Projected future changes in cryosphere and hydrology of a mountainous catchment in the Upper Heihe River, China

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Abstract: Climate warming exacerbates the degradation of the mountain cryosphere, including glacier retreat, ~~**reduction in snow cover area, and**~~ permafrost degradation

and snow cover reduction. These changes dramatically alter the local and downstream hydrological regime, posing significant threats to basin-scale water resource management and sustainable development. However, ~~there~~this issue is still ~~a lack of systematic research~~not adequately addressed, particularly ~~that evaluates the variation of cryospheric elements~~ in mountainous catchments~~ and their impacts on future hydrology and water resources~~. ~~In this study, w~~We developed an integrated cryospheric-hydrologic model, ~~referred to as the~~ FLEX-Cryo model,~~.~~ ~~This model~~ to comprehensively consider~~s~~ glaciers, snow cover, frozen soil, and their dynamic impacts on hydrological processes. Taking ~~in~~ the mountainous Hulu catchment located in the Upper Heihe river of China as a case,~~.~~ w~~W~~e utilized the state-of-the-art climate change projection data under two scenarios (SSP2-4.5 and SSP5-8.5) from the sixth phase of the Coupled Model Intercomparison Project (CMIP6) to simulate the future changes in the mountainous cryosphere and their impacts on hydrology. Our findings showed that ~~the two glaciers in the Hulu catchment will completely melt out around the years 2045-2051. By~~under the medium (SSP2-4.5) and high emission scenario (SSP5-8.5), by the end of the 21st century, the glacier will completely melt out around the years 2051 and 2045, respectively. T~~t~~he annual maximum snow water equivalent is projected to decrease by 41.4% and 46.0%, while the duration of snow cover will be reduced by approximately 45 and 70 days. The freeze onset of ~~seasonal frozen soil~~seasonally frozen soil is expected to be delayed by 10 and 22 days, while the thaw onset of permafrost is likely to advance by 19 and 32 days. Moreover, the maximum freeze depth of ~~seasonal frozen soil~~seasonally frozen soil is projected to decrease by 5.2 and 10.9 cm per decade, and the depth of the active layer will increase by 8.2 and 15.5 cm per decade. Regarding hydrology, catchment total runoff exhibits a decreasing trend ~~until~~and the ~~complete~~

~~**melt-out**~~tipping point of ~~**glaciers, resulting in a total runoff decrease of 15.6% and 18.1%. Subsequently, total runoff shows an increasing trend, primarily due to an increase in precipitation.**~~glacier runoff occur approximately between 2019 and 2021. Permafrost degradation ~~**causes**~~will likely reduce the duration of low runoff in the early thawing season~~ **to decrease, and**~~, the discontinuous baseflow recession gradually transitions into linear recessions~~, **leading to an**~~ and the increase ~~**in**~~of baseflow. Our results highlight the significant changes expected in the mountainous cryosphere and hydrology in the future. These findings enhance our understanding of cold-region hydrological processes and have the potential to assist local and downstream water resource management in addressing the challenges posed by climate change.

Keywords: Glacier, Snow cover, ~~Seasonal frozen soil~~Seasonally frozen soil, Permafrost, Runoff, Model prediction

1. **Introduction**

"How will cold region runoff and groundwater change in a warmer climate?" was identified by the International Association of Hydrological Sciences (IAHS) as one of the 23 unsolved scientific problems (Blöschl et al., 2019). The mountain cryosphere, which includes glaciers, snow cover, and frozen soil in high-altitude regions, has a significant impact on water resources (Adler et al., 2019; Arendt et al., 2020; Rasul et al., 2020; Zhang et al., 2022). The ~~M~~mountain cryosphere is considered a crucial "water tower" and a climate change indicator due to its sensitivity to climate change (Tang et al., 2023). However, the cryosphere is rapidly retreating in many parts of the world, including glacier retreat, expansion of glacier lakes, northward movement of the permafrost southern limit, and shrinking snow cover area (Moreno et al., 2022; S. Wang et al., 2022; Ding et al., 2019; Wang et al., 2023). These changes have disrupted the water tower region and pose significant challenges to sustainable water resources management (Ragettli et al., 2016; Yao et al., 2022).

The degradation of the mountain cryosphere varies from region to region (Andrianaki et al., 2019; Wang et al., 2019). Lower altitudes experience a decreasing trend in snow cover days, snow depth, snow water equivalent, and snowmelt due to climate warming, while higher altitudes present a more complex picture (Connon et al., 2021; Nury et al., 2022; Yang et al., 2022). Global continental glacier mass balance from 2006 to 2015 was approximately -123±24 GT yr^{-1}, with significant losses observed in the Southern Andes, Caucasus Mountains, and Central Europe, while the Karakoram and Pamir regions exhibited lesser loss (Intergovernmental Panel on Climate Change (IPCC), 2022; Van Der Geest and Van Den Berg, 2021). Future projections suggest a 40% decrease in global permafrost by the end of the century, potentially transitioning into ~~seasonal frozen soil~~seasonally frozen soil (Chadburn et al., 2017~~).~~; Martin et al., 2023). The mountain cryosphere serves as a significant freshwater reservoir, impacting water resources and the hydrological cycle (Ding et al., 2020).

In a warming climate, ~~-~~glacier runoff exhibits a "tipping point" characterized by an initial increase followed by a subsequent decline (Rosier et al., 2021; Zhang et al., 2012). While small glaciers have already experienced this tipping point, its occurrence in large glaciers remains uncertain (Brovkin et al., 2021; Huss and Hock, 2018). Permafrost degradation leads to an increase in active layer thickness, resulting in the melting of subsurface ice and an augmentation of soil water storage capacity (Abdelhamed et al., 2022). Additionally, the degradation of the cryosphere significantly impacts the atmosphere, biosphere, surface energy balance, ecological water use, and ecosystems (Gilg et al., 2012; Miner et al., 2022; Pothula and Adams, 2022). Understanding the complex interactions between cryosphere degradation and ecosystems is crucial, but quantitatively observing the degradation process in high-altitude regions is challenging. Hydrological models provide an effective approach to analyze degradation patterns and assess the impact on future water resources (Han and Menzel, 2022).

Glacio-hydrology is influenced by both glacier melt and glacier dynamics. Glacier melting models can be categorized into three types: energy balance, temperature index, and hybrid models (He et al., 2021; Gao et al., 2021; Negi et al., 2022; Zekollari et al., 2022). While energy balance models analyze glacier accumulation and melt processes based on solid physical mechanisms, they require extensive forcing data that may not be readily available in mountainous regions (Huss et al., 2010). ~~On the other hand~~In contrast, temperature index models are simpler and more effective, requiring fewer parameters (including degree-day factor and threshold temperature) and forcing data (temperature and precipitation) (Bolibar et al., 2022; Vincent and Thibert, 2023). These models~~It~~ perform~~s~~ well at both daily and monthly scales. Glaciers ~~are ~~move~~ing~~ slowly~~,~~ due to the combined effects of gravity and high viscosity of ice. Due to climate change, ice becomes thinner, and glacier loses its mass balance, which will cause the glacier morphology to evolve to a new balance status. Glacier dynamic models, with full-Stokes approach as the most complete form, and many other simplifications, such as the shallow-ice approximation, and the shallow-shelf approximation~~ etc~~, are still computationally expensive, hindering their implications in large scale studies. Three conceptual models are commonly used for glacier evolution: volume-area scaling (V-A) method, accumulation area ratio (AAR) method, and Δh-parameterization (Michel et al., 2022; Wiersma et al., 2022). The first two approaches do not consider the detailed changes in different elevation bands, while the Δh-parameterization approaches only require glacier mass balance as forcing data to analyze changes in ice thickness at different elevation bands based on the relationship between glacier mass balance and glacier area (Huss et al., 2010). The temperature index method coupled with the Δh-parameterization approach serves as an effective module to simulate glacier evolution and its impacts on hydrology.

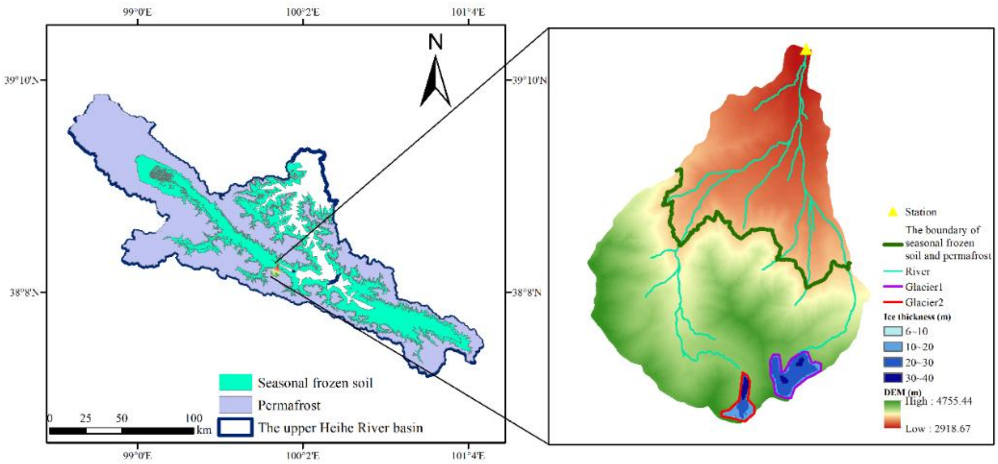
Permafrost hydrology models can be classified into one-dimensional models and distributed watershed models (Elshamy et al., 2020). One-dimensional hydrological models, such as the Stefan equation, the temperature at the top of permafrost (TTOP) model, CoupModel, and SHAW model, are effective in simulating freeze depth, hydrothermal transport, and carbon or nitrogen transport, but they are unable to capture the broader impact of permafrost on hydrology at catchment scale (Kaplan Pastíriková et al., 2023; Li et al., 2022; Liu et al., 2023). On the other hand, distributed watershed models, such as the Cold Regions Hydrological Model (CRHM), Hydrogeosphere (HGS), and Distributed water-heat coupled model (DWHC), consider the spatial variability of permafrost properties and simulate the interactions between permafrost, surface water, and groundwater (Chen et al., 2008; He et al., 2023; Pomeroy et al., 2022). These models operate on a small-scale basis and require extensive prior knowledge, following a "bottom-up" approach that relies on small-scale field observations and situational models to comprehend the effects of permafrost on hydrology. (Peng et al., 2016). However, the freeze-thaw cycle is influenced by multiple interconnected factors, including climate, topography, slope orientation, snowpack, and vegetation (Chang et al., 2022). The process of upscaling would lead to the neglect of some variables and the amplification of others (Fenicia and McDonnell, 2022). In contrast, the FLEX-Cryo model is based on the FLEX-Topo-FS model, which employs a "top-down" modeling procedure that involves observed data analysis, qualitative perceptual modeling, quantitative conceptual modeling, and the testing of model realism. This model exhibits the ability to accurately and expeditiously identify key elements in permafrost hydrological processes and then simulate hydrology at the catchment scale (Beven., 2012; Gao et al., 2022).

The aim of this study is to integrate the FLEX-Topo-FS model and a glacier evolution model (Δh-parameterization) to develop a landscape-based model of the mountain cryosphere, referred to as FLEX-Cryo. This model will be utilized to simulate changes in various components of the mountain cryosphere and evaluate their impacts on hydrological processes, thereby enhancing our understanding of the hydrological cycle. The model will be driven by eight bias-corrected Global Climate Models (GCMs) under SSP2-4.5 and SSP5-8.5 scenarios obtained from the Coupled Model Intercomparison Project Phase 6 (CMIP6), which will be used to predict future changes in glaciers, snow, and frozen soil, as well as their effects on hydrology.

2.Study area and data

2.1 Study area

The Hulu catchment is located in the upper reaches of Heihe River basin (38° 12′ N-38° 17′ N, 99° 50′ E-99° 53′ E) and about 23.1 km^2. The elevation ranges from 2960-4820m. The Hulu catchment belongs to continental monsoon climate. Rainfall is the major phase of precipitation, and there is also snowfall in the winter. Four landscapes are identified, i.e. glacier (5.6%), alpine desert (53.5%), vegetation hillslope (37.5%), and riparian zone (3.4%; Fig.~~2).~~1 (c)). The landscape pattern in Hulu catchment has typical altitude zonality. The vegetation and riparian are almost distributed in the lower elevation bands. Alpine desert, and glacier are in the high elevation bands. There is almost no human activity in the catchment~~.~~ (Liu and Chen, 2016; Li et al., 2014). There are two major glaciers, i.e. Glacier1 and Glacier2 (Fig.1 (b) and Fig.2) in the catchment. And the Galcier1 was also named as the Shiyi Glacier in the glacier catalogue of China. ~~Seasonal frozen soil~~Seasonally frozen soil and permafrost both exist in the catchment. The lower limit of permafrost is around in 3650-3700 m. Permafrost region account for 64% of the total catchment and the others are ~~seasonal frozen soil~~seasonally frozen soil. The soil generally starts to freeze in the October~~.~~ (Gao et al., 2019). Thus October 1 was set as the start of hydrological year, so forth. All the interannual variations in this study were based on the hydrology year.



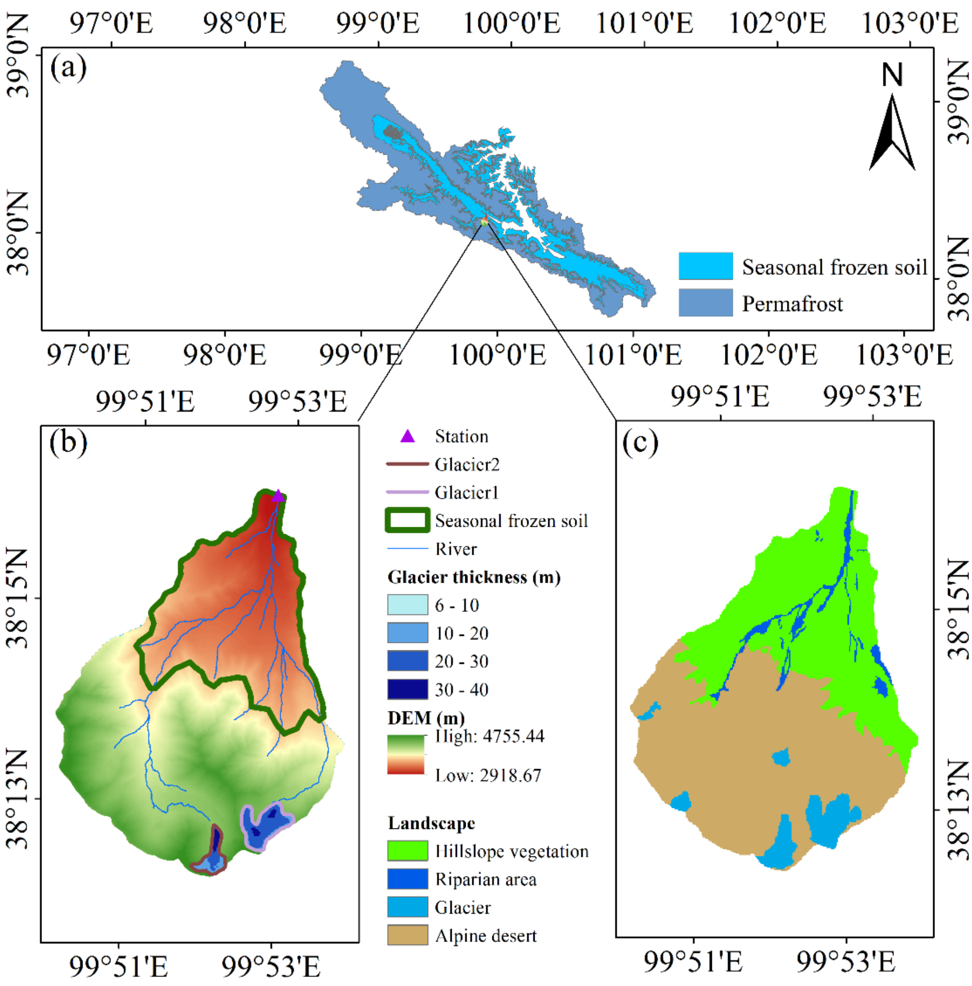
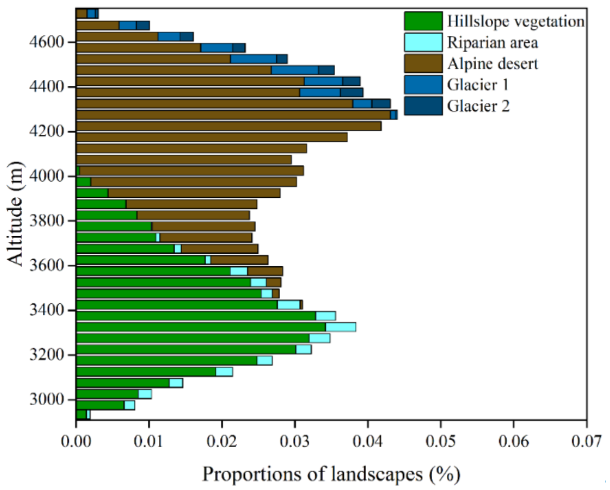


Figure 1. (a) The distribution of permafrost and seasonally frozen soil on the upper Heihe River basin, and the location of Hulu catchment. (b) The digital elevation model~~,~~ and the thickness of the two major glaciers. (c) Spatial distribution of four landscapes (glacier~~ and the location of study area~~, alpine desert, vegetation hillslope, and riparian zone)



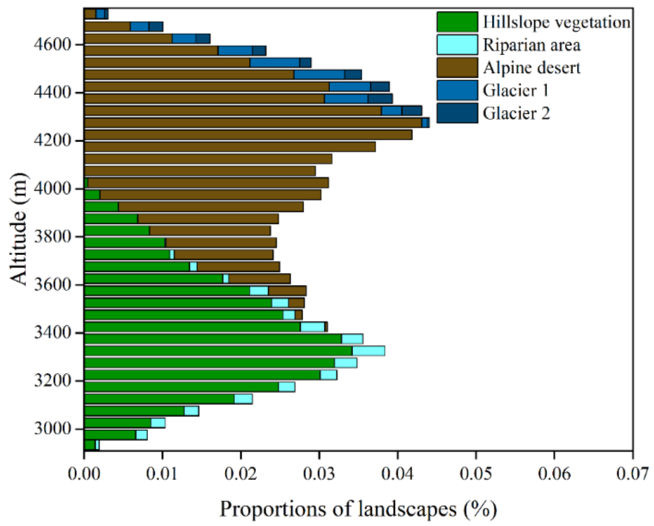


Figure 2. Landscape classification at different elevation bands

2.2 Data

Temperature and precipitation are observed at 2920 m, near the outlet of the catchment, from ~~January 1,~~ 2011 ~~to December 31, 2014.~~ to 2014. Farinotti et al. (2019) used five models which used the ice flow dynamics to invert ice thickness from surface features to estimate the ice thickness distribution of about 21500 glaciers outside the Greenland and Antarctic ice sheets. We used the estimated data for the initial thickness distribution of Glacier1 and Glacier2 (data downloaded from https://doi.org/10.3929/ethz-b-000315707).

The Couple Model Intercomparison Project phase 6 (CMIP6) is widely used to predict future climate. Eight general circulation models (GCMs) (Table 1) under two climate scenarios (SSP2-4.5 and SSP5-8.5) are used for predicting future climate. The selected models have been well validated at the nearby catchments (Xing et al., 2023; Yin et al., 2021; Ma et al., 2022; Zhu and Yang, 2020; Chen et al., 2022). SSP2-4.5 scenario represents medium part of the future pathways, which is usually a referenced experiment comparing others CMIP6-Endorsed MIPs and it produces a radiative forcing of 4.5 W m^{-2} in 2100. SSP5-8.5 scenario represents the high emission scenario and it produce a radiative forcing of 8.5 W m^{-2} in 2100.

~~There~~Although the reliability of GCMs has been verified in the previous studies, there is certain bias in the output ~~of GCMs~~ that needs to be corrected. Firstly, outputs from eight GCMs under two climate scenarios are interpolated to 0.5°×0.5°, then the bias corrects are carried out by CMhyd software (download from https://swat.tamu.edu/software/cmhyd/) in which four methods were used including: distribution mapping of precipitation and temperature, linear scaling of precipitation and temperature, variance scaling of temperature and local intensity scaling (LOCI) of precipitation (Teutschbein and Seibert, 2012). The bias-corrected precipitation and temperature were calculated by using the equal weighted average method to obtain the multi-model ensemble average values under the SSP2-4.5 and SSP5-8.5 scenarios, which reduce the uncertainty caused by a single bias correction method and a single GCM~~.~~, the method is described as follow:

$$P_{\text{ave}} = \frac{1}{N_{GCM}} \left(\sum_{j=1}^{N_{GCM}} \left(\frac{1}{N_{bias}} \left(\sum_{i=1}^{N_{bias}} (P_i) \right) \right) \right) \quad (1)$$

Where the P_{ave} is the average value of the multi-model and multi -method, P_i is the projected climate data of an GCM, N_{bias} is the number of correction methods (N_{bias} is 3 in this research) and N_{GCM} is the number of GCM (N_{GCM} is 8 in this research).

Table 1. Details of data from eight GCMs used in this study

GCM	Institutions	Grid	Lon. × Lat.
ACCESS-CM2	Australian Community Climate and Earth System Simulator	192×144	1.875°×1.250°
ACCESS-ESM1-5	Australian Community Climate and Earth System Simulator	192×144	1.875°×1.250°
BCC-ECM1	Beijing climate center	320×160	1.125°×1.125°
CMCC-CM2-SR5	Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici	288×192	1.25°×0.938°
CMCC-ESM2	Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici,	288×192	1.25°×0.938°
GFDL-CM4	National Oceanic and Atmospheric Administration	144×90	2.5°×2°
MPI-ESM1-2-LR	Max Planck Institute for Meteorology	192×96	1.875°×1.875°
NESM3	Nanjing University of Information Science and Technology	192×96	1.875°×1.875°

3.Methodology

3.1 FLEX-Cryo model

The FLEX-Cryo model is a landscape-based cryospheric hydrological model~~,~~ that ~~which~~ considers multiple elements~~multi-elements~~ of cryosphere and their impacts on hydrology, including glacier, snow and frozen soil. Figure 3 shows the structure of the FLEX-Cryo model.

The model parameters used in this research were obtained the optimal parameter set from a previous study conducted in the same~~is~~ catchment (Gao et al., 2022). The

~~finally~~ selected parameters are listed in Table 2 and the other variables in calculating (Fig. 3) are listed in Table 4.

Table 2. Model parameters and their values in this study

Parameter	Name	Parameter value
F_{dd} (mm°C $^{-1}$d^{-1})	Snow degree day factor	3.10
C_g (-)	Glacier degree factor multiplier	2.27
S_{umax_V} (mm)	Root zone storage in vegetation hillslope	100.32
S_{umax_D} (mm)	Root zone storage in alpine desert	20.63
S_{umax_R} (mm)	Root zone storage in riparian wetland	20.26
β (-)	The shape of storage capacity curve	0.11
C_e (-)	Soil moisture threshold for reduction of evaporation	0.50
D (-)	Splitter to fast and slow response reservoirs	0.20
T_{lagf} (days)	Lag time from rainfall to peak flow	2.00
K_f (days)	Fast recession coefficient	1.65
K_s (days)	Slow recession coefficient	79.09
k (W (m K)$^{-1}$)	Thermal conductivity	2.00
ω (-)	Water content as a decimal fraction of the dry soil weight	0.12
ρ(kg/m^3)	Bulk density of the soil	1000
Pcalt (%/100m)	Precipitation increasing rate	4.20
Tcalt (°C/100m)	Temperature lapse rate	0.68

3.1.1 Glacier and snow melting

The ~~T~~threshold temperature (T_t) determines the phase of precipitation, i.e. snowfall or rainfall. Snow reservoir (S_w) accounts for the snow accumulating, melting (M_w) and water balance(Eq. 9). The number of days when S_w is non-zero represent the snow cover days and the maximum S_w is the maximum snow water equivalent of a year (Giovando, J. and Niemann, J. D., 2022). Both Glacier and snow melt were calculated by the temperature index method, -which is on basis of the degree-day factor (F_{dd}). If there is no s~~n~~'ow cover, the glacier starts to melt. Due to the lower albedo, the degree-day factor of ice is greater than that of snow cover, and is multiplied by a coefficient C_g to calculate glacier melt (Eq. 14).

3.1.2 Rainfall-runoff module

The rainfall and snow melt enter the root zone reservoir S_u, then runoff (R_U) generates based on the input water and the relative root zone soil moisture (S_u/S_{umax}) and the shape of root zone storage capacity distribution determined by parameter β (Eq. 16). Actual evaporation E_a is also estimated based on the soil moisture S_u/S_{umax} and the potential evaporation by Hamon equation (Hamon, 1961). The generated runoff (R_U) is separated, by parameter D, into two linear reservoirs, i.e. the fast response reservoir (S_f) and slow response reservoir (S_s) (Eq. 18 and 19). The two reservoirs are respectively controlled by fast recession parameter K_f and slow recession parameter K_s to simulate the subsurface storm flow Q_f and groundwater runoff Q_s (Eq. 7,8).

Different landscapes, for example, alpine desert, vegetation hillslope and riparian zone, have different sizes of root zone storage capacity (S_{umax}) (Aubry-Wake et al., 2023). In the vegetation hillslope, plants have well-developed root systems and the root zone has a larger storage capacity. ~~So~~Therefore, the S_{umax_V} was set to ~~with~~ a larger value. For the alpine desert and riparian zone, the S_{umax_D} and S_{umax_R} were both limited due to the less developed root system and storage capacity.

~~**(Gao et al., The Ah-parameterization method was employed, which relies on empirical curves that are dependent on the size of the glacier.**~~ **3.2 Frozen soil module**

The Stefan equation was employed to estimate freeze (thaw) depth. This equation is calculated by the freeze (thaw) index (F), which neglects~~ed~~ the sensible heat. The equation is as follows:

$$\varepsilon = \left(\frac{2 \cdot 86400 \cdot k \cdot F}{L \cdot \omega \cdot \rho}\right)^{0.5} \qquad (2)$$

w~~W~~here, the ε is the freeze / thaw depth (m), k is the thermal conductivity (2 W (m K)$^{-1}$), F is the freeze/ thaw index(℃), Q_L is the volumetric latent heat of soil (J m^{-3}), L is the latent heat of the fusion of ice (3.35×10^5 J kg^{-1}), ω is the water content as a decimal fraction of the dry soil weight (0.12), and ρ is the bulk density of the soil (1000 kg m^{-3}).

Since the Stefan equation requires ground surface temperature, which is difficult to measure and often lacks data. During freezing, the air temperature was translated into ground temperature by multiplier 0.6 and the ground temperature was the same as the air temperature during thawing (Gisnås et al., 2016). In this research, the freeze-thaw process was simulated at each Hydrologic Response Unit (RHU) by the Stefan equation driven by distributed air temperature. The lower limit of permafrost was also estimated by the distributed soil freeze index and thaw index where the freeze index is equal to the thaw index in the mountain region.

In the freezing and frozen season, there is no runoff generated due to precipitation in the form of ~~precipitation being~~ snowfall and the soil being frozen. During ~~In~~ this period, runoff only comes from the groundwater of the supra-permafrost and no runoff (R_U) is generated from root zone reservoir to the fast response reservoir (S_f) and slow response reservoir (Ss). ~~So~~Therefore, we set the R_U is zero in this season. In the freezing season, when the freezing depth is less than 3 m, the groundwater discharge in the supra-permafrost ~~was~~ is still connected, which ~~could~~can be simulated with a linear groundwater reservoir (S_s) and the slow recession coefficient (K_s). When the freezing depth is greater than 3 m at a Hydrologic Response Unit, the groundwater ~~was~~is frozen and there ~~was a~~is little runoff generated from the groundwater discharge at the Hydrologic Response Unit. So, in the FLEX-Cryo model, the groundwater reservoir (S_s) was reduced to 10% of its storage to represent the groundwater being frozen (Eq. 3,4). The other 90% of the storage water was frozen in the groundwater system (Eq. 4). In the model, the soil beg~~an~~ins to freeze from high elevation to the lower elevation, which affects the groundwater. The groundwater reservoir freezes along the elevation, stopping the function of a series of cascade groundwater buckets, which is the key reason for discontinue recession.

In the thawing season, the freeze statue at the lowest elevation control~~ling~~s the hydraulic connectivity between groundwater system and soil. If the freeze depth is larger than thaw depth calculated by the Stefan equation, the soil is still frozen and the connectivity between groundwater system and soil is still closed. There is no runoff generated (Ru) but the ~~z~~root soil moisture (Su) ~~is a~~accumulat~~ing~~es and ~~the~~ evaporation is the only outflow from the root zone. Once the thaw depth is larger than the freeze depth, the frozen groundwater reservoir is ~~was~~ released to the groundwater discharge (Eq. 4). Complete~~ly~~ thawing at the lowest elevation represents the end of the thawing season and the start of completely thawed season. In the completely thawed season, the groundwater and soil are connected and ~~which is~~ not affected by the frozen soil.

$$\frac{dS_s}{dt} = R_s - Q_s - F_s \quad (3)$$

$$F_s = \begin{cases} 0.9 \cdot S_s & freeze\ depth\ (\varepsilon) \geq 3\ m \\ -0.9 \cdot S_s & once\ thaw\ depth\ reach\ to\ yearly\ \max \\ & or\ thaw\ depth\ \geq thaw\ depth \end{cases} \quad (4)$$

3.3 Δh-parameterization

The Δh-parameterization is a mass conservation method to assess the change of ice-covered, glacier length and glacier thickness in response to global warming. The glacier mass balance (GMB) calculated by FLEX-Cryo was redistributed to glacier elevation bands. It is an observed truth that the lower elevation bands loss more ice than higher elevation bands. The lost ice volume, calculated by a mass balance model, is converted into a distributed ice thickness change according to the Δh-parameterization. (Gao et al., 2021; Huss et al., 2010).

The Δh-parameterization method was employed, which relies on empirical curves that are dependent on the size of the glacier. The study categorized glaciers into three size classes: large valley glacier (area > 20 km^2), medium valley glaciers (5 km^2 < area < 20 km^2), and small glaciers (area < 5 km^2). Both Glacier1 and Glacier2 had areas less than 5 km^2, and categorized as small glaciers. The small glacier equation in this study is as follows:

$$\Delta h = (h_r - 0.30)^2 + 0.60(h_r - 0.30) + 0.09 \quad (5)$$

Where, Δh is normalized surface elevation change and h_r is the normalized elevation range. Based on this equation, the glacier elevation and surface area were evolved every 5 years to avoid the circumstance of glacier advancing. The corresponding glacier melting HRU was transformed into alpine desert (Wei et al., 2023).

Table 3. The FLEX-Cryo model equations

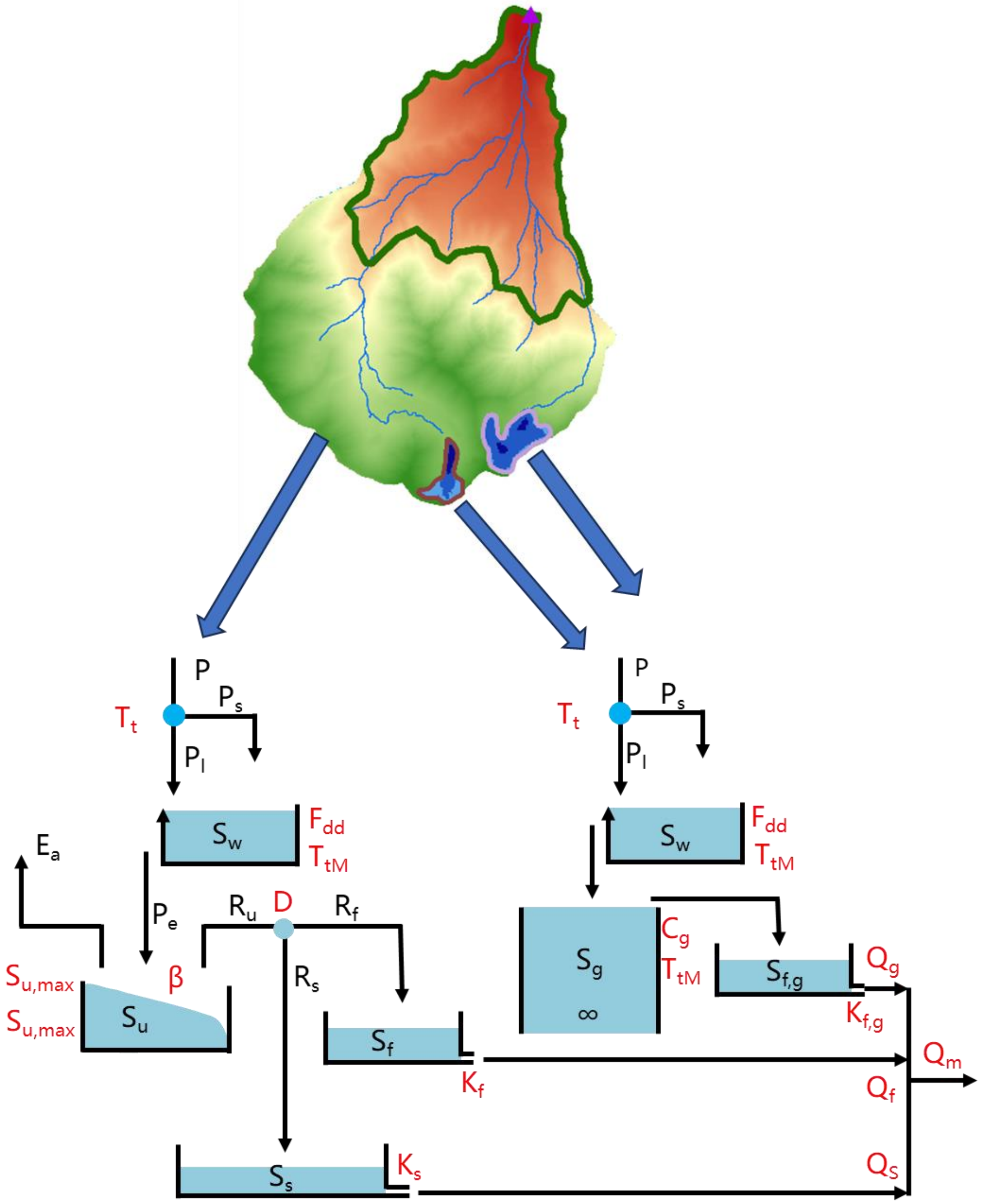
Landscape	Runoff equation	Water balance equation	Structural equation

Glacier	$Q_g = \frac{S_g}{K_{f,g}}$ (6)	$\frac{dS_g}{dt} = P_l + M_g - Q_g$ (9)	$M_g = \begin{cases} F_{dd} \cdot T \cdot C_g & S_w \text{ and } T > 0 \\ 0 & S_w \text{ and } T > 0 \end{cases}$ (14)
Alpine desert Hillslope vegetation Riparian area	$Q_f = \frac{S_f}{K_f}$ (7) $Q_s = \frac{S_s}{K_s}$ (8)	$\frac{dS_w}{dt} = P - M_W$ (10) $\frac{dS_u}{dt} = P_l + M_W - E_a - R_u$ (10) $\frac{dS_f}{dt} = R_f - Q_f$ (12) $\frac{dS_s}{dt} = R_s - Q_s$ (13)	$M_w = \begin{cases} F_{dd} \cdot T & T > 0 \\ 0 & T > 0 \end{cases}$ (15) $R_u = (P_l + M_w) \cdot \left(1 - \left(1 - \frac{S_u}{S_{umax}}\right)^{\beta}\right)$ (16) $E_a = E_p \cdot \left(\frac{S_u}{C_e \cdot S_{umax}}\right)$ (17) $R_f = R_u \cdot D$ (18) $R_s = R_u \cdot (1 - D)$ (19) $R_{fl}(t) = \sum_{i=1}^{T_{lagf}} cf(i) \cdot R_f(t - i + 1)$ (20) $cf(i) = i / \sum_{u=1}^{T_{lagf}} u$ (21)

3.4 Spatial discretization of the catchment

The catchment area was divided into 37 elevation bands ranging from 2960 m to 4820 m, with an interval of 50 m. These elevation bands were classified based on four landscapes: glacier, alpine desert, vegetation hillslope, and riparian zone~~.~~ (Fig. 2 and Fig. 3). As a result, there were a total of 148 Hydrologic Response Units (HRUs) in the catchment. The landscape of alpine desert was the most widespread, covering an elevation range of 3425 m to 4727 m. The glacier was found in higher altitude areas, specifically between the elevation bands of 3725 m and 4727 m.

~~The model parameters used in this study were obtained from a previous study conducted in this catchment (Gao et al., 2022). These parameters are listed in Table 2.~~



~~The Δh-parameterization method was employed, which relies on empirical curves that are dependent on the size of the glacier. The study categorized glaciers into three size classes: large glacier, area > 20 km^2; medium-sized glacier, 5 km^2< area < 20 km^2; small glacier, area < 5 km^2. Both Glacier1 and Glacier2 had areas less than 5 km2, making them small glaciers. The glacier mass balance (GMB) was calculated using the glacier module of the FLEX-Cryo model. The calculated GMB~~

was then distributed to different elevation bands using the Δh-parameterization method. Simultaneously, the glacier area and thickness were updated accordingly. When a glacier was completely melted, the corresponding HRU was transformed into alpine desert. The evolution of these landscapes was updated every 5 years (Wei et al., 2023).

This study focused on the degradation of glaciers, changes in snow cover and permafrost, and their impacts on runoff under climate warming. Factors such as solar radiation, land surface temperatures influenced by snow cover, and vegetation restoration were not considered. Average annual temperatures and annual precipitation were used as indicators of future climate change. Glacier thickness at the highest elevation band and glacier volume were used to quantify the thinning process of glaciers. The maximum freeze depth of seasonal permafrost, thickness of the active layer, and freeze-thaw cycle were used to characterize the thawing of frozen soil. Snow cover days and snow water equivalent were utilized to measure the decreasing trend of snow. Changes in runoff and runoff coefficient were analyzed to assess the impact of mountain cryosphere degradation on water resources. Additionally, the study examined the effect of degradation on runoff yield by observing the low runoff during the early thaw season and the discontinuation of baseflow recession.

Table 2. Model parameters and their values or ranges in this study

Parameter	Name	Prior range
F_{dd} (mm ℃$^{-1}$d^{-1})	Snow degree day factor	(1.0-5.0)
C_g (-)	Glacier degree factor multiplier	(1.0-3.0)
$S_{\text{Umax\_V}}$ (mm)	Root zone storage in vegetation hillslope	(50-200)

S_{Umax_D} (mm)	Root zone storage in alpine desert	(10-100)
S_{Umax_R} (mm)	Root zone storage in riparian wetland	(10-100)
β (-)	The shape of storage capacity curve	(0-1)
C_e (-)	Soil moisture threshold for reduction of evaporation	(0.1-0.6)
D (-)	Splitter to fast and slow response reservoirs	0.2
T_{lagf} (days)	Lag time from rainfall to peak flow	(0.8-3)
K_f (days)	Fast recession coefficient	(1-10)
K_s (days)	Slow recession coefficient	(10-100)
k (W (m K)$^{-1}$)	Thermal conductivity	2
ω (-)	Water content as a decimal fraction of the dry soil weight	0.12
ρ (kg/m^3)	Bulk density of the soil	1000
Pcalt	Precipitation increasing rate	4.2
Tcalt	Temperature lapse rate	0.68

3.1 FLEX-Cryo model

FLEX-Cryo model is a landscape-based cryospheric hydrological model, which considers multi-elements of cryosphere and their impacts on hydrology, including glacier, snow and frozen soil. The elevation is also an important factor affecting the temperature and precipitation. The temperature and precipitation are interpolated based on the band in situ observation (2980 m). the temperature regression rate is -0.68℃/100m and the precipitation increasing rate is 4.2%/100m. The value of 0 ℃ is the threshold temperature to split snowfall (P_s) and rainfall (P_l).

3.1.1 Glacier and snow module

Glacier and snow melt were both calculated by the temperature - index method which is on basis of the degree-day factor F_{dd} (mm ℃$^{-1}$ d^{-1}) (F_{dd} in Table 2; equation

(11) in Table 3). Due to the lower albedo, the degree-day of ice is greater than snow, and multiplied by a coefficient C_g (C_g in Table 2; equation (9) in Table 3). The glacier area runoff Q_g is calculated through the linear reservoir S_g which the liquid rain P_l and glacier melt M_g inflow and the runoff outflow ((Equation (4) in Table 3) and a recession parameter K_{fg} (Equation (1) in Table 3).

3.1.2 Frozen soil module

The Stefan equation was calculated at the different elevation bands based on the interpolated temperature (Equation (18) in Table 3). The observed temperature was multiplied by 0.6 to translate the air temperature to ground temperature which was required in the equation. In this equation, the ε is the freeze / thaw depth (m), k is the thermal conductivity (2 W (m K)$^{-1}$), F is the freeze / thaw index(℃) which represents the cumulative value of the temperature below (above) 0℃, Q_L is the volumetric latent heat of soil (J m^{-3}), L is the latent heat of the fusion of ice ($3.35 \times 10^5 J\ kg^{-1}$), ω is the water content as a decimal fraction of the dry soil weight (0.12), and ρ is the bulk density of the soil (1000 kg m^{-3}).

The frozen soil impacts on the runoff by the soil water and groundwater. In the frozen season, the baseflow comes merely from the groundwater discharge at the supra-permafrost layer (Qs). In the freezing season, when the freeze depth is greater than 3 m and the supra-permafrost groundwater is frozen. And due to certain amount of unfrozen water in frozen soil, the volume of slow reservoir S_s (Equation (19) and (20)) will be reduced to 10%. The groundwater system in seasonal frozen soil region is still connected in winter. When the soil completely thaws at the lowest elevation band, the runoff generated by the frozen S_s will rapidly release to the Q_s. The baseflow generation is assumed to be a linear recession process. The generated baseflow is controlled by the reservoir S_s, recession coefficient K_s, the time t and initial runoff Q_0 (Equation (21)).

$$\frac{dS_s}{dt} = R_s - Q_s - F_s \qquad (19)$$

$$F_s = \begin{cases} 0.9 \cdot S_s & \varepsilon \geq 3m \\ -0.9 \cdot S_s & completely\ thaw \end{cases} \qquad (20)$$

$$Q = Q_0 \cdot e^{-t/K_s} \qquad (21)$$

3.1.3 Rainfall-runoff module

The root zone reservoir S_u (equation (6) in Table 3), fast response reservoir S_f (equation (7) in Table 3) and slow reservoir S_s (equation (8) in Table 3) are critical reservoirs for simulating rainfall-runoff processes. The runoff yield process is governed by the root storage capacity and the water input to the soil (equation (12) in Table 3) meanwhile the actual evaporation is determined by soil moisture and potential evaporation. The generation runoff flows into two linear reservoirs (S_f and S_s) which represents the storm flow (Q_f) and groundwater runoff (Q_s), respectively. The runoff yield process has similarity in alpine desert, vegetation hillslope and riparian zone and the difference is the root zone storage capacity (S_{umax}). In the vegetation hillslope, plants have well-developed root systems and the root zone has a larger storage capacity. So, the S_{Umax-V} was set with larger value. For the alpine desert and riparian zone, the S_{Umax-D} and S_{Umax-R} were both limited due to the less developed root system and storage capacity.

Table 3. The FLEX-Cryo model equations

Landscape	Runoff equation	Water balance equation	Structural equation

Glacier	$Q_g = \frac{S_g}{K_{fg}}$ (1)	$\frac{dS_g}{dt} = P_l + M_g - Q_g$ (4)	$M_g = \begin{cases} F_{dd} \cdot T \cdot C_g & S_W = 0 \text{ and } T > 0 \\ 0 & S_W > 0 \text{ and } T \le 0 \end{cases}$ (9) $\Delta h = (h_r - 0.30)^2 + 0.60(h_r - 0.30) + 0.09$ (10)
Alpine desert Hillslope vegetation Riparian area	$Q_f = \frac{S_f}{K_f}$ (2) $Q_s = \frac{S_s}{K_s}$ (3)	$\frac{dS_W}{dt} = P - M_W$ (5) $\frac{dS_u}{dt} = P_l + M_W - E_a - R_u$ (6) $\frac{dS_f}{dt} = R_f - Q_f$ (7) $\frac{dS_s}{dt} = R_s - Q_s$ (8)	$M_W = \begin{cases} F_{dd} \cdot T & T > 0 \\ 0 & T \le 0 \end{cases}$ (11) $R_U = (P_l + M_W) \cdot \left(1 - \left(1 - \frac{S_U}{S_{U\max}}\right)^{\beta}\right)$ (12) $E_a = E_p \cdot \left(\frac{S_U}{C_e \cdot S_{U\max}}\right)$ (13) $R_f = R_U \cdot D$ (14) $R_s = R_U \cdot (1 - D)$ (15) $R_{fl}(t) = \sum_{i=1}^{T_{lagf}} cf(i) \cdot R_f(t - i + 1)$ (16) $c_f(i) = \frac{i}{\sum_{u=1}^{T_{lagf}} u}$ (17) $\varepsilon = \left(\frac{2 \cdot 86400 \cdot k \cdot F}{Q_L}\right)^{0.5} = \left(\frac{2 \cdot 86400 \cdot k \cdot F}{L \cdot \omega \cdot \rho}\right)^{0.5}$ (18)

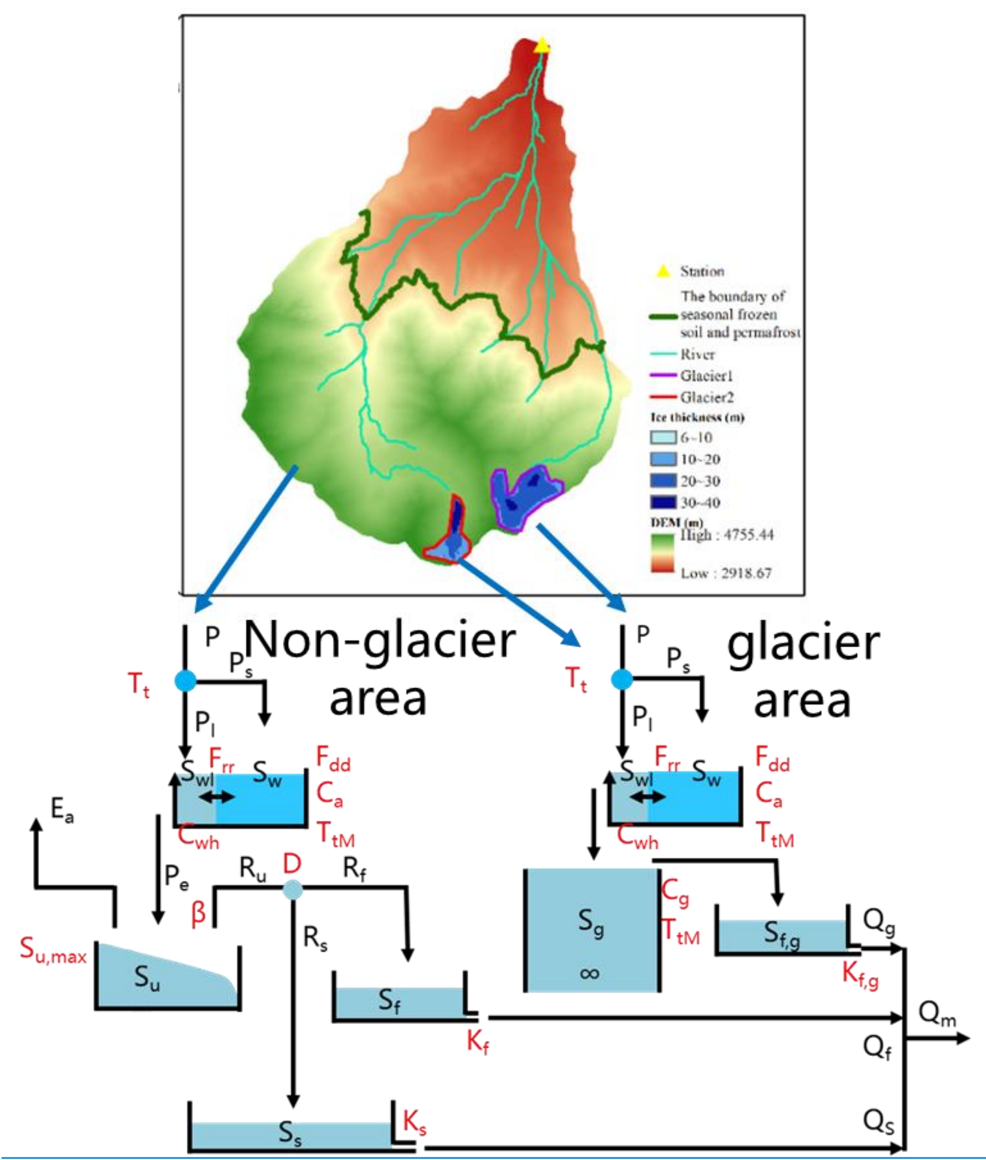


Figure.3 Structure of the FLEX-Cryo model. The abbreviation in red color indicates paraments and the abbreviations in black indicate storage components and fluxes.

Table 4. -The variables in Table 3 and ~~f~~Figure 3 and their meaning

Variables	~~Name~~Meaning
P (mm/day)	precipitation
T_t (℃)	Threshold temperature
P_s (mm/day)	Solid precipitation
P_l (mm/day)	Liquid precipitation
S_{wl} (mm)	Liquid water inside the snow pack.
S_w (mm)	Solid snow pack

T_{tM} (℃)	The threshold temperature for snow and glaciers melting
P_e (mm)	Generated runoff to soil/ice surface
E_a (mm)	Actual evaporation
R_u (mm)	water that exceeds the storage capacity
S_f (mm)	Fast flow reservoir
S_s (mm)	Slow flow reservoir
$S_{f,g}$ (mm)	Glacier linear reservoir
Q_f (mm/day)	Subsurface storm flow
Q_s (mm/day)	Groundwater runoff
Q_g (mm/day)	Runoff in glacier region
Q_m (mm/day)	All runoff

3.5 Model evaluation metrics

The Kling–Gupta efficiency (KGE), Nash–Sutcliffe efficiency (NSE), coefficient of correlation (R) and root mean square error (RMSE) were used to comprehensively assess ~~assessment of~~ the model performance and ~~it also indicates~~ the reliability for the model. All The KGE, NSE, R and RMSE are all less than 1. For KGE, NSE and R, values closer to 1 indicate ~~The first three valuation closer 1 indicates the~~ better performance. ~~and the~~A lower RMSE value indicates less error and better model performance. These metrics can be calculated as follows:

$$KGE = 1 - \sqrt{(r-1)^2 + (\alpha-1)^2 + (\beta-1)^2} \quad (22)$$

$$NSE = 1 - \frac{\sum_{t=1}^{n}(Q_0 - Q_m)^2}{\sum_{t=1}^{n}(Q_0 - \overline{Q_0})^2} \quad (23)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{n}(Q_0 - Q_m)^2} \quad (24)$$

$$R = \frac{\sum_{t=1}^{n}(Q_0-\overline{Q_0})(Q_m-\overline{Q_m})}{\sqrt{\sum_{t=1}^{n}(Q_0-\overline{Q_0})^2}\sqrt{\sum_{t=1}^{n}(Q_m-\overline{Q_m})^2}} \quad (25)$$

w~~W~~here, r is linear correction coefficient between simulation and observation, α

is the ratio of the stand deviation of simulated variables and observed variables, β is the ratio of the average value of simulated and observed variables, Q_0 is the observation runoff, $\overline{Q_0}$ is the average observed runoff and Q_m is the simulation runoff.

4. Results

~~4.1~~4.1 Performance of bias correction and runoff depth simulation

4.1.1 Bias correction performance

The ~~precision~~accuracy of climate projection varied with the multiple bias correction method (Fig. 4). The distance between the observation and the projection is inversely proportional to the accuracy~~precision~~. Before the bias correction, the distance is relatively far especially for precipitation indicating that there is a large error between observatiosn and GCMs projection. After the bias correction, the distance diminishes~~minish~~, indicating that the bias correction improves the accuracy, particularly for ~~precision especially for~~ precipitation.

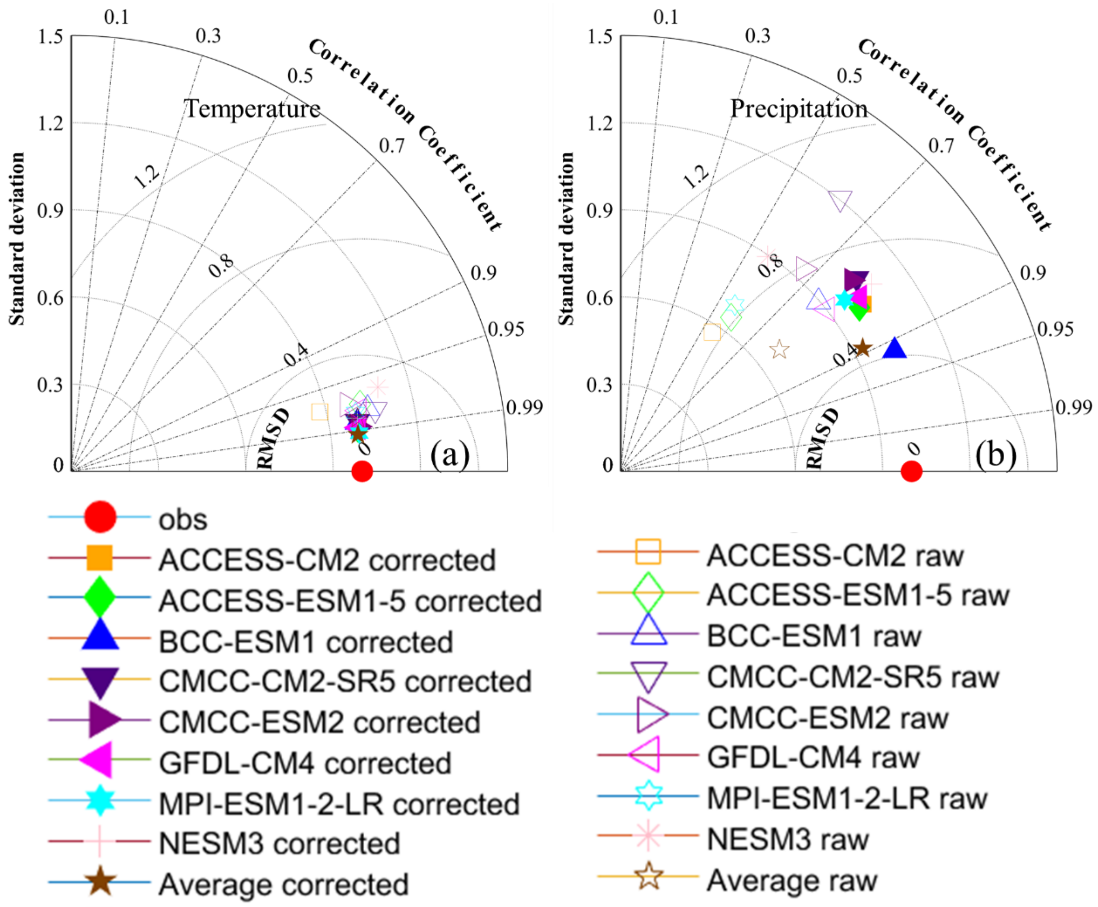


Figure ~~.~~4. ~~-~~Taylor diagram of monthly temperature and precipitation simulation. The hollow points are the uncorrected projection, the solid point are the corrected projection and the solid red circle is the reference values (observation).

4.1.2 Performance of runoff simulation

We assessed ~~FLEX-Cryo~~ the performance of the FLEX-Cryo model for runoff simulation based on historical observations. Throughout the entire assessment period, the KGE is 0.83, NSE is 0.73, R is 0.74, and RMSE is 0.77 mm/day. These results indicate that the model can reproduce hydrographs effectively. The good model performance demonstrates the robustness of the FLEX-Cryo model, ensuring accurate estimation of future hydrological changes (Fig. 5).

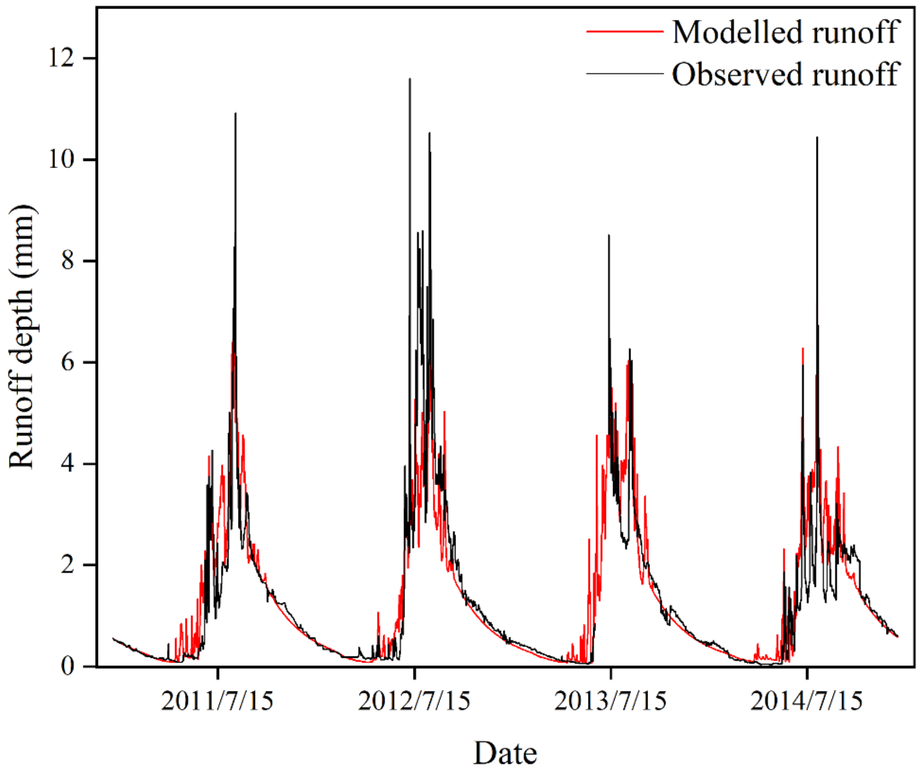
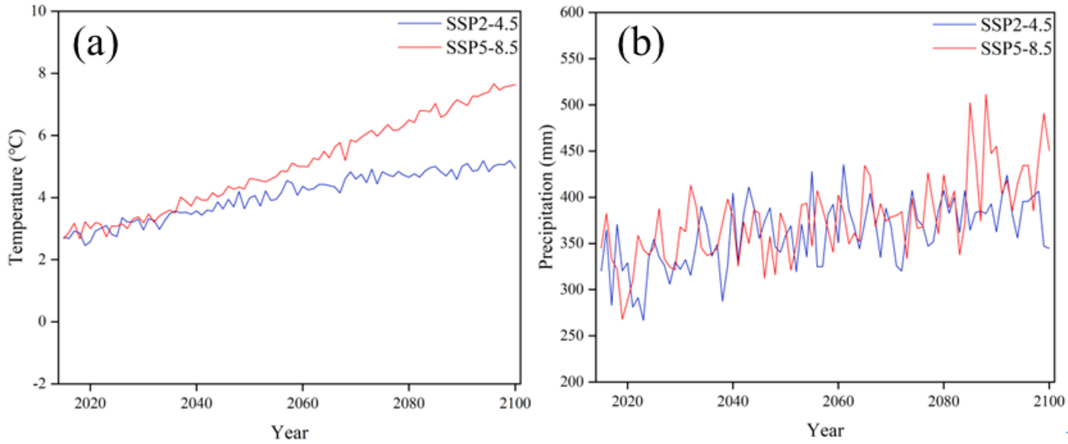
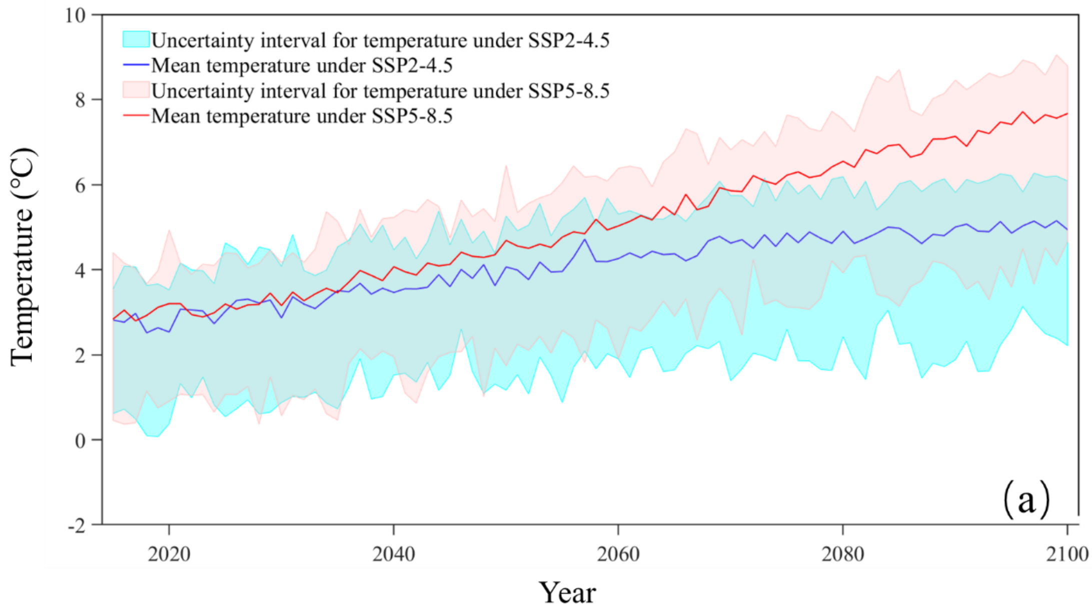


Figure.5 Simulation results of the FLEX-Cryo model and the comparisons with observation from 2011 to 2014.

4.2 Future climate change

Figure 46 shows the prediction of future climate in 2015-2100 under the SSP2-4.5 and SSP5-8.5 ~~scenarios~~ based on the average values of eight climate models (adjusted for bias). According to the SSP2-4.5 ~~scenario~~, the temperature will increase by 2.07°C relatively steadily by 2100. Under the SSP5-8.5 ~~scenario~~, temperatures are projected to continue to rise by 5.04°C over the course of the century. Precipitation changes are more ~~drastic~~variable than temperature, especially after the eighties of the 21st century under the SSP5-8.5 ~~scenario~~. Overall, the precipitation under the SSP2-4.5 ~~scenario~~ increased by 14.25 %, and the precipitation increased by 33.50 % under the SSP5-8.5 ~~scenario~~. Before the ~~80s of the 21st century~~2080s, the increase in precipitation was almost the same under different scenarios, about 8.9 mm 10 years^{-1} and 8.5 mm 10 years^{-1}, respectively. Although there are some uncertainties associated with temperature and precipitation, the increasing trend of temperature and precipitation are still distinguished, especially for the SSP5-8.5.





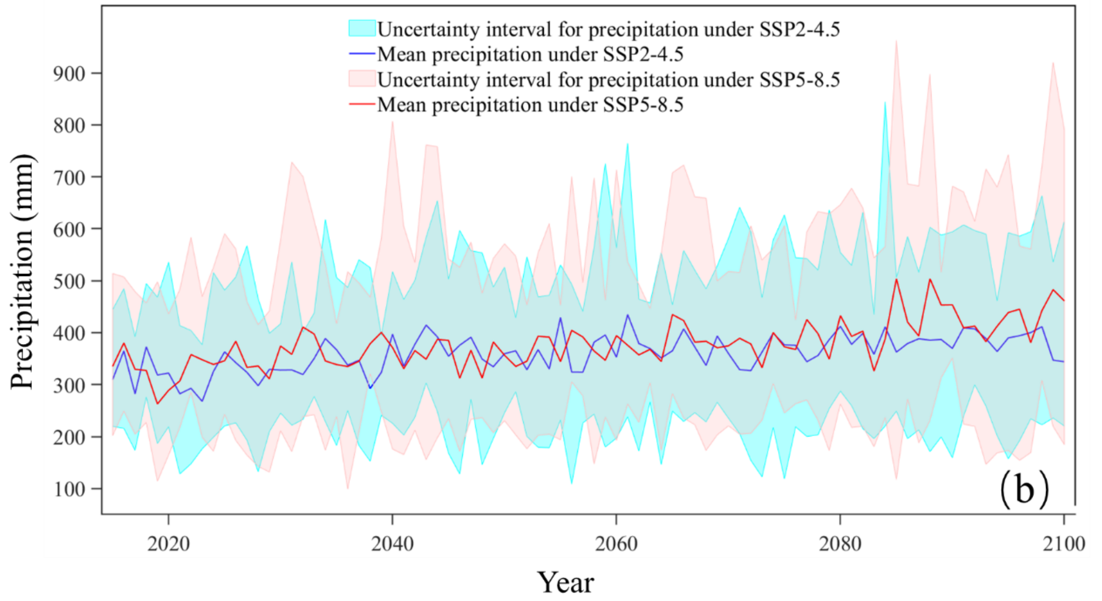


Figure ~~4. The~~6. (a) the annual average temperature ~~(a)~~ and (b) annual precipitation mean ~~(b)~~ of bias adjusted multi-Global Climate Model from 2015-2100. The blue and red areas indicate the uncertainty caused by 8 climate change models of SSP2-4.5 and SSP 5-8.5 scenarios.

4.~~2~~3 The change of cryosphere in the future

4.3.1 Predicting glacier retreat

~~In the initial status (~~Figure ~~5), the Glacier1 and Glacier2 had areas of 8.78×10^5 m^2 and 4.08×10^5 m^2, and ice volumes of 20.13×10^6 m^3 and 8.86×10^6 m^3, respectively. Glacier1 exhibited greater~~ 7 shows changes in glacier thickness at the highest elevation band and volume ~~compared to Glacier2.~~

~~Both Glacier1 and Glacier2 experienced retreat, characterized by a decrease in glacier volume and thinning of glacier thickness (Figure 5).~~for the Glacier 1 and the Glacier 2 under two SSPs from years 2015–2100. Starting from the 2020s, the glacier volume showed a rapid decline, and after the 2030s, ~~the highest-altitude portion of~~ the glacier entered a phase of rapid thinning. Around 2040, the glacier degradation reached a stabilization period, during which glaciers were only present in the highest elevation band. According to the SSP2-4.5 scenario, Glacier1 and Glacier2 are projected to completely melt and disappear by 2051 and 2046, respectively. Under the SSP5-8.5 scenario, the complete melt-out time is slightly earlier, occurring in 2045 and 2044 for Glacier1 and Glacier2, respectively. After the glaciers completely melt~~, approximately 5.6% of the~~ ablated glacier area will transform into alpine desert.

Taking the glacier changes in 2025, 2035, and 2045 as examples, under the SSP2-4.5 scenario, the area of Glacier1 is projected to decrease to 5.49×105 m^2, 1.52×105 m^2, and 0.26×105 m^2, with corresponding volume reductions to 5.27×10^6 m^3, 1.03×10^6 m^3, and 0.26×10^6 m^3, respectively (~~Figure 7~~Fig. 9). Comparatively, the retreat trend is more pronounced under the SSP5-8.5 scenario. The area of Glacier1 is projected to be 4.00×10^5 m^2, 0.81×10^5 m^2, and 0.26×10^5 m^2, with volumes of 4.86×10^6 m^2, 0.71×10^6 m^3, and 0.03×10^6 m^3, respectively. The degradation of Glacier2 follows a similar pattern to that of Glacier1, except that Glacier2 experiences less ice loss. According to the SSP5-8.5 scenario, Glacier2 is projected to completely melt by 2045. In 2025 and 2035, the area of Glacier2 ~~remains consistent, with values of~~is 1.67×105 m^2 and 0.51×105 m^2 for both scenarios, respectively. These glaciers are only distributed within the elevation bands from 4625 m to 4727 m and from 4675 m to 4727 m.

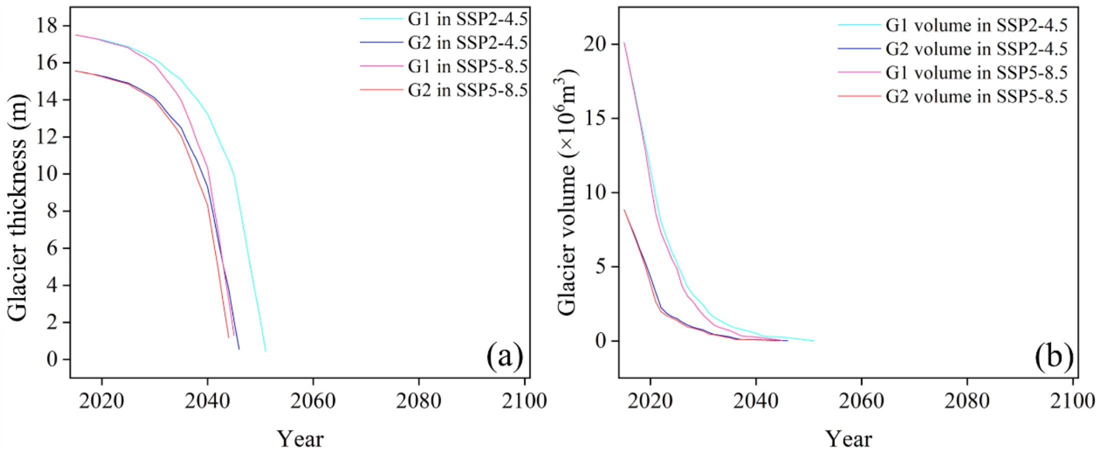


Figure ~~5.~~ 7. The glacier thickness (a) and glacier volume (b) change from 2015 to 2100 for the Glacier1 and Glacier 2

4.3.2 Forecasting the degradation of frozen soil

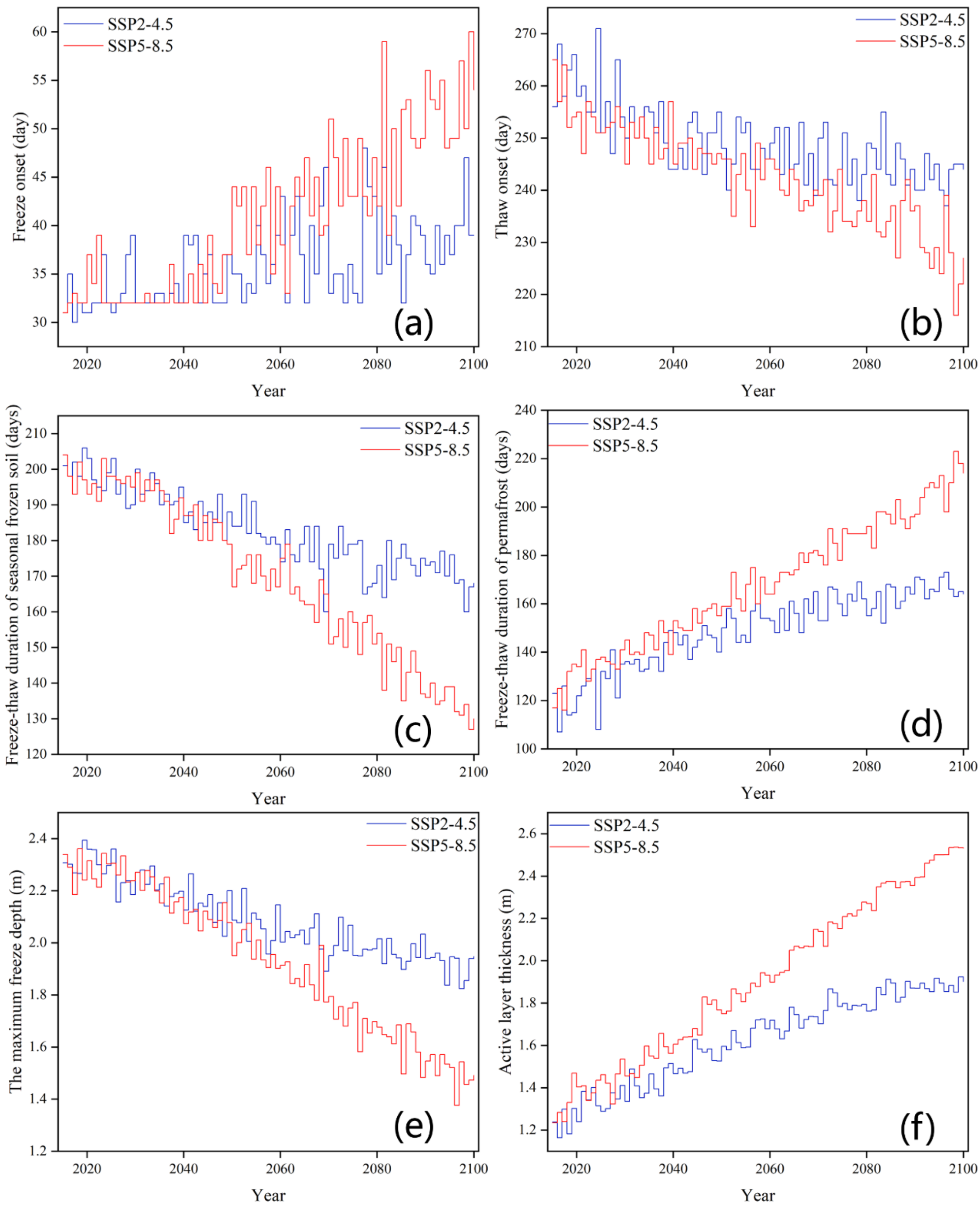
~~In the initial state (Figure 6), the~~ The degradation of ~~seasonal frozen soil~~seasonally frozen soil ~~exhibited an early freeze onset in early November, with a freeze duration of approximately 200 days at the lowest elevation band. The~~and permafrost~~, on the other hand, experienced a thaw onset in mid-June, lasting around 120 days at the highest elevation band. The maximum freeze depth was approximately 2.30 m at lower altitudes, while the active layer thickness measured around 1.27 m at the highest elevation.~~

~~By the end of the 21st century, under the SSP2-4.5 scenario, several changes~~ are projected ~~to occur. The~~by FLEX-Cryo model. Under SSP2-4.5, by the end of 21st century, the freeze onset of ~~seasonal frozen soil~~seasonally frozen soil will be delayed by 10 days~~, resulting in a shortened~~ and the freeze-thaw cycle duration ~~of~~will shorten approximately 1 month. The maximum freeze depth of seasonally frozen soil is expected to decrease by 5.17 cm per decade. The thaw onset of permafrost will be advanced by 19 days~~, leading to an increased~~ and the freeze-thaw cycle duration ~~of~~ would increase nearly 50 days. ~~Additionally, the maximum freeze depth is expected to~~

~~decrease by 5.17 cm per decade, while the~~The active layer thickness will ~~increase~~rise by approximately 8.24 cm per decade. ~~The~~ Meanwhile, the degradation trend of permafrost is more severe under the SSP5-8.5 scenario. ~~By the end of the 21st century, compared to the~~Under SSP2-4.5~~ scenario~~, the freeze onset of ~~seasonal frozen soil~~seasonally frozen soil will be shortened by 22 days~~, resulting in a further reduction of~~ and the freeze-thaw cycle duration will reduce by over 2 months. The thaw onset of permafrost will occur approximately 1 month earlier, and the freeze-thaw cycle duration of permafrost will increase by nearly 3 months. ~~The~~Compared with the SSP2-4.5, the decreasing trend of the maximum freeze depth and the increasing trend of the active layer thickness are approximately twice as pronounced under the SSP5-8.5~~ scenario compared to the SSP2-4.5 scenario. While the freeze onset of seasonal frozen soil exhibits significant variation between consecutive years, the other frozen soil elements follow a more stable change pattern. Before 2040, there is little difference between the two scenarios, except for the active layer thickness.~~. By 2100 ~~Seasonal frozen soil~~Seasonally frozen soil will begin to freeze around mid-November and late November, while permafrost will start to thaw in mid-May and early June by the year 2100 under two SSPs.

Under the SSP2-4.5 and SSP5-8.5~~ scenarios~~, the lower limit of permafrost gradually expands along the altitudinal gradient, with rates of 4.30 m per year and 8.75 m per year, respectively (~~Figure 7~~Fig. 9). In the SSP2-4.5~~ scenario~~, the lower limit of permafrost is projected to reach altitudes of 3685 m, 3795 m, 3835 m, 3865 m, 3985 m, and 4015 m in the years 2025, 2035, 2045, 2055, 2075, and 2095, respectively. The lower limit of permafrost in 2095 under the SSP2-4.5 scenario is comparable to the lower limit of permafrost (~~3965 m~~3965m) in 2055 under the SSP5-8.5 scenario.~~ Before~~

~~2045, the lower bound exhibits similar changes under both scenarios, but a significant divergence occurs afterward.~~ The lower limit is projected to increase to 4355 m by 2095 under the SSP5-8.5 scenario.



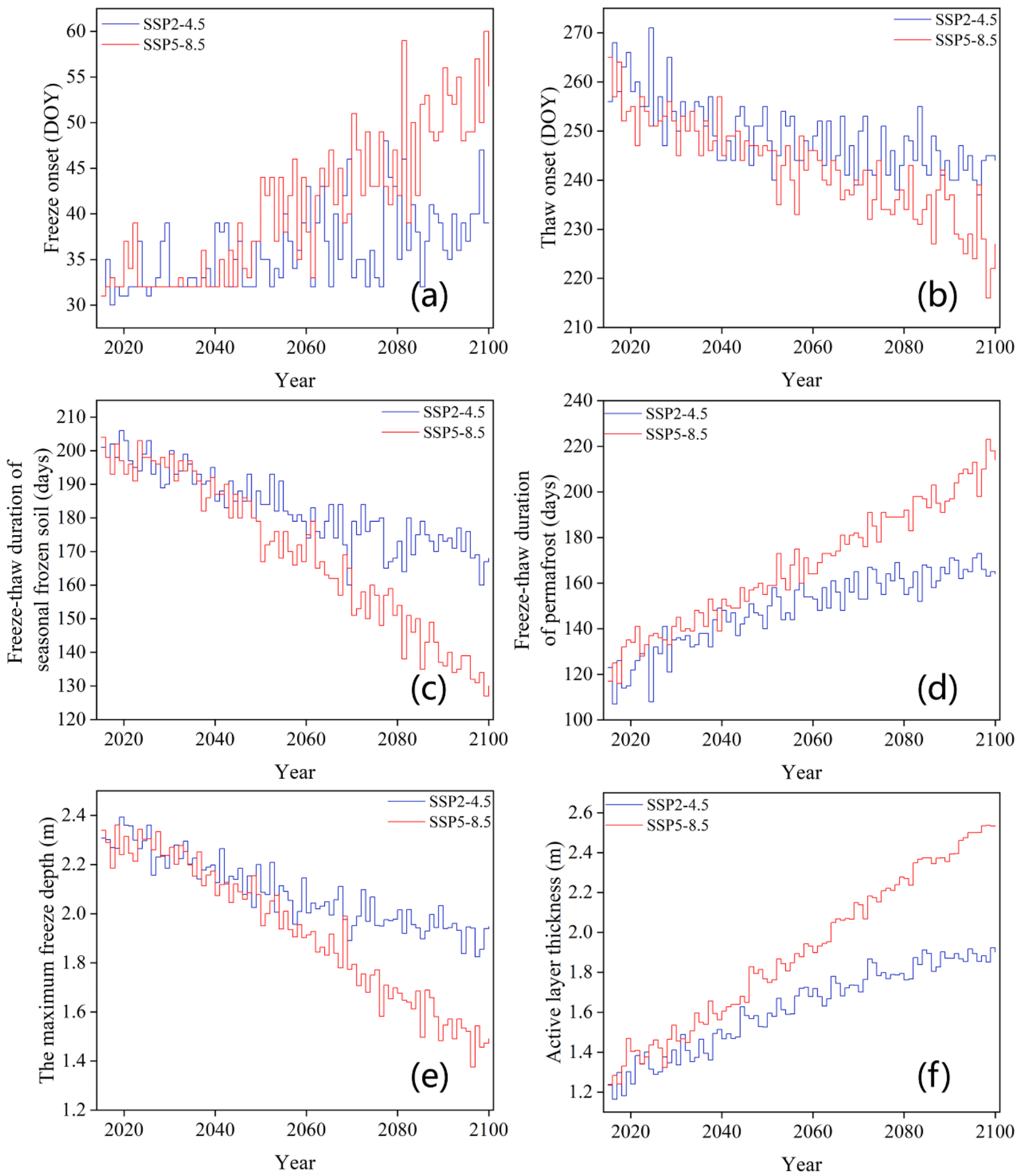
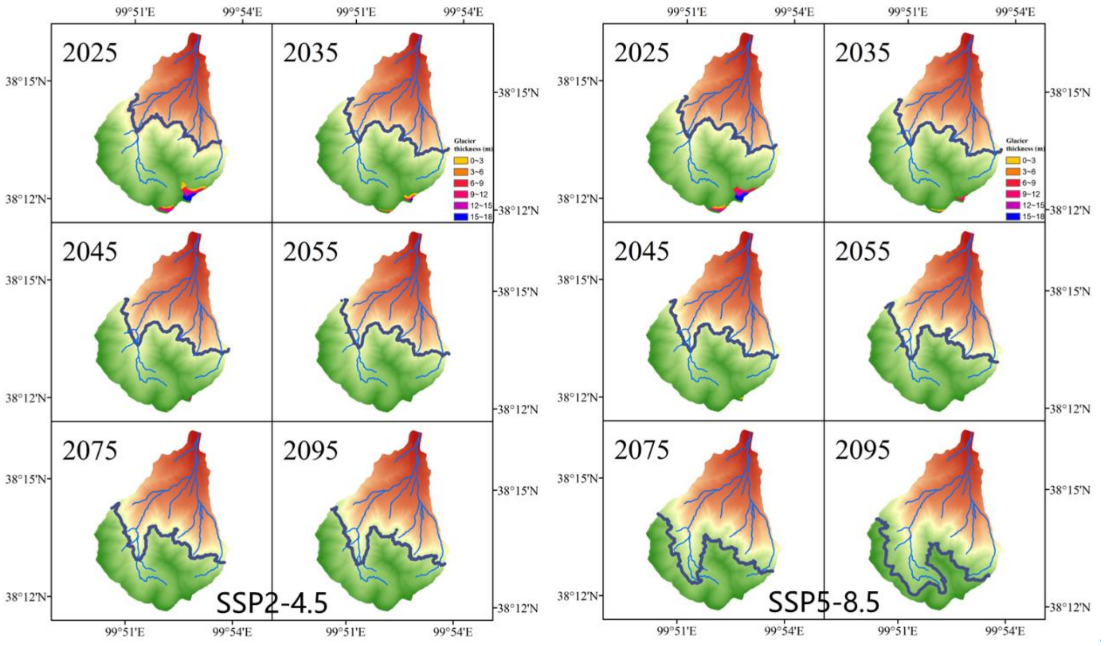


Figure ~~6~~8. Changes in ~~seasonal frozen soil~~seasonally frozen soil and permafrost from 2015-2100 under SSP2-4.5 and SSP5-8.5 scenarios. (a, b) Freeze and thaw onset. (c, d) Freeze-Thaw duration of frozen soil and permafrost. (e, f) The maximum freezing depth and active layer thickness.



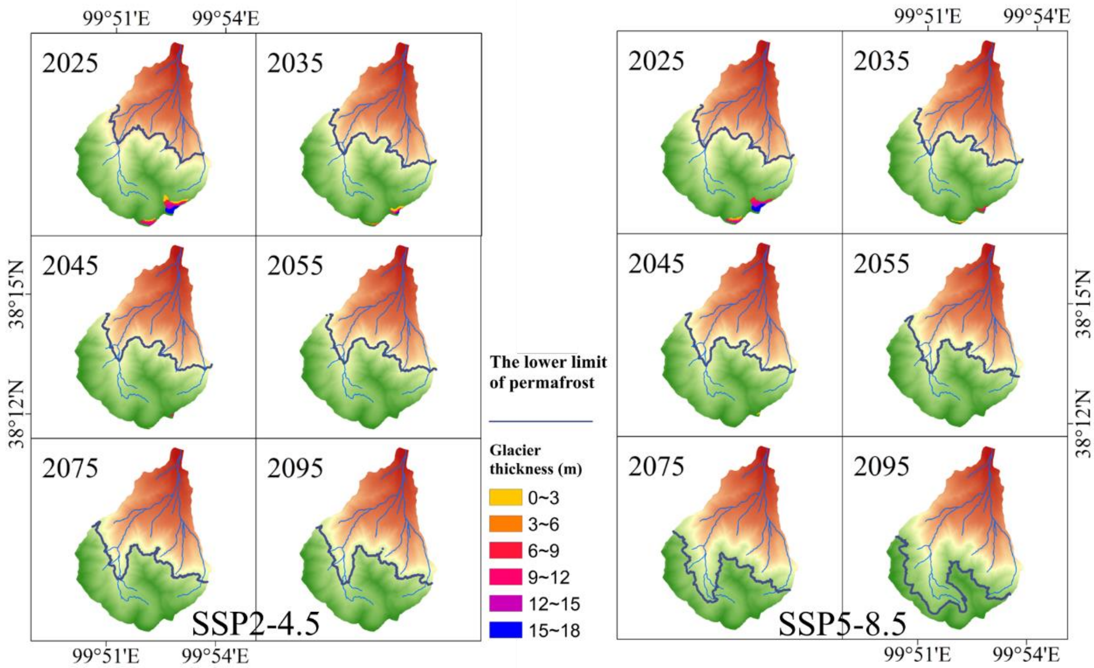


Figure ~~7~~9. Changes of ice thickness and the lower limit of permafrost in 2025, 2035, 2045, 2055, 2075 and 2095 under SSP2-4.5 and SSP5-8.5.

4.~~4~~3.3 Snow change in the future

The duration of snow cover is projected to decrease continuously in the future~~.~~ (Fig. 10). Under the SSP2-4.5~~ scenario, the~~, snow cover days are likely to be shortened by 45 days~~, while under the more severe SSP5-8.5 scenario, the reduction is~~

expected to be around 76 days. Simultaneously, the snow water equivalent, which measures the amount of water contained in the snowpack, is projected to exhibit more variable changes but with an overall decreasing trend. For the SSP2-4.5 scenario, the and snow water equivalent will decrease by 0.24 mm per year, resulting in. Compared with SSP 2-4.5, snow cover has a more reduction of approximately 41.4%.under SSP5-8.5. Under the SSP5-8.5 scenario, the decrease in snow water equivalent is more pronounced, with a drop of 0.35 mm per year, corresponding to a reduction of up to 46.0%.

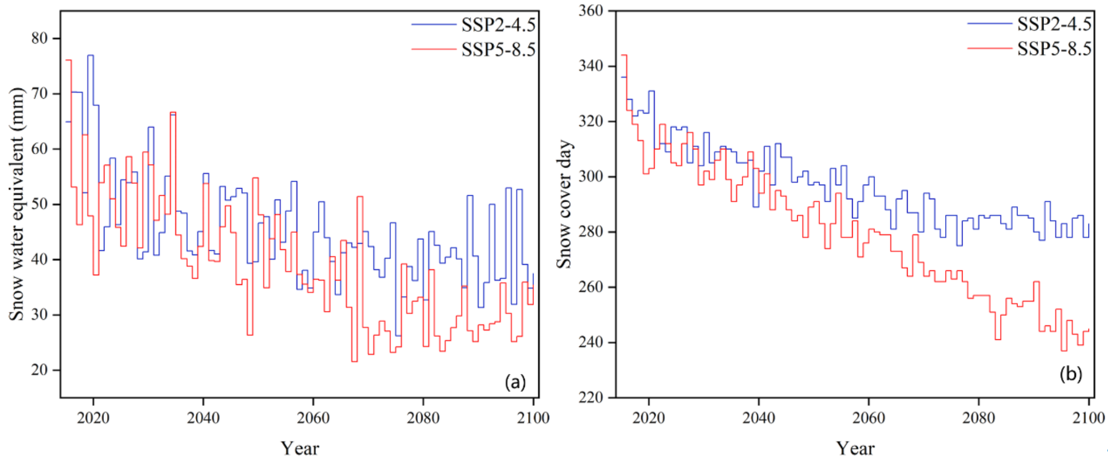


Figure 8. (a) snow water equivalent at entirely watershed and (b), snow cover day at the highest band.is expected to be around 76 days and snow water equivalent will decrease by 0.35 mm per year.

4.5

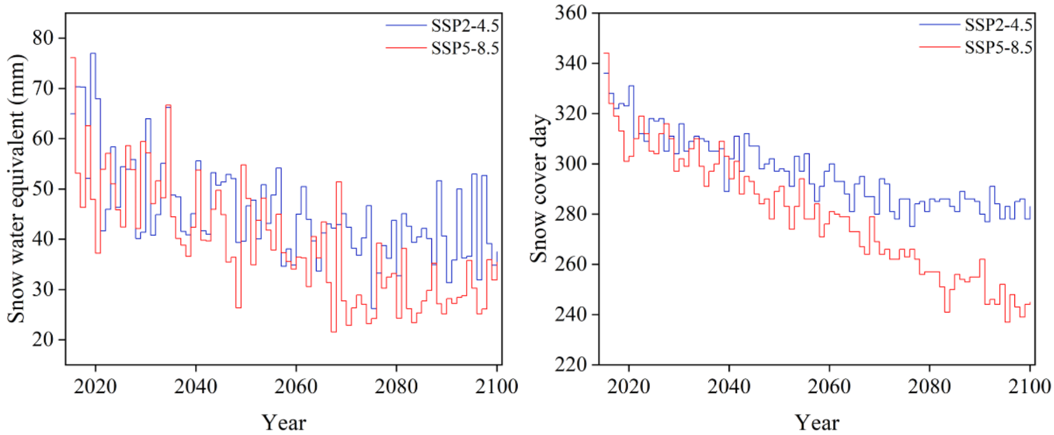


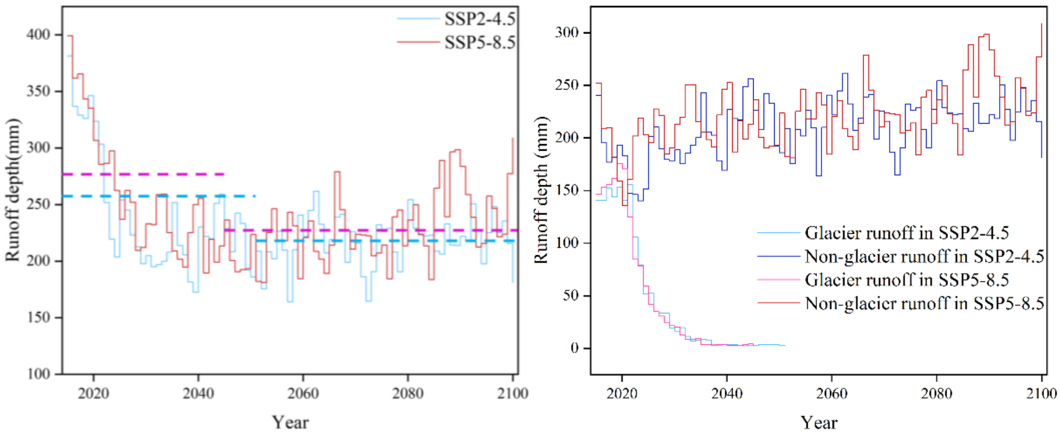
Figure 10. Changes of snow water equivalent and snow cover day from 2015-2100 under SSP2-4.5 and SSP5-8.5.

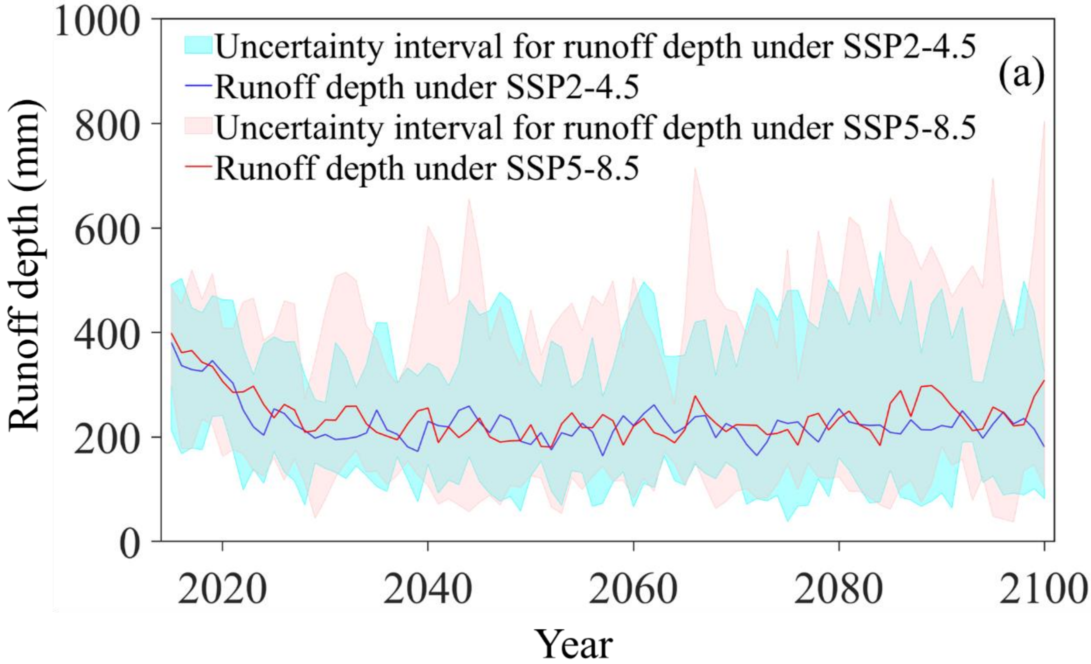
4.4 Projected future runoff

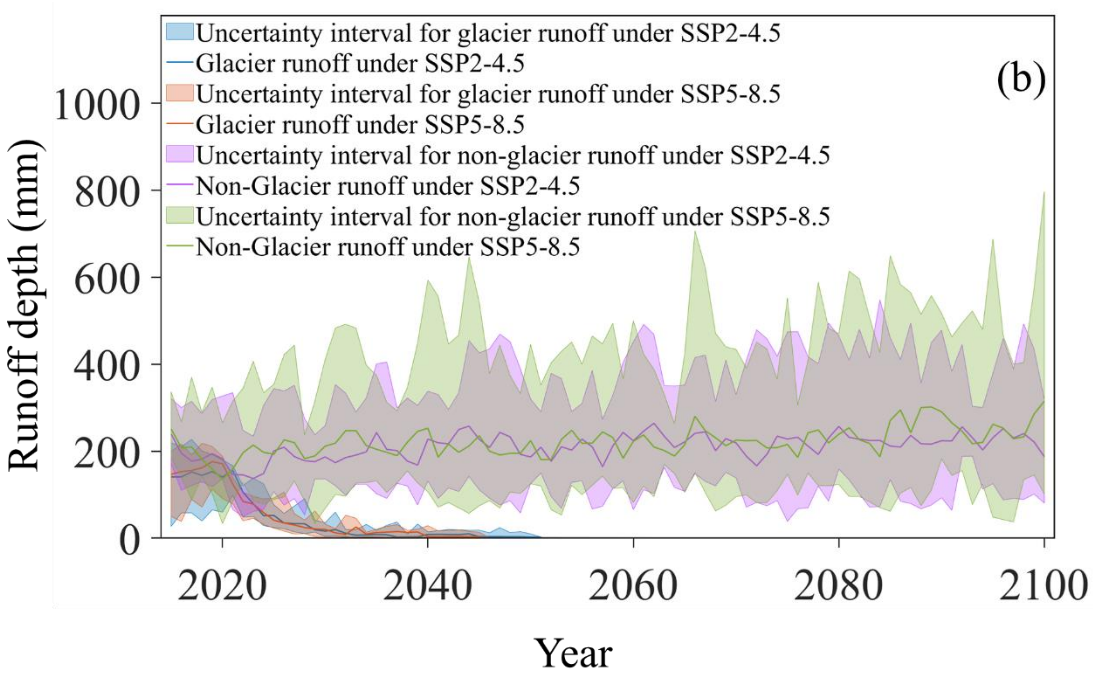
~~The depth of runoff in the entire basin shows a declining trend in the future. Under both the SSP2-4.5 and SSP5-8.5 scenarios, before the complete melting of glaciers, the runoff depth is estimated to be around 257 mm and 277 mm, respectively. After the glaciers completely melt, the runoff depth is projected to decrease by 15.56% and 18.05% for the SSP2-4.5 and SSP5-8.5 scenarios, respectively (Figure 9). By 2100, the average annual runoff depth is expected to be similar for both scenarios, at approximately 217 mm and 227 mm. In the SSP2-4.5 and SSP5-8.5 scenarios, the tipping point for the runoff depth in the glacier area is projected to occur in 2021 and 2019, respectively, with values of 155.93 mm and 175.98 mm. After reaching the tipping point, the runoff depth in the glacier area is likely to continue decreasing until the glaciers completely melt. In non-glacier areas, the runoff depth shows an increase of 0.48 mm per year and 0.65 mm per year.~~

The runoff in the catchment were predicted by the FLEX-Cryo model under SSP2-4.5 and SSP5-8.5. The tipping point of the glacier melting has already occurred (around 2020). After the turning point, glacier runoff and runoff of the total basin decreases dramatically until glacier completely melt. Then the runoff of the total basin will moderate increase. After glacier completely melt, runoff of the total basin would decrease by 15.56% and 18.05% respectively. The runoff coefficient, which represents the proportion of precipitation that becomes runoff, follows a similar pattern to the glacier runoff changes. It initially increases until the turning point of glacier melting occurs, then decreases, and eventually reaches a relatively stable state after the glaciers completely melt (~~Figure 10).~~Fig. 11 (c)). Before the turning point, runoff coefficient is almost equal or even greater than 1. The maximum values of the runoff coefficient occur in 2021 and 2019, coinciding with the tipping points of the glacier runoff. By the end of the 21st century, the runoff coefficient is projected to be dramatically reduced to approximately 0.42. These results indicate~~s~~ that glacier play a key role in water resource supply.

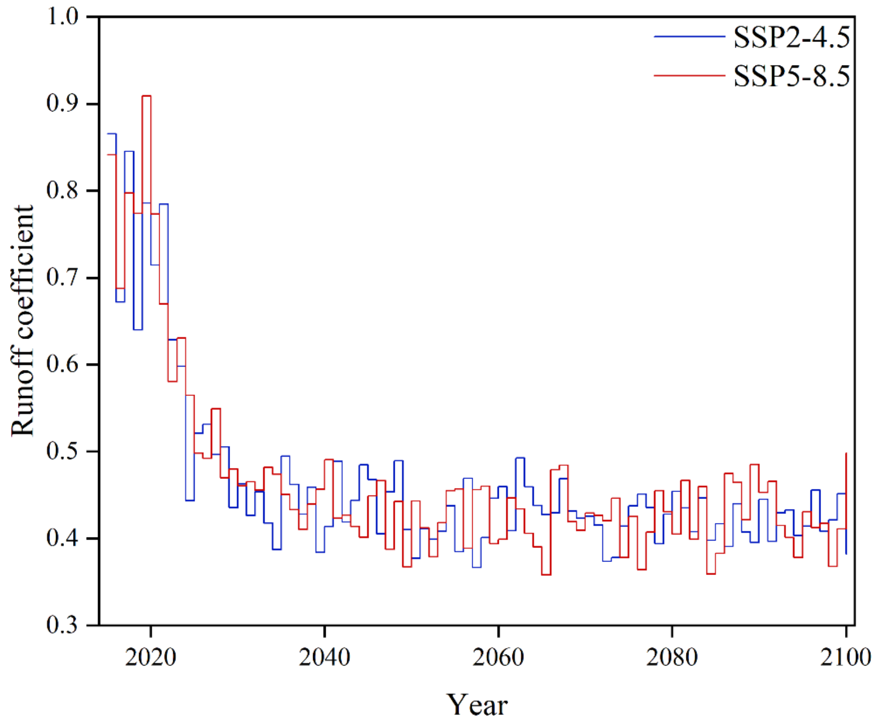
Two hydrological phenomena observed in permafrost mountainous catchments, namely the low runoff in the early thawing season (LRET) and discontinuous baseflow recession (DBR) (Gao et al., 2022), are expected to persist in the future (~~Figure 11~~Fig. 12). Meanwhile, baseflow, which represents the sustained flow of water from groundwater, shows an increasing trend. The duration of the early thawing season is projected to be further reduced. The first recession coefficient remains unchanged, while the second recession coefficient progressively increases. Under the SSP2-4.5 scenario, the second recession coefficient is equal to 74 days, which is consistent with the recession coefficient in 2060 under the SSP5-8.5 scenario. This suggests that the permafrost area undergoes less significant changes under SSP2-4.5 scenario than SSP2-8.5 scenario according to Figure ~~7~~9. The baseflow gradually increases, especially in the SSP5-8.5 scenario, as indicated by the runoff depth on a logarithmic scale (Fig~~ure XX~~. 12).

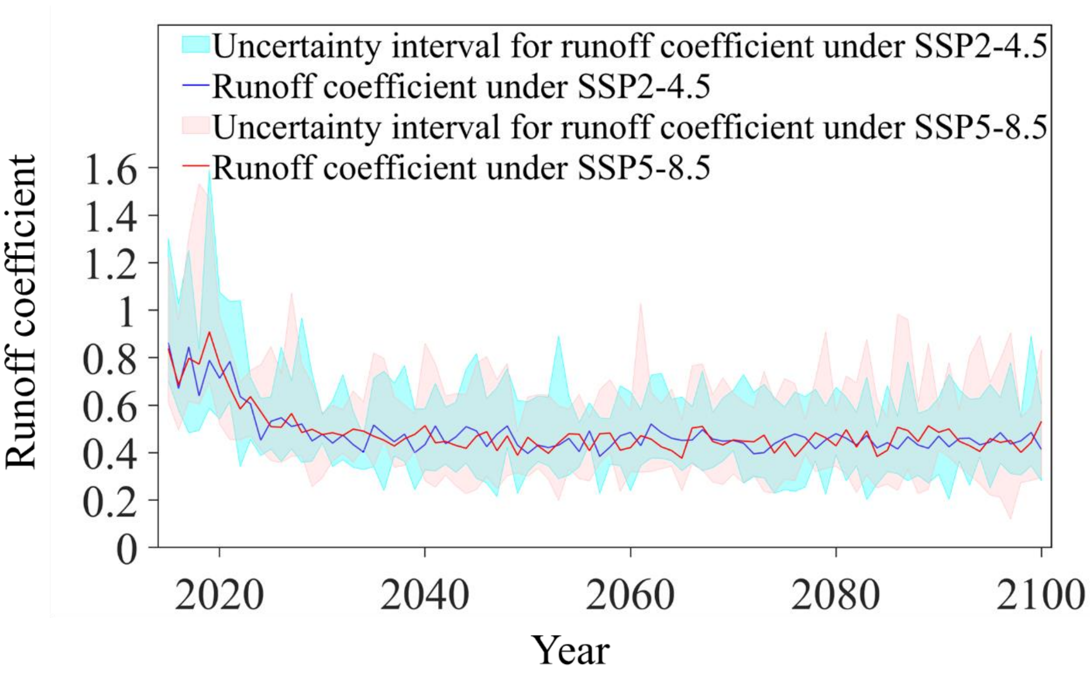

SSP2-4.5
SSP5-8.5
Runoff depth(mm)
Year
Glacier runoff in SSP2-4.5
Non-glacier runoff in SSP2-4.5
Glacier runoff in SSP5-8.5
Non-glacier runoff in SSP5-8.5
Runoff depth (mm)
Year


Uncertainty interval for runoff depth under SSP2-4.5
Runoff depth under SSP2-4.5
Uncertainty interval for runoff depth under SSP5-8.5
Runoff depth under SSP5-8.5
(a)
Runoff depth (mm)
Year



~~Figure 9. (a) The predicted runoff depth of the total basin (b) Runoff in the glacier and in the non-glacier from 2015-2100~~





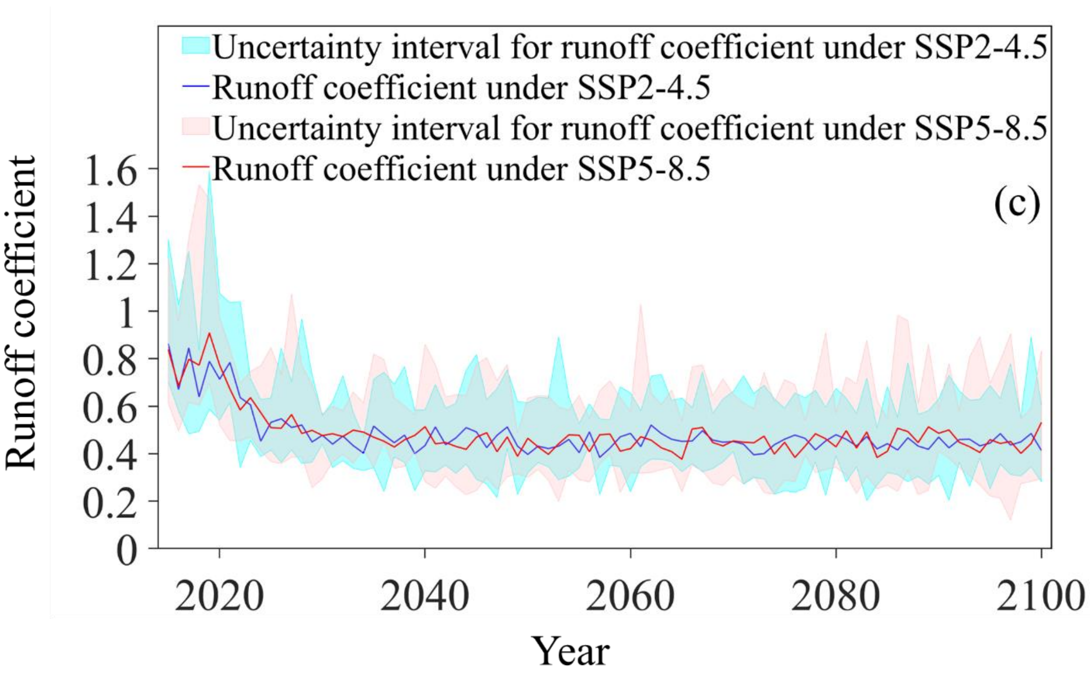
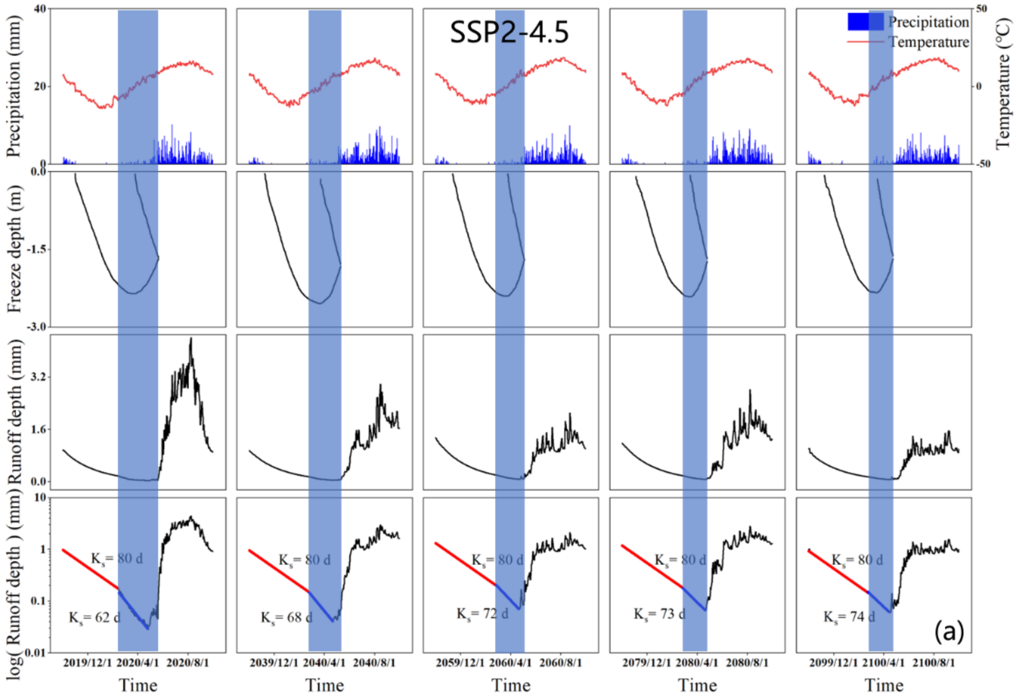
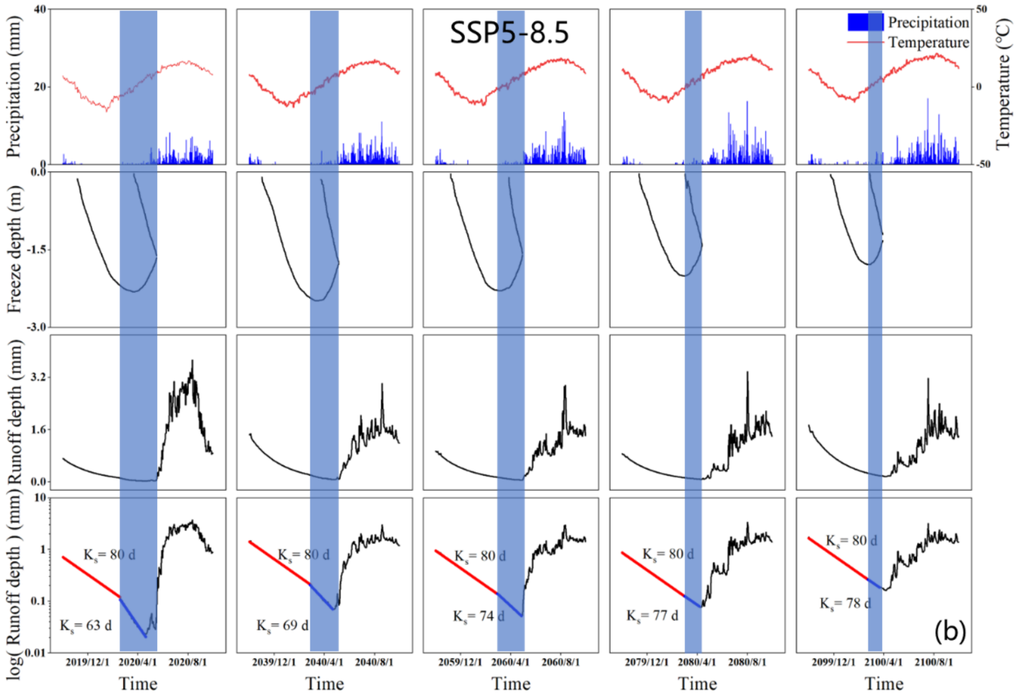


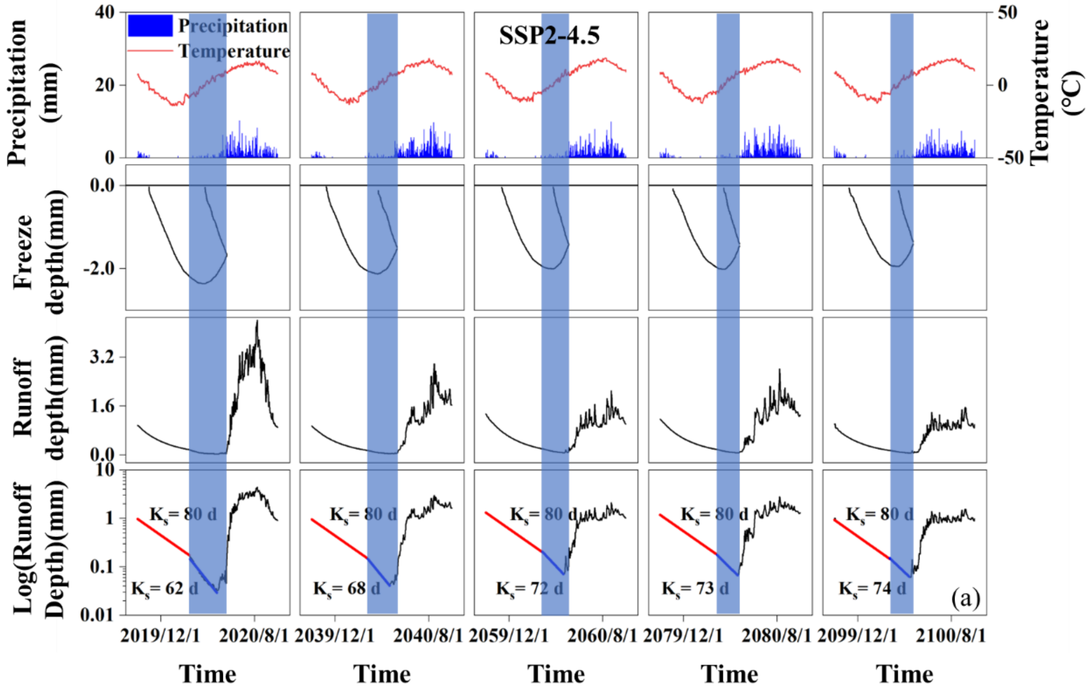
Figure 11. (a) The predicted runoff depth of the total basin. (b) Runoff in the glacier and in the non-glacier from 2015-2100. (c) Project runoff coefficient under SSP2-4.5 and SSP5-8.5 scenarios.~~Figure 10. Project runoff coefficient under SSP2-4.5 and SSP5-8.5 scenarios.~~



SSP2-4.5
Precipitation
Temperature
Precipitation (mm)
Temperature (°C)
Freeze depth (m)
Runoff depth (mm)
log(Runoff depth) (mm)
K$_s$= 80 d
K$_s$= 62 d
K$_s$= 68 d
K$_s$= 72 d
K$_s$= 73 d
K$_s$= 74 d
2019/12/1 2020/4/1 2020/8/1
2039/12/1 2040/4/1 2040/8/1
2059/12/1 2060/4/1 2060/8/1
2079/12/1 2080/4/1 2080/8/1
2099/12/1 2100/4/1 2100/8/1
Time
(a)



SSP5-8.5
Precipitation
Temperature
Precipitation (mm)
Temperature (°C)
Freeze depth (m)
Runoff depth (mm)
log(Runoff depth) (mm)
K$_s$= 80 d
K$_s$= 63 d
K$_s$= 69 d
K$_s$= 74 d
K$_s$= 77 d
K$_s$= 78 d
2019/12/1 2020/4/1 2020/8/1
2039/12/1 2040/4/1 2040/8/1
2059/12/1 2060/4/1 2060/8/1
2079/12/1 2080/4/1 2080/8/1
2099/12/1 2100/4/1 2100/8/1
Time
(b)



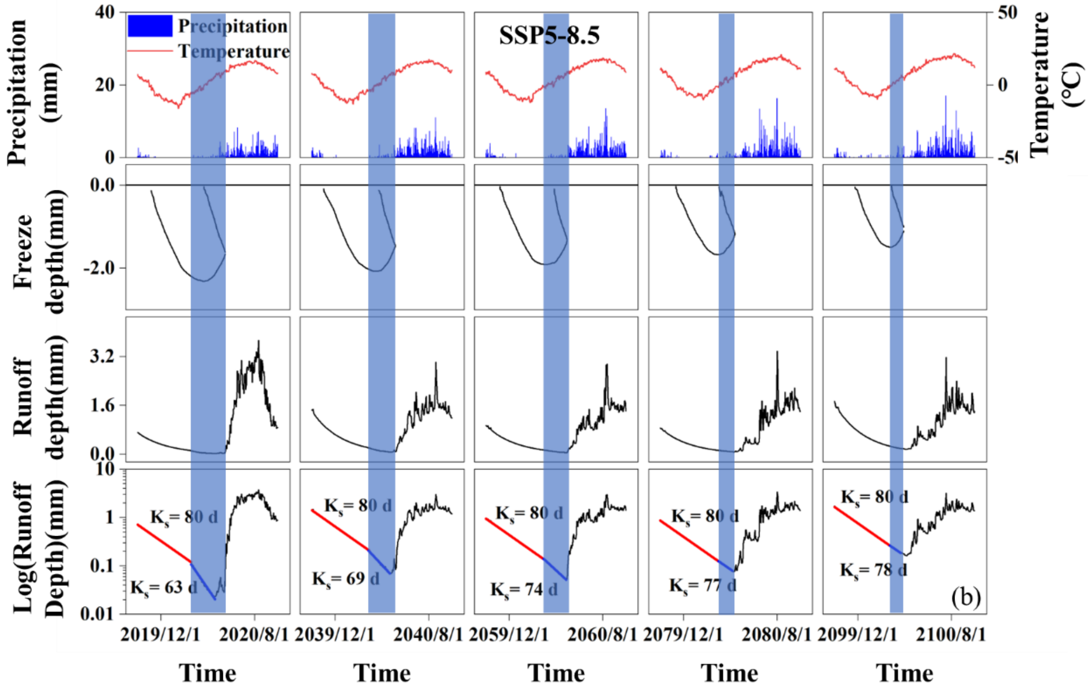


Figure ~~11~~12. Temperature, precipitation, runoff depth and freeze-thaw cycle in 2020, 2040, 2060, 2080 and 2100 under SSP2-4.5 (a, top) and SSP5-8.5 scenarios (b, bottom).

5.Discussion

~~5.1 Changes of the mountain cryosphere in future~~5.1

~~The cryosphere, which encompasses glaciers, snow, frozen soil, and permafrost, plays a vital role in storing approximately 75% of the world's freshwater resources, while around 17% of the global population resides in cryosphere regions (Qin et al., 2021). Understanding the changes occurring in the cryosphere is crucial for assessing the long-term sustainability of water resources (Whitfield et al., 2021). The Hulu catchment, located in the northeast Tibet Plateau, exhibits a diverse distribution of cryosphere elements, making it an ideal area for studying these changes (Gao et al., 2019; Xu et al., 2019). However, there is a lack of research on the degradation of multiple cryosphere elements within the Hulu catchment and its implications for future hydrology, despite the Heihe River Basin being recognized as a typical region for studying hydrological and water resource changes in cold regions (Ning et al., 2008). In this study, we projected a future warming trend of 0.3°C per decade and 0.6°C per decade, accompanied by an increase in precipitation of 7.9 mm per decade and 12.0 mm per decade under the SSP2-4.5 and SSP5-8.5 scenarios, respectively (Figure 4). These projections align with the findings of Chen et al. (2022), who observed similar warming trends of 0.3-0.4 °C per decade and 0.7-0.8°C per decade, as well as precipitation increases ranging from 1.6-14.8 mm per decade and 6.0-20.6 mm per decade under similar scenarios. This consistency between our projections and previous research supports the reliability of the forcing data used in the FLEX-Cryo model.~~

~~Furthermore, Wang et al. (2018) predicted an increase in the annual maximum freeze depth in the Heihe River Basin from 2011 to 2066 at a rate of 5.4 cm per decade, which closely aligns with the predicted change of 5.2 cm per decade in our~~

~~study (Figure 6). While there have been limited studies investigating future changes in glaciers and other cryosphere elements within the Hulu catchment, including the Shiyi Glacier, conducting a comparative analysis with projections from other regions can enhance our understanding of mountain cryosphere retreat. Although the comparative analysis approach may have some limitations in terms of rigor, it provides valuable insights (Han et al., 2023).~~

~~5.2~~ The effect of the mountain cryosphere degradation on runoff

Glaciers and snow are sensitive to climate change and cover play a crucial role in water retention, with meltwater contributing significantly to downstream water resources and the ecological environment (Stecher et al., 2023; Nan and Tian, 2024). The turning point of glacier runoff represents a critical tipping point that signifies not only the rapid thinning of glaciers but also the irreversible stage of water resources in the basin (Brovkin et al., 2021). After the turning point the glacier thickness and glacier volume rapidly decrease (Fig. 7). But the glacier thickness showed in this paper is the change at the highest elevation band, which means the turning point would lag in this band fort change of glacier thickness. In the Hulu catchment, the proportion of glacier runoff reached 51% to 55% between 2019 and 2021, indicating that it is in the turning point period (~~Figure 9~~Fig. 11). Subsequently, the contribution of glacier runoff gradually decreases until complete melting occurs. Temperature is the primary factor influencing glacier runoff, while precipitation and temperature together determine the proportion of glacier runoff in relation to total runoff. Although the highest contribution of glacier runoff and the tipping point of glacier runoff may not align precisely, after the tipping point, the capacity of glacier runoff to contribute to overall runoff continuously diminishes. From 2015 to 2021, there has been a decreasing trend in precipitation, leading to a corresponding decline in non-glacier runoff (~~Figure 4~~Fig. 6 and ~~9~~Fig. 11). Thus, while glacier runoff has increased, the total runoff has decreased. However, between 2032 and 2038, even though rainfall continues to decline, the contribution of glacier runoff to overall runoff becomes negligible due to the limited volume of ice remaining (glacier volume < 1×10^6 m^3), resulting in minimal glacier melting runoff (~~Figure 5~~Fig. 7 and ~~Figure 9~~Fig. 11). On the other hand, once the glaciers have completely melted, the total runoff in the Hulu catchment is reduced by 16% to 18%, and the runoff coefficient is halved (~~Figure~~Fig. 9 and ~~Figure~~Fig. 10). This highlights the critical role of glaciers as solid freshwater reservoirs in regulating water sources and mitigating droughts (McCarthy et al., 2022).

The freeze-thaw cycle has a significant impact on runoff yield and hydrological response routines in the Hulu catchment (Sun et al., 2022; Wang et al., 2020). Precipitation in the Hulu catchment is primarily concentrated in the summer when soil moisture is high and even close to saturation, making saturation excess flow the main mechanism for runoff generation (Li et al., 2016). During the freeze-thaw cycle, the weak permeability of frozen soil affects both surface runoff and infiltration. Soil runoff primarily occurs through underground in hillslope and surface water flow in riparian area, resulting in a faster response to rainfall and snowmelt and contributing to a higher runoff coefficient (Hu et al., 2022; Jones et al., 2023). However, it is important to note that shallow frozen soil does not completely block the interaction between deeper soil layers and the surface. Frost heave in the soil creates large pores, allowing snowmelt water and precipitation to bypass the matrix layer and reach the deeper soils (Jiang et al., 2021; Zhang et al., 2023). This phenomenon is considered one of the significant reasons for low runoff in the early thawing season (Mohammed et al., 2021). Low runoff is observed between the frozen season and complete thawing season (~~Figure 11~~Fig. 12). The duration of freeze-thaw cycles in ~~seasonal frozen soil~~seasonally frozen soils is shortening, and freeze onset is being delayed due to the warming climate, resulting in a decreasing duration of low runoff. However, the temperature during the freezing season remains lower than the initial frost heave temperature of the soil, and there is still a deficit of soil water in the early thaw, indicating that the prevalence of low runoff will persist in the future (Teng et al., 2022; Wen et al., 2024).

The freezing state has a significant impact on the recession process of baseflow, and permafrost plays a crucial role in discontinuous baseflow (Cooper et al., 2023; J. Wang et al., 2022). During the freezing season, baseflow follows a linear recession process (K_s = 80 days), with contributions from both permafrost and ~~seasonal frozen soil~~seasonally frozen soil regions (~~Figure 11~~Fig. 12). In the frozen season, the groundwater under the supra-permafrost layer becomes inactive, and baseflow is solely derived from the ~~seasonal frozen soil~~seasonally frozen soil regions, causing a discontinuous recession. With climate warming, the lower limit of permafrost gradually moves upward along the elevation, resulting in the shrinking of the permafrost region. This suggests that in the future, an increased proportion of baseflow will originate from the expanding area of ~~seasonal frozen soil~~seasonally frozen soil, leading to a gradual decrease in the influence of permafrost on baseflow. Consequently, the discontinuous recession of baseflow will gradually transition into a linear recession. Furthermore, an increase in the thickness of the active layer enhances the soil water storage capacity, contributing to a gradual rise in baseflow (Yao et al., 2021).

5.2 Comparison with other studies

The cryosphere, ~~which encompasses~~including glaciers (ice sheets), seasonal snow cover, frozen soil, and permafrost, plays a vital role in storing approximately 75% of the world's freshwater resources~~, while around 17% of the global population resides in cryosphere regions~~ (Qin et al., 2021). Although there are some differences in the the driving data and models, the trends of the cryospheric elements and runoff changes are still comparable and consistent. In this study, the small glaciers are projected to ~~will~~ completely melt in the Mid-21st century, which is also reported ~~this discovery~~ in the other area (Mukhopadhyay and Khan, 2015; Baraer et al., 2012; Schwank et al., 2014). The projected maximum freeze depth of seasonally frozen soil calculated in this research is 5.2 cm per decade, similar to ~~is similar with~~ the 5.4 cm per decade predicted by Wang et al. (2018). Ni et al. (~~,~~2021) showed that Qinghai-Tibet Plateau permafrost is at ~~suffering from the~~ risk of disappearance based on statistical and machine learning (ML) modeling approaches. This shift in regions with permafrost impacts hydrological connectivity, fostering improved hydrothermal conditions that enhance vegetation growth (Han and Menzel, 2022; Jin et al., 2022). ~~There are f~~Few studies have focused on the change ~~of~~ in the snow cover days and snow water equivalent in ~~on~~ the ~~h~~Heihe river basin in the future, but many researches have indicated that the snow-free period increases and the snow water equivalent decreases due to ~~caused by~~ climatic warming in Tibet Plateau (Zhang and Ma, 2018). The reduction of the snow cover period may result in an earlier peak in spring snowmelt floods, thereby increasing the risk of flooding (Chai et al., 2022). Simultaneously, the decrease in snow water equivalent may impact plant water supply, placing pressure on ecosystems (Guan et al., 2022). Although cryospheric elements have a trend of degradation in different regions, the impact on runoff may ~~be different~~differ. However, ~~But~~ on a longer time scale, the degradation of the cryosphere will lead to a decrease in runoff ~~decrease~~ (Xu et al., 2024).

T~~In t~~his study confirmed that~~,~~ runoff from cryospheric melting is one of the main factors controlling runoff, and degradation of the cryosphere may exacerbate the risk of future droughts.

5.3 Uncertainty and limitations

~~The uncertainty in this study arises from the forcing data of the General Circulation Models (GCMs), the bias correction methods, and the parameters selected in the FLEX-Cryo model (Wilby and Harris, 2006). The coarse spatial resolution of the GCMs prevents a comprehensive description of the climate at the basin scale, particularly in plateau and mountainous regions heavily influenced by altitude. The selection of parameters for the FLEX-Cryo model is also a significant source of uncertainties. Due to the complex topography in the mountain cryosphere, degree-day factor, altitude effect on climate and soil water storage capacity cannot be fully reflected at the catchment scale. To mitigate some of the uncertainties associated with the GCM outputs, a multi-model and multi-method approach is employed in this study. The equal weighted average method is used to combine the values from different models and methods, aiming to reduce uncertainties and provide a more robust assessment of the results. It is important to note that the optimal parameter group selected for the FLEX-Cryo model in this study has been chosen based on previous research~~U~~The sources of u~~ncertainty in this study comes from the GCMs, the downscaling and bias correction methods, and the structure and parameters of the FLEX-Cryo model. The temperature and precipitation projections ~~are uncertainty~~ from different GCMs at the basin scale introduce uncertainty. Moreover, four bias correction methods were used to correct ~~conduct a correction of~~ the GCMs based on the observation, which may ensure consistent relative trends but not improve the accuracy of precipitation and temperature frequency distribution and seasonal variations. This~~It~~ may cause some uncertainty in the simulation results (Jia et al., 2023).

In this research, the time-variant albedo information and the aspect are worthwhile to be taken into account for~~to~~ improving~~e~~ glacier melting simulations, which ~~need~~ require further observation and quantitative studies (Arnold et al., 2006; Feng et al., 2024). The change ~~of~~in elements ~~in the cryosphere~~ is sensitive to energy. The snow cover and the effect of topographic shading may also have an effect on the degradation and thus hydrologic response, which ~~is worth to~~warrants further investigation (Zhang, 2005). On a long time scale, the degradation of frozen soil and glacier may result in ~~the~~ thaw lake generation and ~~the~~ other landscapes changes, which may effect on the runoff yield and baseflow recession (Serban et al., 2021).

~~(Gao et al., 2022). While this helps to establish a more reliable parameterization, there may still be inherent limitations in the chosen parameter values. Overall, the uncertainties and limitations associated with the forcing data, bias correction methods, and parameter selection in the FLEX-Cryo model need to be considered when interpreting the results of this study. Further research and improvements in these areas can enhance the accuracy and reliability of future assessments of the effects of mountain cryosphere degradation on runoff.~~

6.Conclusions

~~The mountain cryosphere, encompassing glaciers, snow, and frozen soil, plays a critical role in downstream water resources and the ecological environment. Understanding its response to climate change is crucial for effective water resource management and flood prevention.~~ In this study, we employed the FLEX-Cryo model and data from eight Global Climate Models (GCMs) under the SSP2-4.5 and SSP5-8.5

scenarios to predict~~oject~~ the potential impacts of climate change on the mountain cryosphere and hydrology. ~~Based on our simulation results, the following conclusions can be drawn:~~Results from the projected change of mountain cryosphere elements, glacier, snow and frozen soil are expected to undergo degradation. The glacier will completely melt by the middle of the 21st century. Snow cover day will decrease by 45 and 76 days, and snow water equivalent will decrease by 0.24mm/yr and 0.35mm/yr. The thaw onset is expected to advance 19 days and 32 days. The active layer thickness will increase by 8.24cm/10yr.

~~(1)~~ The ~~air temperature is projected to increase by 2.1 ℃ and 5 ℃ by 2100, while precipitation is expected to increase by 8 mm/10 years and 12 mm/10 years. These changes in temperature and precipitation patterns indicate a significant shift in the climatic conditions of the study area.~~

~~(2) Glacier and snow cover are anticipated to experience retreat and shrinkage in the future. Under the SSP5-8.5 and SSP2-4.5 scenarios, glaciers are projected to completely melt by 2045 and 2051, respectively. Additionally, the duration of snow cover will be shortened by 45 days and 76 days, while the snow water equivalent will decrease by 0.24 mm/yr and 0.35 mm/yr.~~

~~(3) The frozen soil is expected to undergo~~ degradation~~. By 2100, the freeze onset of seasonal frozen soil is projected to delay by 10 days and 22 days, and the thaw onset of permafrost is expected to advance by 19 days and 32 days. The lower limit of permafrost is estimated to reach altitudes of 4015 m and 4355 m along the altitudinal gradient. Moreover, the maximum freeze depth will decrease by approximately 5.17 cm/10 years and 10.93 cm/10 years, while the active layer thickness will increase by 8.24 cm/10 years and 15.47 cm/10 years.~~

~~(4) The degradation of the~~ of the mountain cryosphere has significant implications for water ~~resources in the catchment area, particularly in terms of runoff yield.~~resources. The tipping point ~~for~~of glacier runoff is projected to ~~occurred between 2019 and 2021.~~occur in the 2020s. Once the glaciers have completely melted, the ~~depth of~~ runoff is projected to decrease by approximately 16% and 18% under the SSP2-4.5 and SSP5-8.5 scenarios, respectively. ~~However, in non-glacier areas, the depth of runoff is expected to increase by 0.22 mm/yr and 1.07 mm/yr from 2015 to 2100. By the end of the 21st century, the runoff coefficient in the catchment is projected to reach approximately 0.42.~~ Importantly, the duration of low runoff ~~during the early thawing season will be shorter. The discontinuous~~will shorten, baseflow will increase and the discontinue recession of baseflow will ~~is~~ gradually ~~transitioning towards a~~transform to a more linear pattern ~~pattern, resulting in increased baseflow. The second recession coefficients are estimated to be around 74 days and 78 days, respectively, by the year 2100.~~.

~~**In conclusion, this**~~This study provides insights into the potential impacts of climate change on the mountain cryosphere and hydrology. The projected changes in ~~**temperature, precipitation,**~~ glacier retreat, snow cover, and frozen soil dynamics highlight the urgent need for proactive water resource management strategies in the face of a changing climate. Further modelling research and monitoring efforts are necessary to refine these projections and guide effective adaptation measures to sustainably manage water resources in mountainous regions.

Competing interests

At least one of the (co-)authors is a member of the editorial board of Hydrology and

Earth System Sciences.

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