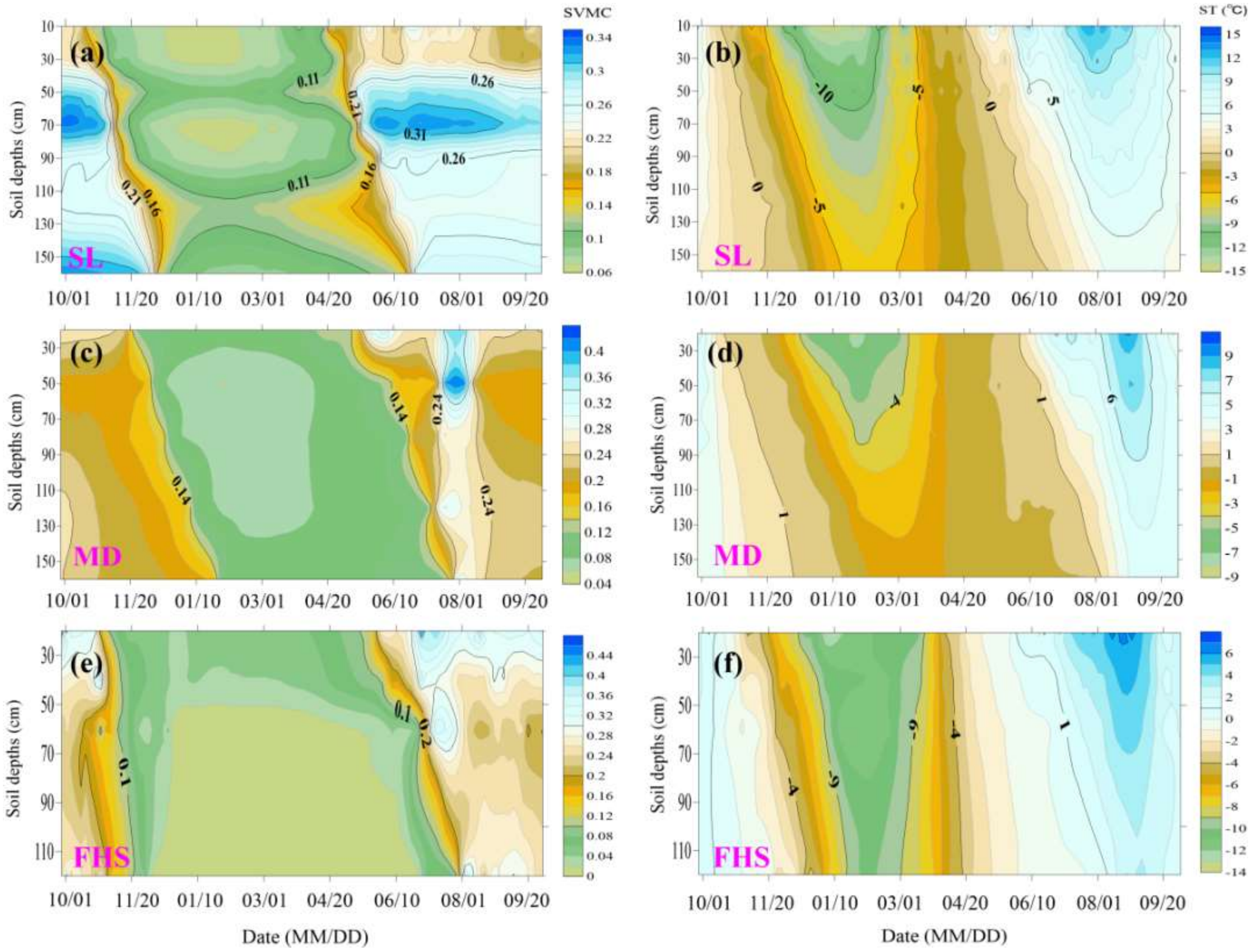


Figure 3: Vertical variations in soil temperature (ST) and soil volumetric moisture content (SVMC) in the different sites of the QTP.

Moreover, ~~it is inferred that~~ precipitation is a major water source that ~~recharges~~ replenishes SG during the thawing stability period of AL according to the seasonal dynamic of SGL and precipitation (Fig. 2). The SGL in p~~P~~eriod D responded rapidly to rainfall and dropped to a low value ~~when no~~in the absence of rainfall~~ occurred~~. In this period, AL ~~reaches~~ reached its maximum depth in a year, while~~and~~ SGL ~~is~~ was stable at a high groundwater level. For example, the SGL in Period D was stable above 80 cm depth at the SL station, rising rapidly ~~when~~ with rainfall ~~occurred~~ and slowly reducing ~~slowly~~ to a stable level ~~after~~ following rainfall (Fig. 2). The delayed SGL ~~falling~~ reduction after ~~a~~ rainfall ~~event shows that~~ suggested that AL has had a distinct role in water conservation and can could significantly regulate soil water transport and runoff processes in a permafrost watershed. This water-conservation effect is crucial for alpine ecosystems.

4 Impact of ST and SVMC on SG in the study area

Figuress. 4 and 5 show the correlations between ST and SGL, as well as between SVMC and SGL, in different soil layers at the SL station. The nonlinear relationships between the measured ST and SG are were very good (R^2>0.8, P <0.01) during pPeriod A (also the rapid freezing period of AL) (Fig. 4a). The results in Figure Fig. 4a show a significant nonlinear correlation between SGL and ST at different depths ranging from 0– to 160 cm, with a determinable coefficient (R^2) ranging from 0.81–0.98 (P <0.05). However, significant differences were observed in the response of the SGL to the ST at different depths. For example, the range of ST at a depth of 10 cm at the SL station was approximately –10–5 °C, corresponding to rapid changes in SGL, while it narrowed to approximately –4–4 °C at a depth of 50 cm, –1–4 °C at a depth of 90 cm,; and approximately –0.2–3 °C at a depth of 160 cm (Fig. 4a). This is consistent with the gradual decrease in ST with increasing depth, which indicates that SG is more sensitive to ST changes in the deeper AL than in the shallow layer in pPeriod A. According to the fitting analysis shown in Figure Fig. 4a, the correlation between ST and SGL gradually increasesincreased with increasing depth. In the early stage of pPeriod A, as the ST decreased, the soil froze gradually, and the liquid water in the soil transformed into solid ice, resulting in a thereby decreasing e in the SGL. The correlation coefficient between ST and SGL was the lowest in shallow soil, especially in the soil layer of 0–10 cm depth. This, indicates ing that the impact of shallow soil freezing on the SGL was weak during the freezing process in Period A. This has a limited impact on the SGL, which can obtain a particular amount ofsome surface water through fissure infiltration and lateral flow.

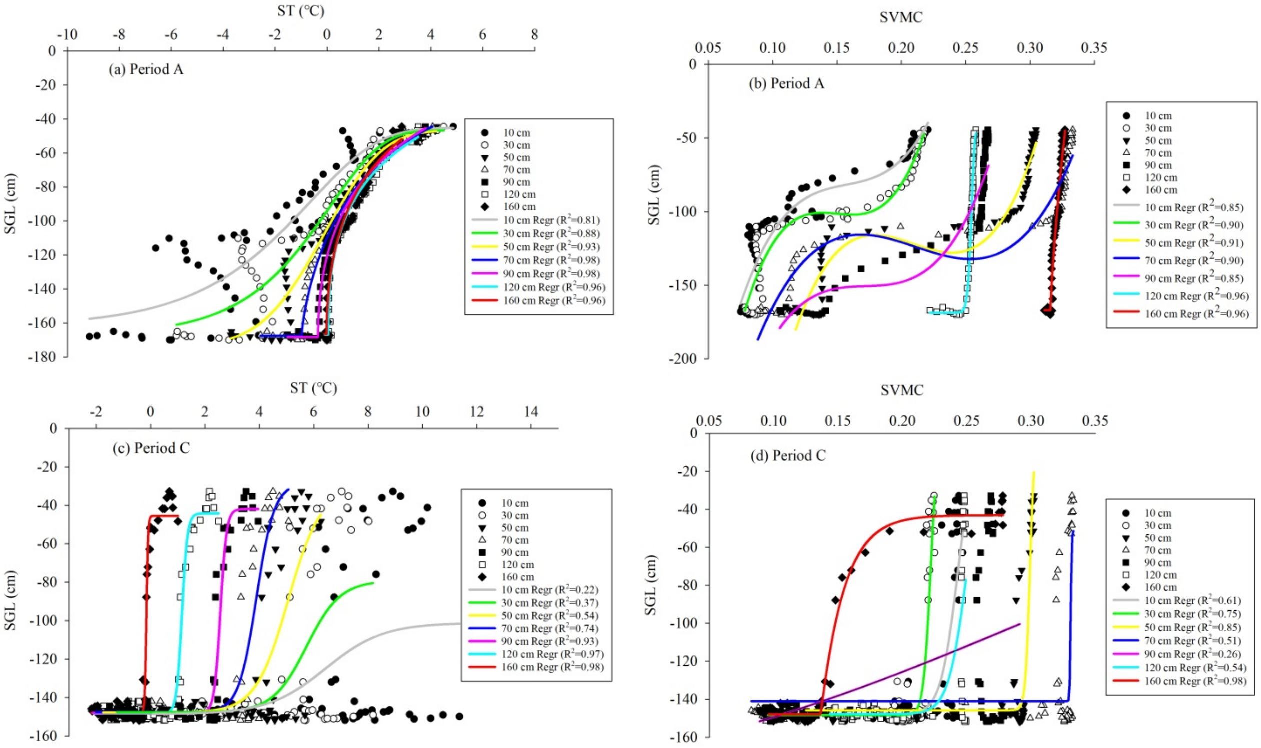


Figure 4: Correlations of SGL and SVMC (ST) in different depths of AL during Periods A and C.

~~While~~ Meanwhile, in ~~the p~~Period C (also the rapid thawing period of AL), the nonlinear relationships between the measured ST and SG fit well only in the deeper soil layers (below 50 cm depths) of AL (Fig. 4c). ~~,~~ The SG in the deeper soil layers was more dominated by ST compared with that in the shallow soils ~~during Period C~~. ~~In the period~~During this, there was no significant relationship between ST and SGL at depths of 10, 30, ~~and~~ or 50 cm (P >0.05). ST at 70, 90, 120~~, and~~ and 160 cm depths had a significant effect on SGL (P <0.01)~~.~~; ~~H~~however, the overall correlation between ST and SGL improved with increasing depth, and the impact of ST on SGL became more significant (Fig. 4c). The shallow soils (0–50 cm) in AL rapidly thawed in the initial stage of p~~P~~eriod C, with ~~the~~ rapidly rising SGL ~~rising rapidly,~~ caused by the rapid supply of external water sources, including the potential lateral flow from thawed soils, rainfall and snowmelt infiltration (Yongjian et al., 2017). In the subsequent stage of Period C, soil water replenishment was relatively stable, and SGL dynamics were significantly affected by the thawing depths of AL dominated by ST, according to the good consistency between SGL and the thawing process (Figs. 2 and 3). In addition, the variation range of ST in ~~the~~ different soil layers differed, as ~~during Period C. As shown in Fig. 4c,~~ the ST range in shallow soil was substantially wider than that in deep soil (Fig. 4c)~~.~~. During the SGL variation period, the variation range of ST at a depth of 10 cm was 3–12 °C,~~, while~~ and the response of SGL to ST in deep soil was more intense. For example, the fluctuation of SGL from low to high water levels was completed within the range of approximately –0.5–0.5 °C at 160 cm (Fig. 4c). This indicates that the ST impacts SGL dynamics only after soil thawing (>-~~–~~0.5 °C).

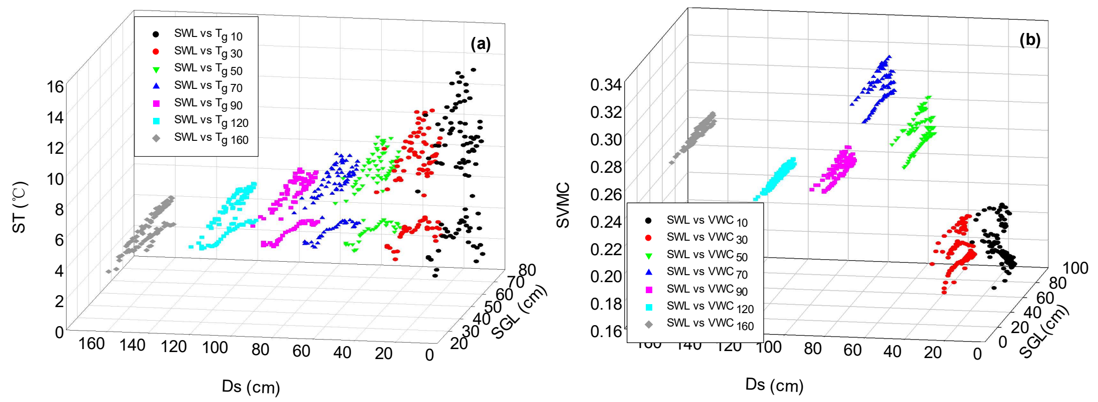
Compared ~~to~~ with ST, the impact of SVMC on SGL is limited during p~~P~~eriod A, although the nonlinear relationships between SGL and SVMC fit well ~~both~~ in the 0–90 cm deep soils (0.85 ≤ R^2 ≤ 0.96, P <0.05) and 120–160 cm deep soils (R^2 =0.96, P <0.01) ~~during Period A~~ (Fig. 4b). As ST ~~continued to~~ decreases during p~~P~~eriod A, the liquid water in the AL soil gradually ~~froze~~ freezes into solid water, resulting in the observed SVMC (liquid water content)~~,~~ and the SGL ~~continuously~~ accordingly ~~decreased~~ decreases~~accordingly~~. Although there was a good relationship between SGL and SVMC at the 120–160 cm depth, the impact of soil moisture below 120 cm on SGL may be limited ~~because~~ since SGL drops rapidly from high to low levels with minimal decrease in SVMC below 120 ~~a depth of 120~~ cm (Fig. 4b).

When the SGL changed in p~~P~~eriod A, the variation range of the SVMC first increased ~~and~~ then decreased from the shallow to deep soil layers. The SVMC range gradually increased from 7–22 ~~%~~% (10 cm) in the shallowest layer to 10–33 ~~%~~% (70 cm) and ~~then~~ gradually decreased to 32–33 ~~%~~% (160 cm). This indicates that the response rate of the SGL to soil moisture first decreased and ~~and~~ then increased with depth. By comparing the response rate of SGL to ST changes at different depths during p~~P~~eriod A (Fig. 4a), ~~it was~~we found that deeper soils in the 0–70 cm soil layer ~~had~~ showed a larger influence of ST on SGL. Although the SVMC and ST ~~both~~ have good relationships with the SGL at a depth below ~~a depth of~~ 70 cm, the variation scope of the SVMC ~~is~~remains minimal. The freezing process of deep soil determines the uplift process of the AL lower boundary, which affects ~~the~~ SGL. Therefore, the deep layer ~~also more directly~~ impacts ~~the~~ SGL owing to the ST.

The SGL during p~~P~~eriod C ~~is~~ was closely related to the changes in soil water of AL, especially in the shallow soil layers. As shown in ~~Figure~~ Fig. 4d, the correlations between the SGL and SVMC ~~were~~ also fitted well during Period C (RMSE <-10). Except for the soil layers at 70–120 cm depths, where the correlation between the SGL and SVMC was poor~~er~~ (R^2 <-0.6, P >-0.05), the different soil layers of AL showed a good nonlinear correlation between the SGL and SVMC (P <0.01) (Fig. 4d). The SGL changes in soil layers at 0–50 cm depths were more correlated with ~~the~~ SVMC, while SGL changes in a deeper AL layer (70–120 cm ~~depths~~) were more significantly affected by ST, with better correlation (Fig.~~ure~~ 4c, 4d). The ~~correlawwtion~~correlation between SVMC and SGL was also very good (R^2 = 0.93) at the AL bottom ~~of the AL~~ (160 cm depth). The correlation patterns further confirmed that AL began to melt downwards from the surface soil during the warm season. Meanwhile, ~~D~~during the rapid thawing period of AL (p~~P~~eriod C), the shallow soil first ~~melts~~ melted and ~~can~~ could ~~rapidly~~ receive water supply from rainfall and surface meltwater, ~~which further results~~resulting in the rapid response of the SGL. The SGL in a shallow soil layer has a high degree of response to SVMC change, while the thawing of deep soil in AL is primarily controlled by ST. A higher ST leads to deep soil thaws~~,~~ and the water flow channels between the surface AL and deep soil can ~~then~~ be fully connected, ~~resulting in~~causing alternations in SGL ~~changing accordingly~~. When the deep soil ~~insufficiently~~ thaw~~ed~~ing is not significant, the water-resisting effect of frozen soil ~~exists~~becomes more prominent, and the ~~it is difficult to~~ formation of lateral flow and saturated soil flow to replenish ~~recharge~~ the SG becomes challenging. The water movement of the thawed soil layer (including saturated soil flow) ~~cannot~~ does not participate in SG dynamics, ~~resulting in~~

~~a~~thereby weakening the~~er~~ response of ~~the~~ SGL changes to SVMC than to ST in the 70–160 cm deep soil layer throughout p~~P~~eriod C. ~~Based on the analysis above, it can be inferred that~~Therefore, the SG ~~in Period C~~ is primarily replenished ~~recharged~~ by soil water in the shallow layers, and the SGL rise is significantly influenced by thawing depth, dominated by ST in ~~a~~ deeper AL.

In p~~P~~eriod D (also the stable thawing period of AL), SGL was ~~mostly~~ not sensitive to either ST or SVMC changes in different AL depths ~~of the AL~~, according to the correlation analysis (Fig. 5). The range of ST fluctuations gradually decreases with increasing AL depth, though ~~but generally~~ exceed~~s~~ings 2 ℃. ~~Through correlation analysis, we found that t~~The correlation between the ST at different AL depths and ~~the~~ SGL during p~~P~~eriod D was very poor (R^2<0.1) (Fig. 5a). The SVMC ~~shows~~ showed an "increase-decrease-increase" process as depth ~~increases~~increased. The correlation between SVMC and SGL in the shallow soil was better than that in the deep soil, with the highest correlation observed at a depth of 10 cm (R^2 = 0.52) (Fig. 5b). ~~This I~~indicat~~es~~inges that during p~~P~~eriod D, ~~the~~ SGL was more sensitive to SVMC changes in ~~the~~ shallow AL (0–30 cm)~~.~~, whereas ~~The~~ SGL in the remaining depths of ~~the~~ AL ~~were~~was not sensitive to either ST or SVMC changes ~~during Period D,~~ when SGL fluctuated at high values for an extended duration, while ~~and~~ deep soil water remained predominantly ~~saturated~~ or nearly saturated. According to the rainfall process during this period (Fig. 2), the dynamics of the SGL were primarily affected by rainfall, which could rapidly replenish ~~recharge~~ the water storage in shallow soils and subsequently affect ~~the~~ SGL.



linear regression: SGL vs. ST	10 cm	30 cm	50 cm	70 cm	90 cm	120 cm	160 cm
R^2	0.04	0.05	0.06	0.07	0.08	0.07	0.04
P				<0.001			

linear regression: SGL vs. SVMC	10 cm	30 cm	50 cm	70 cm	90 cm	120 cm	160 cm
R^2	0.52	0.15	0.07	0.05	0.10	0.09	0.04
P				<0.001			

Figure 5: Variations and correlations of SGL and ST (a) as well as SGL and SVMC (b) in different depths (Ds) of the permafrost active layer in Period D.

5 Linkage between river discharge and SGL

To further analyze the impact of SG on river runoff, Figure Fig. 6 shows the relationship between SGL and RL in the SL and FHS river basins during pPeriods C and D, respectively. In both the SL and FHS watersheds, the SGL and RL processes were similar (Figure Fig. 6a, 6c). As shown in Figure Fig. 6a, the SGL and RL showed stable fluctuations in the SL watershed during 15–25th of June 15 June 25 (pPeriod C) and 19th of July to the 24th of 19 August 24 (early pPeriod D), with a high ($P < 0.05$)and the consistency of the "SGL-RL" process consistency was high ($P<0.05$). However, compared with early pPeriod D, the changes in the consistency of the SGL and RL processes changes in pPeriod C was slightly poor (R^2 = 0.07, P <0.05), which may might have been caused by the different AL thawing processes and the replenishment recharge of snowmelt water to river runoff. In pPeriod D, the dynamic process of SGL was highly consistent with the regression and flood processes of river runoff, with a high correlation (R^2 =0.57, P <0.001). It can be inferred thatTherefore, the SGL contributed to approximately 57.0 %% of the RL changes in Period D in the SL watershed (Fig.ure 6b). Compared with pPeriod C, the consistency in pPeriod D was superior, and the regression and flood processes were quicker.

Similar to the SL watershed, the SGL and RL in the FHS watershed had consistent fluctuations fromfrom the 31st of August to the 18th of 31 October 18 (pPeriod D), then. Both showed a significant downward trend from the 2nd of October 2 (late pPeriod D);, and their curves were also in good agreement (Figure Fig. 6c). It can be inferred from Figure Figure 6d indicates that the SGL contributed approximately 65.8 %% of the RL changes in pPeriod D in the FHS watershed;. hHowever, the rate of decrease in SGL was larger than that of RL. The decrease in SG was larger than 0.3 m, while that of RL was approximately 0.12 m. This may be because the surface soil begins to gradually freeze with as the temperature drops in late pPeriod D when the river water can be replenished recharged by rainfall or snowmelt water. The freezing of shallow soil weakens the hydraulic connection between AL and the land surface, resulting in poorer water replenishment recharge conditions, fewer water supply sources for AL, and a relatively largesignificant decrease in SGL.

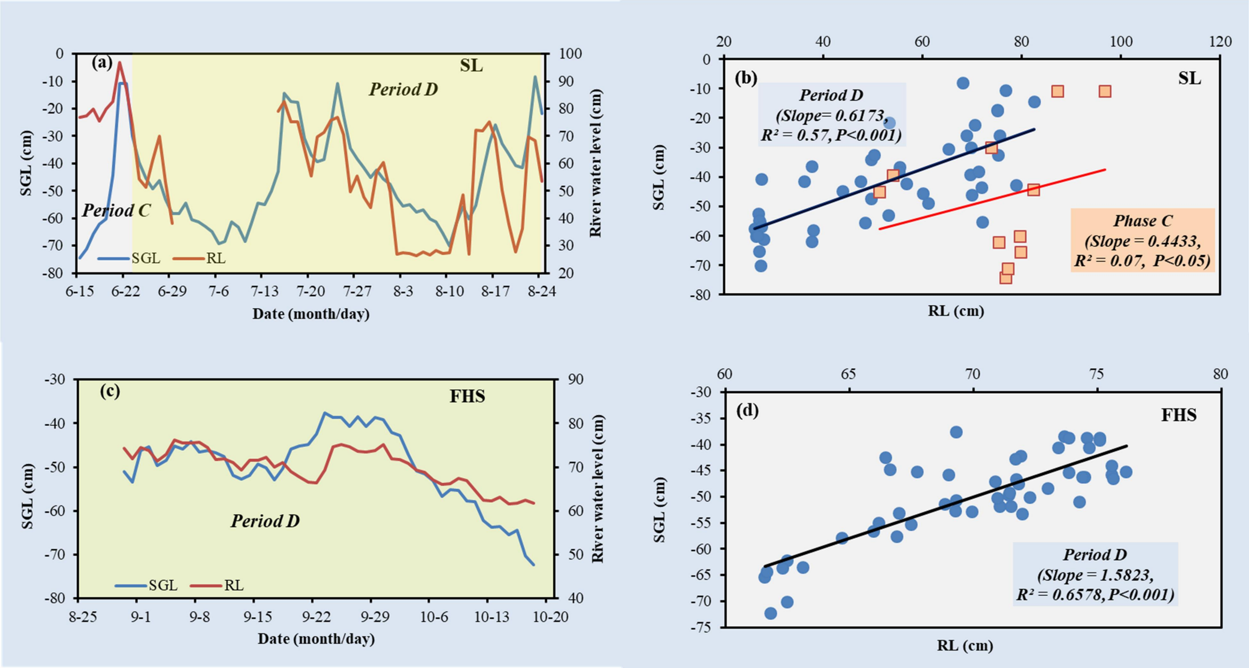


Figure 6: Variations of SGL (a, c) and ~~the~~ correlations between SGL and river level (RL) (b, d) in p~~P~~eriods C and D, respectively, in the SL and FHS watersheds.

6 Framework of watershed hydrology responding to the freeze–thaw of AL

According to the above analysis, the yearly hydrothermal changes have four distinct periods with seasonal AL freezing and thawing. The characteristics of the AL depth, SVMC, SGL,~~,~~ and surface RL changes in the four periods significantly varied ~~significantly~~ (Fig~~ure~~. 7). In p~~P~~eriod A, ST rapidly decreased, ~~leading to~~causing the upper layer and~~ the~~ bottom of the AL to ~~begin~~ freez~~ing~~e ~~approximately~~ simultaneously, which ~~resulted in the~~ limited ~~of~~ the external water supply to the AL. The~~n, the~~ SGL rapidly decreased and reached the minimum value, as the surface RL rapidly ~~also~~ decreased~~ rapidly~~. However, ~~because of~~due to the replenishment ~~recharge~~ of rainfall runoff or snowmelt runoff, the rate of RL decline~~ of RL~~ was relatively slower than that of SGL. In p~~P~~eriod B, the ST was consistently~~stably~~ low, the AL was entirely frozen,~~,~~ and the SGL dropped to the lowest level with ~~small~~ minimal changes,~~.~~ though t~~T~~he RL changes, in this period, were not always consistent with the SGL~~ at all times during the period~~.

~~When~~ During snowmelt water replenishment~~recharge occurs~~, RL significantly increases, and the runoff process fluctuates and changes accordingly. In p~~P~~eriod C, the warming of the air temperature led to the rapid downward thawing of the AL from the surface, resulting in the rapid rise of SGL, ~~rising rapidly and~~ reaching ~~its maximum~~ a peak value. Affected by the recharge of the lateral outflow of the SGL and rainfall runoff, the RL ~~also~~ rose rapidly. In p~~P~~eriod D, high temperatures led to the deepest AL thawing~~. During this period~~, during which SGL and RL were significantly affected by rainfall. The SGL can increase rapidly with rainfall ~~events~~ during the rainy season and maintain a higher value for a year with ~~small~~ few fluctuations. In late p~~P~~eriod D, when rainfall decreases~~,~~ or ~~no rain occurs~~is absent, the SGL rapidly falls~~,~~ and the river runoff is primarily replenished ~~recharged~~ by a small amount of SG flowing out from AL, resulting in RL ~~falling back~~decreasing to a low value. When snowfall occurs in late autumn, snowmelt replenishes ~~recharges~~ river runoff and causes the RL to rise. In addition, river runoff reverses the replenishment ~~recharge~~ of the SG, leading to a moderate increase in ~~the~~ SGL. Under the scenario of continuous warming in the future, AL will be thicker, ~~and~~ the precipitation processes, and vegetation underlying surfaces will change~~,~~ leading to a more complex water regulatory mechanism ~~of~~ associated with AL change.

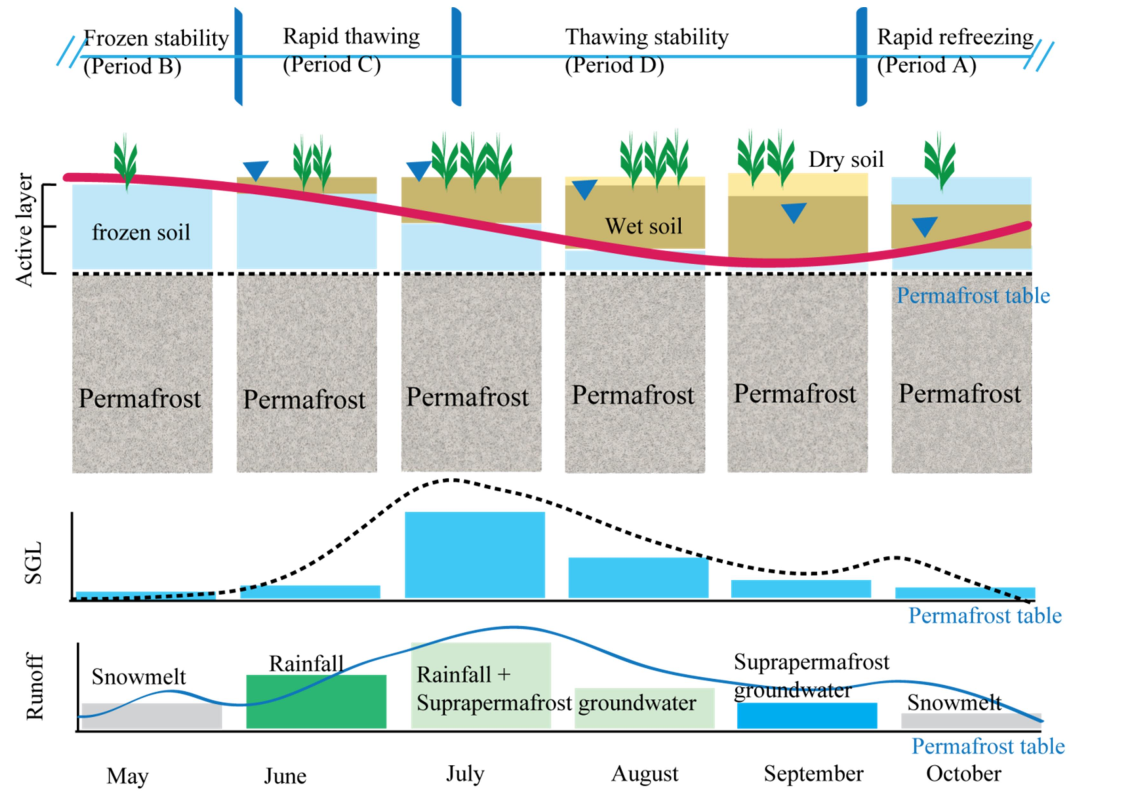


Figure 7: Framework of watershed hydrology responding to the freeze–thaw of the permafrost active layer.

7 Discussion

This study identified the tipping points of SG change ~~in~~ during a hydrological year in different regions of the QTP ~~by~~ via M-K mutation detection~~,~~ and ~~further~~ divided SG data series into different stages. Although similar stages of seasonal SGL change were ~~also~~ found in ~~some~~ other permafrost regions of the Northern Hemisphere (Wellman et al., 2013; Koch, 2016; Tregubov et al., 2021; Koch et al., 2022), our study is the ~~firstly systematic~~first to systematically ~~summarized~~summarize a four-stage pattern of SG seasonal change in a hydrological year. The seasonal variations of SG in the Q~~inghai~~ T~~ibet~~ P~~lateau~~ ~~are~~ are relatively consistent with the freeze-thaw characteristics of AL~~,~~ and ~~they are~~ mainly influenced by ST and SVMC changes, which has been previously concluded ~~in some previous~~by studies of permafrost groundwater in Alaska (Hinkel and Nelson, 2003; Walvoord et al., 2012; Wellman et al., 2013), Canada (Woo and Xia, 1995; Clark et al., 2001; Liu et al., 2021)~~,~~ and ~~some~~ other pan-Arctic watersheds (Young~~,~~ and Mingko, 2000; Dugan et al., 2009; Throckmorton et al., 2016; Koch, 2016; Koch et al., 2022). ~~What's different is that~~However, this study conducted a more detailed analysis of the ST and SVMC at different soil depths and variation stages impacting ~~on~~ SGL changes~~. We~~ and showed ~~found~~ ~~that~~ limited~~the~~ impact of SVMC on SGL ~~is limited~~, while the ST of AL ~~has~~ had a larger impact on SG during p~~P~~eriod A. ~~.~~ During p~~P~~eriod C, the SG in the deeper soil layers was more dominated by ST, while in the shallow soil layers of AL~~,~~ it ~~is~~ was closely related to the changes in soil water, ~~which mainly comes~~primarily originating from meltwater of ground ice (Gubareva et al., 2018; Tregubov et al., 2021). In p~~P~~eriod D, SGL dynamic ~~is~~ was ~~mostly~~ not sensitive to either ST or SVMC changes ~~in~~ at different AL depths ~~of the AL,~~ and ~~it is~~ was primarily affected by rainfall. In this study, it was observed that SGL in p~~P~~eriod D was the highest compared ~~to~~with other stages of ~~a~~the year, which has been reported before (Rawlins, 2021; Tregubov et al., 2021). While ~~it~~~~This~~ this study ~~also~~ further ~~quantitative~~quantitatively revealed the contribution of SG to the RL changes in the thawing season of permafrost watersheds according to the correlation analysis. For example, ~~it found that~~ over 50 ~~%~~% of the surface runoff in p~~P~~eriod D was replenished ~~recharged~~ by nearby SG in the SL watershed of the QTP. In addition, this study found ~~that there are~~ differences in the degree of ~~close~~ correlation between SG and surface water in different regions of the Q~~inghai~~ T~~ibet~~ P~~lateau,~~ based on the analysis of field observation data.

For example, the SG-RL hydrographs ~~are quite~~significantly differen~~t~~d in the SL and FHS ~~watershed~~watersheds (Fig. 6), indicating significant differences in the amount and rate of complementarity between SG and river runoff. The reasons for this difference may be ~~related~~ attributed to the distance between the river and the measured point of SG, the slope, soil, and vegetation types (O'Connor et al., 2019). ~~Farther~~ The farther the distance~~,~~ the longer the time and~~-~~ slower the process of ~~the~~ mutual replenishment. The differences in water holding capacity and water resistance of different soils also directly affects the complementary amount between SG and river runoff (Wei et al., 2021). In addition, the thickening and deepening of the ~~active layer~~AL does not always exert ~~an appreciable~~a corresponding control on groundwater flows, and the impact that active layer thickening has on groundwater flows depends most on the position (depth) of the saturated thickness (O'Connor et al., 2019). This~~e~~ ~~conclusion~~ was further confirmed in ~~this~~ our study. The SG observation points of FHS and SL are approximately 30 ~~meters~~ and 20 m~~eters~~ far from the river, respectively, with the landscape type ~~is both~~being alpine meadows

(Renzheng et al., 2019; Qin et al., 2022). ~~While t~~The saturated zone in the AL of the SL site ~~is~~ was 50~~–~~–80 cm in depth, ~~and it~~while of the FHS site ~~is~~ was only ~~in~~ 0~~–~~–30 cm in depth (Fig. 3). It was observed that the variation of SGL-RL hydrographs ~~is~~ was more similar in FHS than ~~it in~~ SL watersheds, which implies near ~~–~~surface saturated zone resulting in a closer complementary relationship between SG and river runoff (Fig. 6).

The large proportion of SG replenishing ~~recharging~~ river runoff in this study ~~implies~~ implied that SG ~~is~~ was a crucial replenishment ~~recharge~~ source for permafrost basin runoff, especially ~~in~~ during summer. While this has been ~~supposed~~ previously suggested~~before~~ (~~i.e.,~~ Bense et al., 2009; Shepelev and Pavlova, 2014; Fischer et al., 2017), our analysis provides a quantitative assessment of this impact and ~~shows~~ confirms its~~it to be true~~ in different regions of the QTP. According to ~~the coefficient of determination~~R^2 in p~~P~~eriod D, 57.0–65.8~~ %~~% of the river runoff was replenished ~~recharged~~ by SG in the study areas. In contrast, the SG contributed only approximately 10.0~~ %~~% of the RL changes in p~~P~~eriod C. Tregubov et al. (2021) reached a similar ~~result~~ conclusion in the Ugol'naya-Dionisiya River, Northeast Russia~~n~~, ~~which~~ and reported that the contribution of SG to river discharge in p~~P~~eriod C ~~is~~ was 10~~–~~–30% of the total discharge. The difference of contribution rate in p~~P~~eriods C and D ~~is~~ was closely related to the storage capacity of suprapermafrost reservoir and the recharge intensity of surface water to SG (Ma et al., 2017). During ~~the~~ p~~P~~eriod C, when the AL ~~was beginning to~~began to thaw and the storage capacity of suprapermafrost reservoir was ~~still~~ small, the replenishment ~~recharge~~ of SG to river runoff ~~is~~ was limited (Qin et al., 2022). ~~In the~~During summer, the seasonal thaw moved downward and thus the storage capacity of suprapermafrost reservoir increased, leading to most of the infiltrated rainwater being stored in the AL (Bosson et al., 2013). The larger recharge intensity of surface water (rainfall) and storage capacity of suprapermafrost reservoir result in the drainage of SG to river runoff in p~~P~~eriod D.

Our data showed ~~that there exist~~ two distinct high-water soil layers (saturated zone) in the AL of the QTP during summer: a near surface high-water zone (0–90 cm depth) and a deep layer (from 110 cm depth to the bottom of the AL), with a dry layer (90–110 cm depth) generally present in the middle AL (Fig. 4). ~~The founding~~These results differ ~~is different~~ from ~~the observed results in~~those of previous studies on the Arctic watersheds (Quinton, 1997; Street et al., 2016; Sebastian et al., 2023), ~~where have~~having only one saturated zone in the AL of different specific regions during thawing season, e.g., a near surface saturated zone in the riparian zone and deep saturated zone in the hillslopes (O'Connor et al., 2019).

The feature could be related to rainfall characteristics, Topography (slope), vegetation root depth, as well as water-holding capacity, soil type~~,~~, and ~~soil~~ composition ~~of the soil~~ at different ~~depths~~layers (~~(~~O'Connor et al., 2019~~).~~). Abundant summer rainfall could ~~quickly vertical~~vertically infiltrate ~~into the near surface~~ near-surface soil layer and ~~lead t~~increase the moisture content of ~~the~~ shallow soils ~~having high moisture content~~ (even saturated) in the QTP (Fig. 2) and Arctic watersheds (O'Connor et al., 2019; Sebastian et al., 2023). Figures 2 and 3 show that the surface rainfall could infiltrate downward into a maximum 90 cm depth in the AL~~–~~ on the QTP during summer rainfall events. The ~~soils~~soil in the middle AL often has low moisture content limited by the weak infiltration capacity and poor water-holding capacity (Qin et al., 2022)~~ few~~, while potential gravity ~~water~~ and fissure waters from surface water and shallow soils, coupled with the water-resisting effect of the permafrost table ~~always~~ leads to highly~~, even~~ saturated zone in the bottom of the AL. In addition, the maximum AL depths of several~~large amount of~~ Arctic watersheds are ~~less than~~< 100 cm (Hinkel and Nelson, 2003), while it ~~is~~ was 1.0–~~–~~2.0 m ~~depths in average~~ in the QTP. This and the differences in soil texture and ~~soil~~ hydrological characteristics could partly explain the two observed saturated zones in the AL of ~~the~~ QTP. The two saturated zones in AL, ~~on the other hand,~~in turn, lead to two potential water sources of lateral flow replenishing ~~recharging~~ river runoff and permafrost lakes, which differs from the conclusions ~~that~~ of only one major lateral replenishment ~~recharge~~ zone in AL studied in Arctic watersheds (Koch, 2016; O'Connor et al., 2019; Manasypov et al., 2020). These findings provide novel insights into~~is could enhance the knowledge for~~ hydrological analysis and simulation in permafrost regions.

8 Conclusions

This study analyzed the seasonal dynamics of SG and the correlations between SGL, ST, SVMC,~~, and~~ and RL at different stations ~~on~~ in the QTP. The variation process of the SGL during ~~a~~ the hydrological year can be distinctly divided into four periods, namely~~:~~ a rapid falling period (October–middle November) (A), a stable low-water period (late November–May) (B), a rapid rising period (approximately June) (C),~~;~~ and a stable high-water period (July–September) (D). This synchronously corresponds to the ST and SVMC variations in AL, which experienced a rapid freezing period, frozen stability period, rapid thawing period,~~, and~~ and thawing stability period during periods A–D of the SGL, respectively.

ST and SVMC in AL ~~have important~~ significantly ~~impacts on~~influence the SGL changes in permafrost watersheds, ~~whereas the impact~~however, varied in the four ~~different~~ periods. Compared with the other periods, the SGL in p~~P~~eriod D was permanently higher. The correlations between SGL and ST, as well as ~~between~~ SGL and SVMC, were relatively poor, and the SGL change responded well to rainfall. During p~~P~~eriods A and C, SGL had a good nonlinear correlation with ST and SVMC in the AL, while the correlations varied at different depths. During p~~P~~eriod C, when AL rapidly melted, SVMC in the shallow soils (0–50 cm depth) ~~had a~~ better ~~correlation~~ correlated with SGL, whereas ST in deeper AL soil~~s of AL~~ (below 50 cm) showed a closer ~~relations~~ association with SGL than with SVMC. ~~It can be inferred that~~Therefore, SG in p~~P~~eriod C was primarily replenished ~~recharged~~ by soil water in shallow layers, ~~and~~ while the SGL rise was significantly influenced by the thawing depth dominated by ST in deeper AL. In p~~P~~eriod A, there is a significant nonlinear correlation between SGL and ST at different AL depths ~~of the AL~~ ($0.81 \le R^2 \le 0.98$, $P < 0.05$). As the depth increases in the AL, the impact of the SVMC on the SGL weakens, whereas ST gradually becomes the dominant factor affecting the SGL.

According to ~~the~~ comparative analysis, the retreat and flood processes of river runoff were consistent with the SGL changes in p~~P~~eriods C and D, ~~which are~~ the primary annual runoff periods in permafrost basins. The RL dynamics were closely related to the SGL changes during these two periods. The SG and river runoff ~~are~~ were interconnected, and their water linkages ~~are~~were significantly affected by the freeze–thaw state of AL. The SGL contributed approximately 10.0~~ %~~% of the RL changes in p~~P~~eriod C, whereas~~ile~~ in p~~P~~eriod D~~,~~ approximately 57.0–65.8~~ %~~% of the surface runoff in permafrost watersheds was replenished ~~recharged~~ by SG, primarily ~~by~~ via rainfall infiltration. The SG is a crucial and potential water source for alpine permafrost watersheds.

In ~~summary~~conclusion, the characteristics of SG vary at different periods of the year~~ vary,~~ and~~ they~~ have a crucial regulatory effect on the hydrology of permafrost watersheds. ~~With c~~Continuous climate warming~~, the~~ will thicken AL~~ will thicken~~, and alter ~~the~~ potential precipitation and alpine vegetation~~ also will change~~. Furthermore, ~~T~~the change mechanism underlying~~of~~ SGL will correspondingly become more complex and require further research.

Author contribution

Jia Qin and Yongjian Ding developed the idea and outlines of the article. Jia Qin prepared the manuscript with contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgments

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