

Article

Preliminary Assessment of Frozen Ground Thermal Degradation in the Yangtze–Yellow River Source Regions and Its Hydrological Associations with the Western Sichuan Basins

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Abstract

The Tibetan Plateau sustains major Asian rivers through extensive cryospheric resources. However, hydrological associations of frozen ground degradation on downstream water availability remain insufficiently quantified. This study presents a preliminary assessment of thermal dynamics of frozen ground in the Yangtze–Yellow River source regions and their hydrological associations with the western Sichuan basins during 1961–2017. Using the near-surface ground freezing index (GFI) as a proxy indicator, we quantified contrasting streamflow responses between the Yangtze River source region (YaSR) and Yellow River source region (YeSR), and their connections with four major rivers in the western Sichuan basins. Results reveal divergent streamflow responses across four rivers, with predominantly positive anomalies despite widespread precipitation decline since the 2000s. As a permafrost-dominated basin, the YaSR exhibits enhanced streamflow generation, with contributions increasing from 6.63% to 31.31% as degradation intensifies. Conversely, the YeSR, mainly occupied by seasonally frozen ground, shows immediate streamflow attenuation that diminishes from 65.71% to 13.86% as degradation advances. The YaSR exhibits statistically significant positive associations with Jinsha and Yalong streamflows, while the YeSR develops significant statistical associations with Min River variability despite limited physical connectivity. These findings highlight the importance of frozen ground dynamics in regional water resource assessments under continued climate change.

Keywords: frozen ground degradation; hydrological impact; Budyko framework; Yangtze–Yellow River source regions; western Sichuan basins



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1. Introduction

The Tibetan Plateau (TP), known as the world’s “Third Pole”, exerts profound thermal and dynamical influences on regional and global climate systems. Serving as both a “sensitive zone” and “initiation region” of climate change in China, the TP also functions as a driver and amplifier of global change [1]. Extensive distributions of permafrost and alpine cryospheric resources across the TP sustain the headwaters of major Asian rivers, including the Yellow River, Yangtze River, Lancang River, Salween, and Brahmaputra,

thereby earning it the designation “Asian Water Tower” (AWT) [2]. The active layer of permafrost contains substantial ground ice reserves, representing a critical component of solid water resources on the TP. High-frequency freeze–thaw cycles and distinctive moisture migration processes within this layer play essential regulatory roles in modulating the water resource structure and water balance dynamics of the AWT. The Yangtze–Yellow River source regions, located in the eastern TP, are underlain by extensive permafrost covering approximately $1.82 \times 10^5 \text{ km}^2$, accounting for 67.32% of the total area in the Yangtze River source region (YaSR) and 33.70% in the Yellow River source region (YeSR) [3]. Mean annual ground temperatures in these regions averaged $-0.40 \pm 1.26 \text{ }^\circ\text{C}$ [4], with active layer thickening at a rate of 1.06 cm/y [5]. Over the past half-century, the lower limit of permafrost has risen by 50–80 m since the 1980s [6]. Taking the entire TP as a whole, permafrost has exhibited significant retreat trends in recent decades, manifested primarily in rising ground surface temperature [7], areal extent reduction [8], accelerated melting of ground ice near the permafrost table [9], thickening of the active layer [10], and increasing water storage capacity [11] under the combined influences of climate change and anthropogenic activities. The accelerated thawing of permafrost enhances infiltration of precipitation, alters soil moisture content and migration processes, affects freezing rates and extents, and modifies the regional stability of aquitard functions, thereby exerting substantial impacts on hydrological, climatic, and ecological environments in cold regions, as well as engineering design and maintenance in downstream areas.

As an aquiclude or aquitard layer, permafrost fundamentally modifies soil hydrothermal transport regimes [12]. With intensifying climate change, alterations in the water storage and hydraulic conductivity of the active layer have altered surface water partitioning and migration processes, ultimately affecting groundwater recharge and regional runoff generation. It is reported that prominent warming of upper permafrost increases negative thermal gradients between upper and lower soil layers during thawing periods, while decreasing positive thermal gradients during freezing periods, thus facilitating migration and accumulation of unfrozen water toward the base of the active layer [13]. Simultaneously, active layer thickening triggers basal ice melt, releasing substantial meltwater and enhancing the water storage capacity of the supra-permafrost aquifer [11]. These processes directly influence water cycle components including evaporation, runoff, and groundwater levels [14], altering connectivity between surface water and groundwater. In permafrost-dominated basins, freeze–thaw cycles in the active layer induce seasonal variations in soil temperature gradients that reshape spring and autumn runoff generation [15]. Persistent permafrost degradation enhances surface water infiltration, expands groundwater storage capacity, strengthens baseflow recharge remarkably, and increases baseflow in winter and surface runoff in the warm season [16,17]. Sichuan Province spans the TP, Hengduan Mountains, and Sichuan Basin, where river runoff dominates water resources concentrated in western regions. These vast areas, subject to the polar climate regime of the TP, experience dramatic hydro-meteorological variations. However, sparse hydrological networks limit data availability. Water resources research in this region, particularly long-term runoff variability, remains limited. The TP exhibits significant, spatially heterogeneous warming and wetting during historical periods [18–21]. Previous studies identify atmospheric warming as the direct driver of permafrost degradation [8,22]. Nevertheless, recent studies demonstrate that wetting processes also critically modulate thermal regimes of permafrost on the TP [20,21]. Climatic warming and wetting of the AWT will alter groundwater recharge and regional runoff generation, heightening uncertainty surrounding water resources and environmental changes in western Sichuan. As key components of the AWT, the Yangtze and Yellow River headwaters convey water resource anomalies downstream via the plateau hydrological network. Hydrological impacts of frozen ground thermal responses to wetting

and warming in this source region, and their statistical associations with runoff variability in western Sichuan, require further investigation.

In this study, we aim to quantify the contributions of frozen ground degradation to runoff changes in the Yangtze–Yellow River source regions and to identify their associations with streamflow variability in the western Sichuan basins. By utilizing high-resolution datasets of surface runoff, precipitation, potential evapotranspiration, and soil temperature, we focus on the temporal and spatial changes in streamflow of four major rivers (Jinsha, Yalong, Min, and Tuo) in the western Sichuan basins during 1961–2017, and their hydrological variability in relation to the upper Yangtze–Yellow River regions. Section 2 describes the data and methodology; Section 3 presents the decoupling between precipitation and runoff across the four main rivers of the western Sichuan basins and quantifies the hydrological linkages between thermal dynamics in the Yangtze–Yellow River source regions and downstream rivers. Section 4 gives the conclusions and provides an outlook.

2. Materials and Methods

2.1. Study Area

As the pivotal hinterland of the TP, the Yangtze–Yellow River source regions play an important role in ecological security of the AWT and the downstream hydrological conditions in the western Sichuan basins (Figure 1). In terms of frozen ground type distribution, extensive permafrost is primarily concentrated in the YaSR (30.70–36.50° N, 90.80–102.40° E) due to high elevations and cold climatic conditions, whereas the YeSR (32.50–36.50° N, 95.50–102.00° E), characterized by warmer and wetter environments, is predominantly covered by seasonally frozen ground.

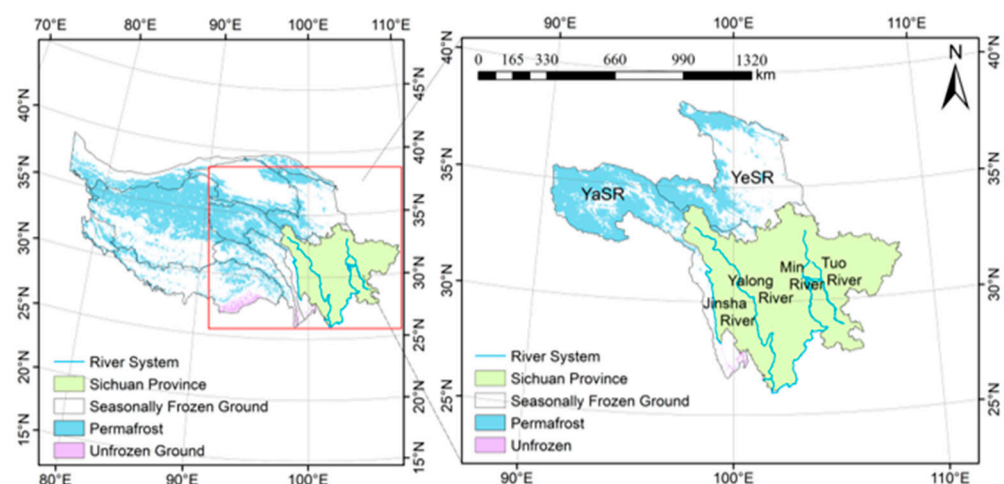


Figure 1. Permafrost distribution in the source regions of the Yangtze and Yellow rivers and the major basins of western Sichuan downstream.

Four major basins in western Sichuan are examined: the Jinsha River (24.28–29.15° N, 99.00–105.18° E), originating from Geladandong Peak in the central TP and spanning 4.70×10^5 km² with a mean discharge of $4750 \text{ m}^3 \text{ s}^{-1}$; the Yalong River (26.60–34.20° N, 96.80–102.70° E), its largest tributary, covering 1.28×10^5 km² with a mean discharge of $1560 \text{ m}^3 \text{ s}^{-1}$; the Min River (27.49–33.09° N, 102.32–104.54° E), from the southern Min Mountains in Songpan, spanning 1.36×10^5 km² with a mean discharge of $2850 \text{ m}^3 \text{ s}^{-1}$; and the Tuo River (28.35–32.27° N, 102.55–105.47° E), a first-order left-bank tributary of the upper YaSR, spanning 2.79×10^4 km² with a mean discharge of $982 \text{ m}^3 \text{ s}^{-1}$.

2.2. Data

2.2.1. China Natural Runoff Data

The monthly gridded surface runoff data employed in this study were derived from the China Natural Runoff Dataset version 1.0 (CNRD v1.0, 1961–2018) [23]. This dataset was constructed based on observed streamflow records from 330 hydrological stations across China at a spatial resolution of $0.25^{\circ} \times 0.25^{\circ}$ and temporal resolutions of daily, monthly, and annual scales. Previous evaluations have demonstrated that the CNRD accurately captures the spatial distribution patterns of natural runoff, with enhanced fidelity at the monthly basin scale: Nash–Sutcliffe efficiency (NSE) coefficients exceed 0.7 for 83% of the 330 basins [23]. Its reliability has been extensively validated in studies concerning land–atmosphere interactions and climate change [23,24]. In this study, monthly runoff series were utilized for subsequent analyses, and are available from the National Tibetan Plateau Data Center <https://data.tpdc.ac.cn/zh-hans/data/8b6a12c7-c8ff9-465a-b449-852fbff51853> (accessed on 16 June 2025).

2.2.2. Multilayer Soil Temperature Data

Soil temperature data are derived from the homogenized and gridded multi-layer daily soil temperature dataset for mainland China (1960–2017), providing daily measurements at six depths (0, 5, 10, 15, 20, and 40 cm) at $0.25^{\circ} \times 0.25^{\circ}$ spatial resolution [25]. Based on observations from over 2400 stations, the dataset reliably captures regional soil temperature variability [26]. This study utilizes temperatures at 5 cm depth, representing the shallowest reliable measurement layer that captures thermal exchange between the soil column and the atmosphere while ensuring data homogeneity across the study area, obtained from the National Tibetan Plateau Data Center <https://data.tpdc.ac.cn/zh-hans/data/f3df77b7-bd0d-4ad2-a0c2-8b93b5cf77b0> (accessed on 14 August 2025).

2.2.3. Precipitation and Potential Evapotranspiration Data

Monthly precipitation [27] and potential evapotranspiration (E_0) [28] datasets at a spatial resolution of 1 km from 1961 to 2017 were employed to characterize water cycle conditions in the study region. The precipitation product, derived from CRU and WorldClim high-resolution climate data, has been validated against observations from 496 meteorological stations, demonstrating satisfactory reliability [29]. E_0 was computed using the Hargreaves equation driven by monthly mean, minimum, and maximum temperatures [28]. Both datasets were obtained from the National Tibetan Plateau Data Center precipitation: <https://data.tpdc.ac.cn/zh-hans/data/faae7605-a0f2-4d18-b28f-5cee413766a2> (accessed on 14 June 2025); E_0 : <https://data.tpdc.ac.cn/zh-hans/data/8b11da09-1a40-4014-bd3d-2b86e6dccc4d> (accessed on 12 July 2025).

2.3. Methods

2.3.1. Near-Surface Ground Freezing Index

In this study, the near-surface ground freezing index (GFI) is adopted as a proxy for thermal degradation of frozen ground. It is based on the established concept of the cumulative value of monthly mean soil temperatures at or below 0°C in the near-surface ground, which has been widely used in previous studies to characterize the intensity and duration of freezing conditions [30–32]. To avoid the potential impact of random weather processes on the movement from one soil phase to the next when determining the onset of freezing, the GFI was calculated over the whole period from 1 July to 30 June of the following year. Following our previous work [32], the soil temperatures at 5 cm depth

were utilized as they are directly subject to atmospheric forcing and highly sensitive to interannual climate variability. The specific formulation is as follows:

$$\text{GFI} = \sum_{i=7}^{M_F} |\overline{T_L}| D_i, (\overline{T_L} < 0^\circ \text{C}) \quad (1)$$

where $\overline{T_L}$ denotes the monthly soil temperature at 5 cm depth; D_i represents the actual number of days in the i th month; and M_F indicates the months with negative mean monthly soil temperature from July (i.e., $i = 7$) to June of the subsequent year.

2.3.2. Attribution Analysis Based on the Budyko Framework

This study employs the decomposition method within the Budyko framework [33] to quantify the response of surface runoff to frozen ground degradation. Generally, changes in annual water storage (ΔS) are non-negligible. Thus, the water balance equation can be expressed as

$$Q = P - ET - \Delta S \quad (2)$$

where Q , P , ET , and ΔS denote annual runoff, precipitation, actual evapotranspiration, and water storage change, respectively (unit: mm).

If ET and Q were determined solely by climatic factors, they would be identical to the estimates derived from the Budyko curve. Ignoring ΔS , the runoff estimated by the Budyko curve (Q_{Budyko}) should be

$$Q_{\text{Budyko}} = f(P, E_0, n) = P - ET_{\text{Budyko}} = P - PE_0 / (P^n + E_0^n)^{1/n} \quad (3)$$

where annual precipitation (P) and annual potential evapotranspiration (E_0) represent available water and energy, respectively; the parameter n characterizes catchment properties, primarily associated with soil texture, topography, and vegetation fraction [33,34]. Assuming that the long-term observed mean annual runoff (Q) equals Q_{Budyko} , the catchment parameter n can be calculated using long-term series of Q , P and E_0 .

However, at the annual scale, discrepancies (Q_{dev}) persist between Q and Q_{Budyko} . Thus, Equation (2) can be further presented as

$$Q = P - (ET_{\text{Budyko}} + ET_{\text{dev}}) - \Delta S = (P - ET_{\text{Budyko}}) + (-ET_{\text{dev}} - \Delta S) = Q_{\text{Budyko}} + Q_{\text{dev}} \quad (4)$$

Q_{dev} comprises two components: the deviation of ET from the Budyko estimate ($ET_{\text{dev}} = ET - ET_{\text{Budyko}}$) and the terrestrial water storage change (ΔS). These discrepancies arise from the combined effects of landscape factors such as frozen ground and vegetation. As this study employs the GFI as an indicator of frozen ground degradation, and assuming its independence from other landscape factors, we have the following equation:

$$Q_{\text{dev}} = g(\text{GFI}) + h(\text{other landscape factors}) \quad (5)$$

It is important to acknowledge that the GFI, while primarily reflecting the thermal state of frozen ground, may covary with climatic variables including air temperature, precipitation, snow cover, and soil moisture [30]. This implies that part of the Q_{dev} could derive from shared climatic drivers rather than being attributed to pure frozen ground degradation effects. Therefore, the assumption that GFI is independent of climatic factors represents a necessary simplification within the Budyko attribution framework. In this context, the relationship of GFI with Q_{dev} provides an empirical basis for quantifying the cryospheric contribution to runoff variability. The functional shape of $g(\text{GFI})$ characterizes the relationship between frozen ground and runoff. To reduce the influence of interannual

climate variability and highlight the underlying long-term trend associated with frozen ground degradation, $g(\text{GFI})$ is fitted using three-year sequential averages of Q_{dev} and GFI, generating 19 sets of samples from 1961 to 2017 (i.e., 1961–1963, 1964–1966, . . . , 2015–2017). This approach smooths high-frequency fluctuations caused by individual weather events while preserving the decadal-scale signal of thermal degradation, thereby improving the robustness of the fitted relationship between frozen ground state and Q_{dev} .

As indicated by Equation (4), the long-term runoff change (ΔQ) between the two periods arises from the superposition of direct climate forcing (ΔQ_c) and underlying landscape change (ΔQ_l):

$$\Delta Q = \Delta Q_{\text{Budyko}} + \Delta Q_{dev} = \Delta Q_c + \Delta Q_l \quad (6)$$

If the parameter n in Equation (5) is assumed time-invariant within a particular region, then $\Delta Q_{\text{Budyko}} = \Delta Q_c$. All remaining runoff change induced by landscape change is attributed to Q_{dev} ; thus $\Delta Q_{dev} = \Delta Q_l$.

To quantify the climatic contribution to runoff change, the climate elasticity method is employed. Originally integrated into the Budyko framework by Roderick and Farquhar [35], this method defines climate elasticity as the ratio of the proportional change in runoff to the proportional change in a climatic variable. Specifically, the precipitation elasticity (ε_P) and potential evapotranspiration elasticity (ε_{E_0}) of runoff are expressed as [33]

$$\varepsilon_P = \frac{dQ/Q}{dP/P} \quad (7)$$

$$\varepsilon_{E_0} = \frac{dQ/Q}{dE_0/E_0} \quad (8)$$

where ε_P and ε_{E_0} represent the precipitation elasticity and potential evapotranspiration elasticity of runoff, respectively. Therefore, runoff change induced by climatic factors (ΔQ_c) can be estimated as

$$\Delta Q_c = \Delta Q_P + \Delta Q_{E_0} = \varepsilon_P \frac{\Delta P}{P} Q + \varepsilon_{E_0} \frac{\Delta E_0}{E_0} Q \quad (9)$$

According to Arora [36], the climate elasticity coefficients (ε_P and ε_{E_0}) can be expressed as

$$\varepsilon_P = 1 + \phi F'(\phi) / [1 - F(\phi)] \quad (10)$$

$$\varepsilon_{E_0} = -\phi F'(\phi) / [1 - F(\phi)] \quad (11)$$

$\phi = E_0/P$ is the aridity index; $F(\phi)$ is the Choudhury–Yang equation [37]:

$$F(\phi) = (\phi^{-n} + 1)^{-1/n} \quad (12)$$

Thus, runoff change induced by climatic factors (ΔQ_c) can be calculated through climate elasticity coefficients, the aridity index, and the parameter n ; the residual runoff change is attributed to landscape change (ΔQ_l), which is further partitioned into contributions from frozen ground degradation (ΔQ_f) and other landscape factors (ΔQ_o):

$$\Delta Q_l = \Delta Q_f + \Delta Q_o \quad (13)$$

ΔQ_f can be expressed as

$$\Delta Q_f = \Delta g(\text{GFI}) = g(\text{GFI}_2) - g(\text{GFI}_1) \quad (14)$$

where GFI_1 and GFI_2 are the mean near-surface freezing indices for two different periods. The function $g(GFI)$, characterizing the association between frozen ground and runoff, is determined following Wang et al. [33]:

$$g(GFI) = a[(GFI - b)/c]^d + e \quad (15)$$

where the parameters a , b , c , d , and e are determined through least squares fitting.

2.3.3. Change Point and Trend Analysis

The moving t -test is employed to detect change points in annual runoff series in individual catchments. It identifies abrupt shifts by examining the differences in significance levels between two sub-periods as follows:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{s \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \quad (16)$$

$$s = \sqrt{\frac{n_1 s_1^2 + n_2 s_2^2}{n_1 + n_2 - 2}} \quad (17)$$

where n_i , $\bar{x}_i$ and s denote the sample size, mean value, and standard deviation of the two independent samples ($i = 1, 2$), respectively; and the degrees of freedom are $n_1 + n_2 - 2$. If the calculated $|t|$ exceeds the critical value $|t_\alpha|$, the point is identified as an abrupt change year at the α significance level. In this study, $n = n_1 = n_2 = 13$ and $\alpha = 0.05$, yielding a critical value of $t_\alpha = 2.16$.

The non-parametric Mann–Kendall (M-K) test is applied to assess tendencies in Q , P , runoff ratio (RR, runoff divided by rainfall), and the GFI. Sen's slope (β) is used to quantify the magnitude of trends [21,32]. This study adopts $|Z| \geq 1.96$ at significance level of $\alpha = 0.05$.

3. Results

3.1. Contrasting Streamflow Sensitivities to Precipitation Forcing in the Western Sichuan Basins

Given that precipitation constitutes the primary meteorological driver of local streamflow variability [38,39], the interannual anomalies in runoff and precipitation across the western Sichuan basins were analyzed (Figure 2). Precipitation anomalies in the Jinsha River and Min River exhibited interannual variability prior to the mid-1990s, followed by a pronounced shift to sustained negative anomalies (Figure 2a,c). Meanwhile, Figure 2b,d demonstrate that the Yalong River and Tuo River exhibited progressively declining precipitation anomalies, which intensified markedly during the late 2000s. In contrast, the runoff exhibited prevalent positive anomalies across the four rivers, especially since the mid-2000s. This suggests a marked asynchrony between hydrological and precipitation regimes in the western Sichuan basins since the 2000s.

To more clearly illustrate the spatiotemporal changes and regional differences in streamflow responses to precipitation forcing across the western Sichuan basins over the long-term record, abrupt change points in annual streamflow were detected using the moving t -test. As shown in Table 1, only the Jinsha River and Yalong River exhibited prominent decreasing tendencies beginning in 1978, whereas all four rivers demonstrated pronounced increasing tendencies in streamflow from 1995 onwards, suggesting a gradual enhancement of regional water variability across the western Sichuan basins, particularly during the 2000s. Accordingly, the past 57 years were divided into three periods: Period 1 (P1, 1961–1978), Period 2 (P2, 1979–2000), and Period 3 (P3, 2001–2017). This uniform division aligns with prominent regional climate shifts detected across the majority of basins

and facilitates consistent inter-basin comparison within the Budyko attribution framework, though individual catchments may exhibit slightly different temporal dynamics.

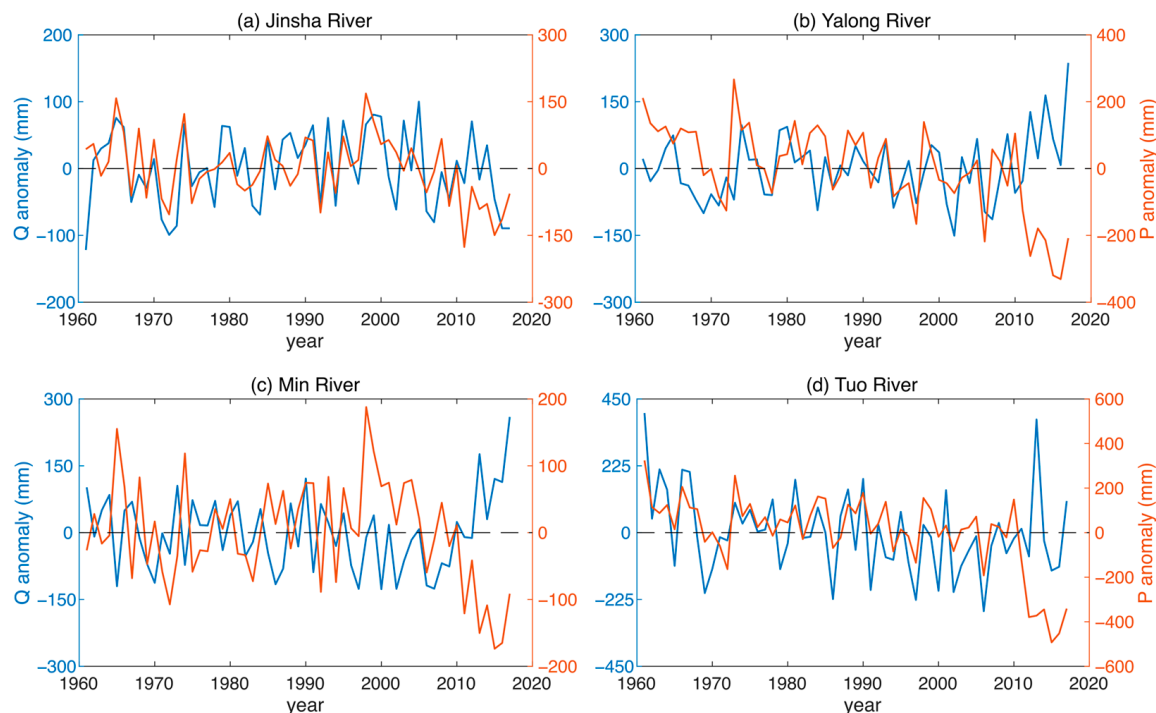


Figure 2. Time series of annual runoff (Q, blue solid lines) and precipitation (P, red solid lines) anomalies for the (a) Jinsha River, (b) Yalong River, (c) Min River, and (d) Tuo River during 1961–2017.

Table 1. Change point detection of annual streamflow using the moving t -test for the major basins over the western Sichuan basins.

Basin	Number of Abrupt Points	Abrupt Change Year
Jinsha River	2	1978↓, 2005↑
Yalong River	2	1978↓, 2012↑
Min River	1	2000↑
Tuo River	2	1995↑

An upward arrow (↑) denotes years with increasing change, and a downward arrow (↓) denotes years with decreasing change.

During P1, streamflow across all four rivers of the western Sichuan basins exhibited consistently insignificant decreasing variations (Figure 3d–g). The discrepancy in streamflow variations among the rivers became gradually clear from P2, as evidenced by the significant rise in streamflow in the Jinsha River ($p < 0.05$). During P3, however, significantly increasing variations in streamflow ($p < 0.05$) were detected in the Yalong River and Min River (Figure 3e,f), whereas the Jinsha River exhibited an opposite negative change (Figure 3c). Spatial distribution maps (Figure 3a–c) corroborate these temporal changes, revealing a distinct northeastward shift in positive streamflow trends from P2 to P3. This signifies that the Jinsha River demonstrated a more rapid positive streamflow response than the remaining three rivers. More specifically, the Jinsha River exhibited an increasing trend of 12.91 mm/10a ($p < 0.05$) during P2, followed by consistent positive trends ranging from 58.20 mm/10a to 168.04 mm/10 in the remaining three rivers during P3 (Table 2). The Tuo River exhibited a relatively milder streamflow response to climate shifts among the four rivers, with statistically insignificant fluctuations across each sub-period (Figure 3g). These divergent streamflow change patterns across the western Sichuan basins underscore the complex interplay between regional climate variability and local geographical factors.

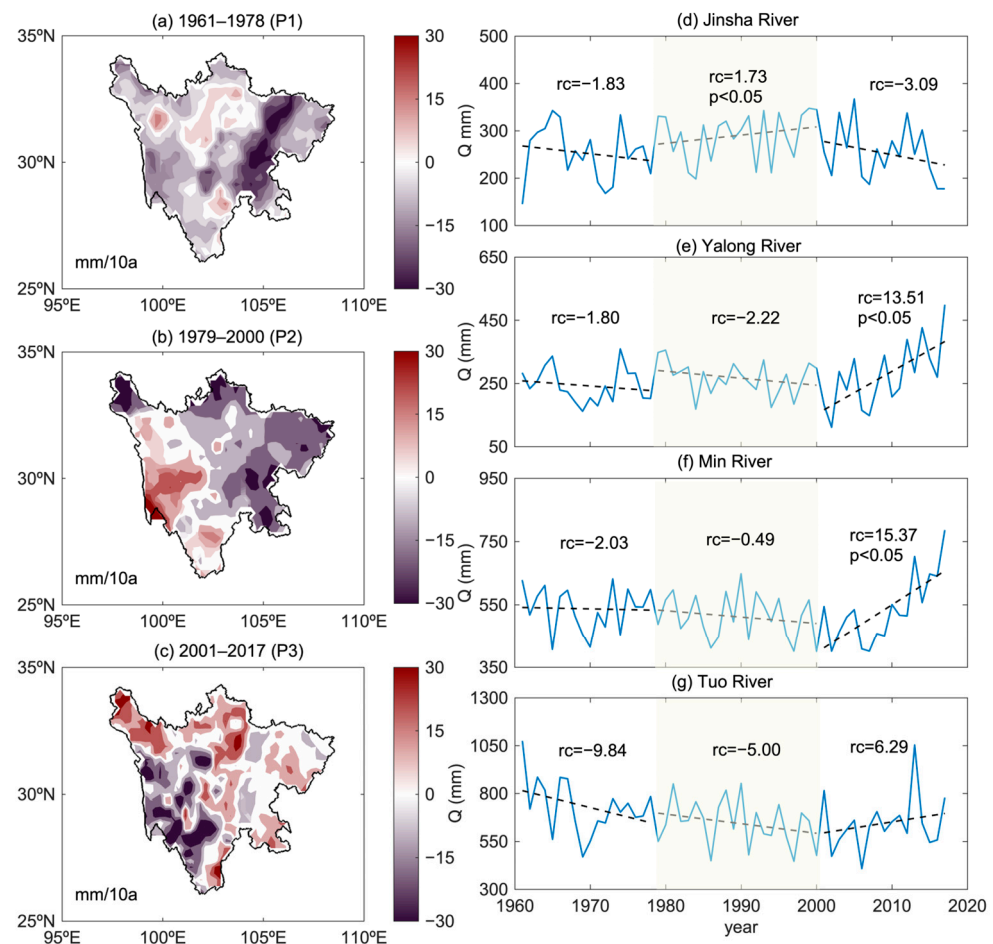


Figure 3. Spatial trends (mm/10a) in streamflow across the western Sichuan basins during (a) 1961–1978 (P1), (b) 1979–2000 (P2), and (c) 2001–2017 (P3), and time series of streamflow in the (d) Jinsha River, (e) Yalong River, (f) Min River, and (g) Tuo River for each sub-period. Vertical shading in the right panel denotes the period P2.

Table 2. Trends (per decade) in runoff (Q, mm), precipitation (P, mm) and runoff ratio (Q/P) for the main basins of western Sichuan basins during P1 (1961–1978), P2 (1979–2000) and P3 (2001–2017).

Variable	Basin	P1–P3	P1	P2	P3
Runoff	Jinsha River	0.49	−21.50	12.91 *	−24.80
	Yalong River	7.14	−21.59	−34.67	137.69 **
	Min River	−3.23	−25.12	−9.01	168.04 **
	Tuo River	−2.75	−112.90	−39.25	58.20
Precipitation	Jinsha River	−12.09 **	−43.27	39.72	−106.98 **
	Yalong River	−49.14 **	−93.79 *	−49.41	−186.41 **
	Min River	−7.65	−24.32	43.37 *	−142.73 **
	Tuo River	−48.20 **	−68.56	−19.99	−305.24 **
Runoff ratio	Jinsha River	0.01	−0.02	−0.01	0.02
	Yalong River	0.02 **	−0.01	−0.02	0.21 **
	Min River	−0.01	−0.04	−0.05	0.40 **
	Tuo River	−0.02	−0.07	−0.03	0.33 **

* $p < 0.05$, ** $p < 0.01$.

Table 2 illustrates that the western Sichuan basins experienced widespread declines in precipitation at rates of 7.65 mm/10a to 49.14 mm/10 over the entire study period. Among the sub-periods, P3 was characterized by the most pronounced decline in precipitation, with the maximum trend of 305.24 mm/10 ($p < 0.01$) observed in the Tuo River. In contrast

to the consistent decrease tendencies in runoff and precipitation during P1, prevalent increases in runoff across most of the rivers indicate a weakened response of streamflow to precipitation shifts since the 2000s across the western Sichuan basins. The Jinsha River and Tuo River demonstrated a marked weakening of the precipitation-runoff relationship from P1 to P3, with correlation coefficients falling from 0.62 and 0.72 to 0.24 and -0.05 , respectively (Table 3). A pronounced decoupling of precipitation and runoff was detected in the Yalong and Min rivers during P3, evidenced by significant negative correlations (-0.44 and -0.57 , $p < 0.05$), indicating concurrent precipitation reduction and runoff enhancement since the 2000s, which is consistent with the statistics in Table 2.

Table 3. Correlation coefficients between annual runoff (mm) and precipitation (mm) for the main rivers of western Sichuan basins during P1 (1961–1978), P2 (1979–2000) and P3 (2001–2017).

Period \ Basin	Jinsha River	Yalong River	Min River	Tuo River
P1–P3	0.52 ***	-0.15	-0.38 ***	0.34 ***
P1	0.62 ***	0.32	-0.40	0.72 ***
P2	0.65 ***	0.36 *	-0.03	0.67 ***
P3	0.24	-0.44 *	-0.57 **	-0.05

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Regarding the runoff ratio (runoff divided by precipitation), which serves as a proxy for catchment water retention capacity, consistent negative trends were observed during P1 and P2, whereas significant positive trends prevailed in P3 ($p < 0.01$). This temporal evolution in runoff partitioning suggests a fundamental shift in the hydrological processes of the western Sichuan basins. The prominent shifts in runoff ratio trends from negative to positive likely reflects intensified direct runoff generation associated with permafrost degradation in the upstream source regions since the 2000s. As ground ice thawed, increased soil permeability and deeper active layers would have promoted greater subsurface water storage, thereby favoring the replenishment of groundwater by precipitation and increasing baseflow, which facilitated enhanced downstream water variability, including in the western Sichuan basins. Taken together, these results suggest that the hydrological potential contributions of the thermal dynamics of frozen ground in the upper source region may have exerted potential linkages with water balance changes in the western Sichuan basins, which exceeded natural climate variability since the 2000s.

3.2. Thermal Degradation of Frozen Ground in Yangtze–Yellow River Source Regions

Figure 4 illustrates prominent shifts in annual GFI across the Yangtze–Yellow River source regions during sub-periods P1, P2, and P3. During P1, a significant negative trend in GFI was observed over the YaSR, in contrast to a comparatively weaker decline in the YeSR (Figure 4a,b). More specifically, the YaSR exhibited a significant GFI decrease at a rate of 38.51 °C·d/10a ($p < 0.05$), compared to 21.39 °C·d/10a in the YeSR (Table 4). This spatial pattern reversed in P2, with the maximum GFI decrease concentrated in the YeSR (Figure 4d) at a rate of 45.54 °C·d/10a (Table 4, $p < 0.05$). During P3, however, both the YaSR and YeSR showed progressive declines in GFI, with rates of -53.31 °C·d/10a and -84.83 °C·d/10a, respectively (Table 4). This implies that the Yangtze–Yellow River source regions have undergone pronounced thermal degradation since the early 1960s, with acceleration occurring consistently since the 2000s. This is coincident with the onset of prominent streamflow shifts detected in the western Sichuan basins. It is important to note that GFI decline reflects the weakening of near-surface freezing intensity, which physically links to broader frozen ground degradation processes in several ways. Reduced GFI indicates diminished winter cooling within the ground surface, leading to higher mean

annual ground temperatures and consequently deeper summer thawing. In permafrost-dominated regions, sustained GFI decreases suggest a shift toward weaker thermal stability of the permafrost table, promoting basal ice melt and enhanced supra-permafrost aquifer recharge [9,11]. In seasonally frozen ground areas, GFI reduction signifies shorter freezing duration and shallower freezing depth, which diminishes the aquitard effect and increases hydraulic connectivity between surface water and groundwater [12,16]. Hence, the temporal changes support its use as a proxy for regional thermal degradation assessment, while GFI alone cannot fully characterize frozen ground loss or deep permafrost temperature profile changes. Persistent long-term GFI decrease induced by ground thermal degradation could alter hydrological connectivity between surface runoff and groundwater recharge, modify seasonal and interannual partitioning between direct runoff and subsurface flows across the source region, and thereby affect the regional hydrological budget balance and downstream water variability.

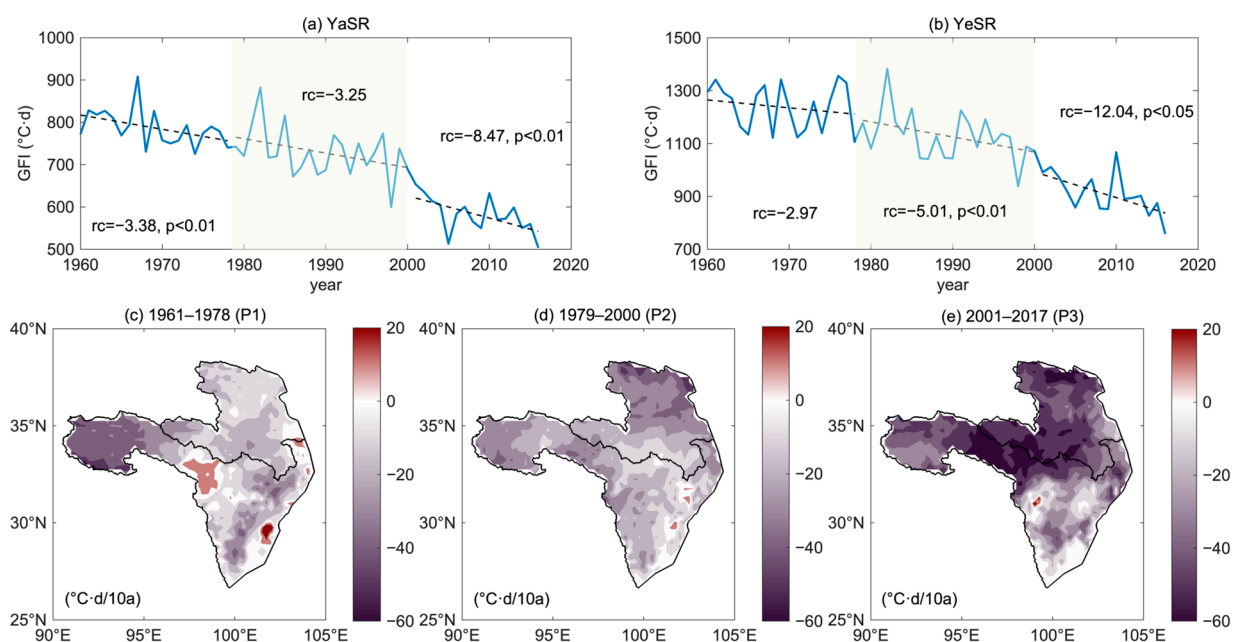


Figure 4. Variabilities of ground freezing index (GFI) over the Yangtze–Yellow River source regions. Time series of mean annual GFI in the (a) Yangtze River basin and (b) Yellow River basin during 1961–2017. The vertical shading marks period P2. (c–e) Maps depicting the spatial trends (unit: °C·d/10a) of GFI during sub-periods P1, P2, and P3, respectively.

Table 4. Trends (per decade) in runoff (mm) and GFI (°C·d/10a) for the Yangtze and Yellow headwaters during P1 (1961–1978), P2 (1979–2000) and P3 (2001–2017).

Variable	Headwaters	P1–P3	P1	P2	P3
runoff	YaSR	4.63	−17.81	19.91	−17.63
	YeSR	3.39	15.09	−27.10 **	48.57 **
GFI	YaSR	−49.84 **	−38.51 **	−25.28	−53.31 **
	YeSR	−80.31 **	−21.39	−45.52 *	−84.83 **

* $p < 0.10$, ** $p < 0.05$.

Table 4 shows that runoff in the YaSR and YeSR exhibited contrasting trends across the three sub-periods. In the YaSR, runoff displayed a pattern of initial decrease, following by increase, and subsequent decrease from P1 to P3. In contrast, the YeSR showed remarkably greater magnitudes of runoff variability during P2 and P3, with significant decreases and increases at rates of 27.10 mm/10a and 48.57 mm/10a ($p < 0.05$), respectively. These

variations correspond to the continuous significant decrease in GFI from P2 to P3 (Figure 4b), suggesting a more pronounced response of surface runoff to diminished ground freezing intensity in this source region.

3.3. Statistical Associations Between Streamflow and Frozen Ground Degradation Across the Yangtze–Yellow Source Regions

We noted distinct temporal variations in energy and water budget indicators (i.e., ET and ΔS) between the YaSR and YeSR. Figure 5a compares the ET and ΔS time series for the YaSR. During P1, the significant reduction in ET ($p < 0.05$) corresponded to enhanced ΔS , whereas P2 was characterized by accelerated ET increase but a marginal rise in ΔS , implying that intensified evapotranspiration likely attenuated terrestrial water storage accumulation. However, ΔS began to drop in P3 despite a slight concurrent decrease in ET, suggesting that terrestrial water storage exhibited a dampened response to evapotranspiration variability during this period. The prominent landscape change trend emerged as one of the major drivers causing the terrestrial water storage anomalies. As the dominant permafrost catchment, the weakening of the aquiclude effect associated with permafrost degradation may have facilitated soil drainage while enhancing groundwater discharge, thus resulting in diminished terrestrial water storage since the 2000s.

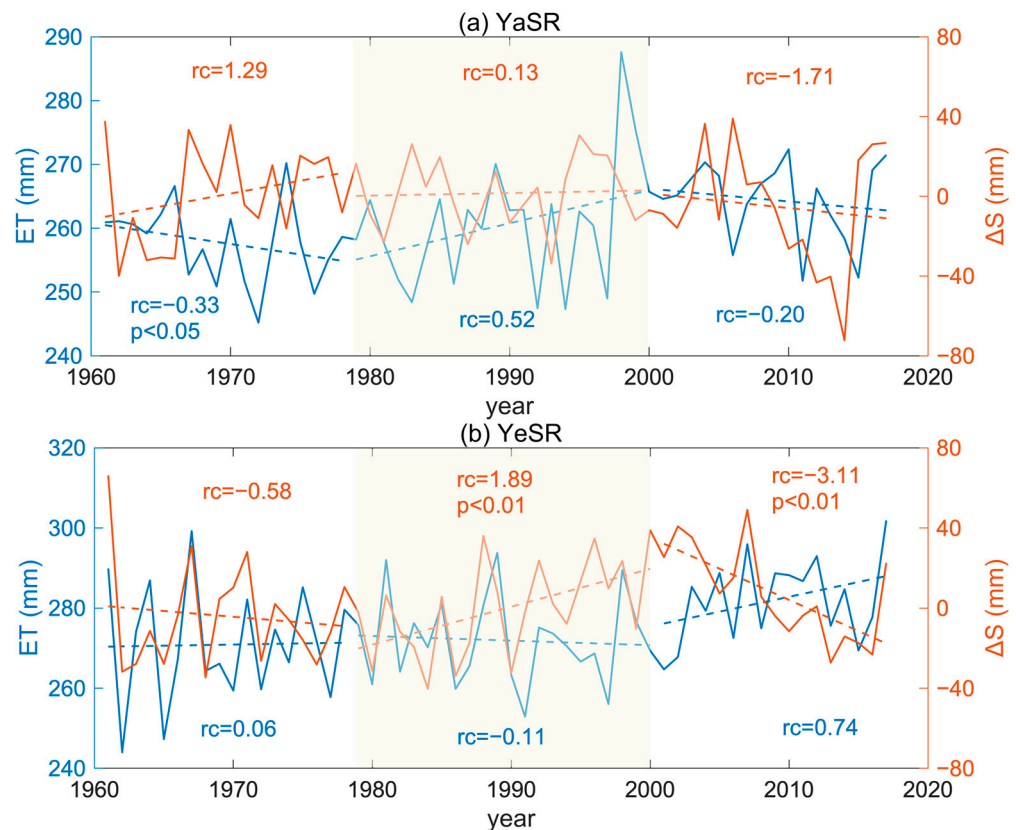


Figure 5. Comparison of annual changes in actual evapotranspiration (ET) and terrestrial water storage change (ΔS) across (a) YaSR and (b) YeSR for periods P1 (1961–1978), P2 (1979–2000), and P3 (2001–2017). Vertical shading denotes P2.

The YeSR exhibited pronounced variability in ΔS throughout P2 and P3 (Figure 5b). The shift from a decreasing to a significantly increasing trend ($p < 0.01$) in ΔS between P1 and P2 coincided with accelerated reductions in GFI ($p < 0.01$, Figure 4b), suggesting that prominent thermal degradation of frozen soils, accompanied by the release of substantial liquid water, enhanced terrestrial water storage across the YeSR. Furthermore, the reduction in runoff (27.10 mm/10a, Table 4), attributable to enhanced infiltration and reduced surface

runoff generation, may also have contributed to this increase in water storage. Nevertheless, despite increasing evapotranspiration, accelerated thermal degradation of frozen ground during the 2000s (Figure 4b) likely enhanced hydraulic connectivity between the upper soil moisture and groundwater, thereby contributing to the marked decline in ΔS during P3 ($p < 0.01$, Figure 5b).

To more clearly quantify the hydrological associations of frozen ground degradation on annual streamflow across the Yangtze–Yellow River source regions, this study establishes explicit non-linear relationships between frozen ground degradation (manifested as GFI) and streamflow deviation (Q_{dev}) in the YaSR and YeSR, respectively (Figure 6). The GFI– Q_{dev} relationships were empirically fitted using the power function form of Equation (15) based on 19 three-year sequential averages (1961–1963 to 2015–2017). For the YaSR, the fitted curve explains a substantial proportion of variance ($R^2 = 0.63$, RMSE = 9.43 mm), with residuals randomly distributed around zero (Figure 6a), supporting the statistical robustness of the empirical association. For the YeSR, the fitting yields $R^2 = 0.47$ and RMSE = 10.81 mm (Figure 6b). Derived from 1000 bootstrap resamples, the 95% confidence bands (7.76 ± 3.12 mm for YaSR and 7.61 ± 2.30 mm for YeSR) quantify the uncertainty bounds of the fitted relationships. It is important to emphasize that these fitted curves represent empirical associations rather than established causal relationships, as both GFI and Q_{dev} may respond to shared climatic drivers.

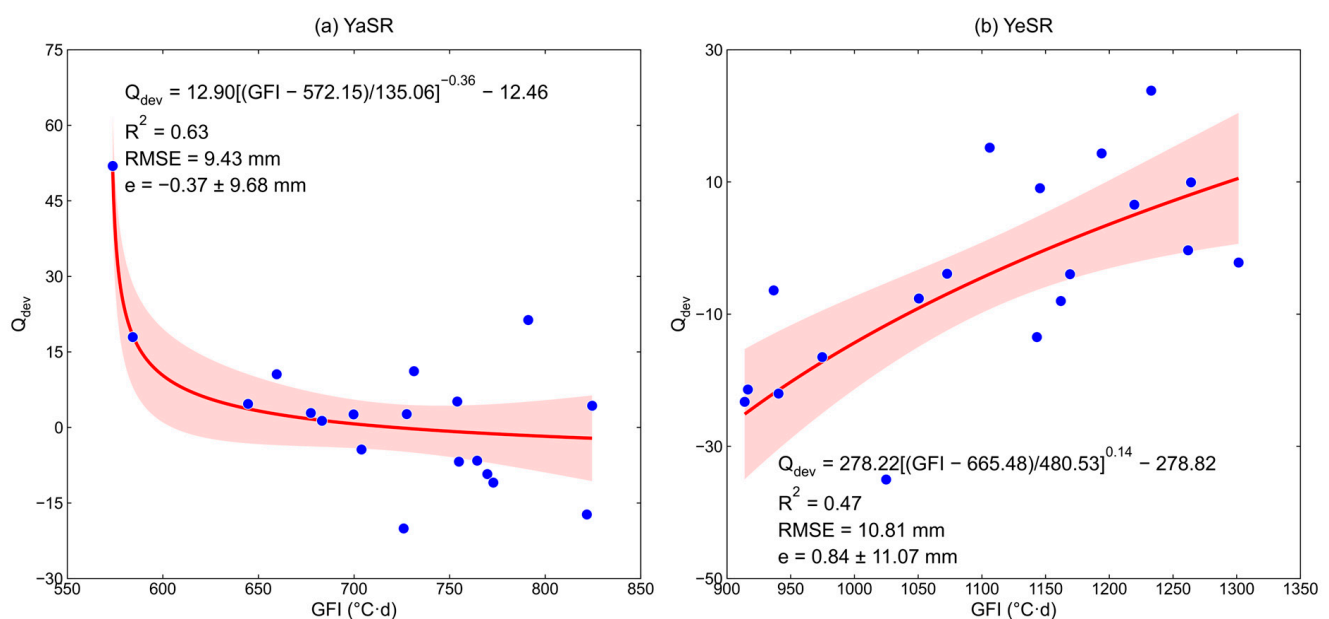


Figure 6. Scatter plots of annual streamflow deviation (ΔQ_{dev}) versus near-surface ground freezing index (GFI) for (a) YaSR and (b) YeSR. The solid curves (sample size $n = 19$) represent the fitted functions (Equation (15)), with shaded areas indicating the 95% confidence bands (95% CI, 7.76 ± 3.12 mm for YaSR and 7.61 ± 2.30 mm for YeSR) derived from 1000 bootstrap resamples. The coefficient of determination (R^2), root-mean-square error (RMSE), and residual distribution (e) are reported for each fit.

The results show that, in the YaSR, annual runoff deviation (Q_{dev}) increased as GFI declined, implying that actual annual runoff exceeded Budyko estimates (Q_{Budyko}) which only consider climate factors. The negative correlation between Q_{dev} and GFI suggests that moderate frozen ground thermal degradation and limited liquid water release are associated with increases in soil water content (Figure 6a). This process is evident as the state point (Q_{dev} , GFI) migrated sharply from the lower-right to the upper-left along the fitting curve once GFI declined beyond a critical threshold. Quantitatively, frozen ground

dynamics accounted for merely 6.63% (approximate 95% uncertainty range: -7.73 – 20.95%) of the streamflow increase in the YaSR from P1 to P2, in contrast to 88.49% attributable to direct climate impacts (i.e., changes in precipitation and potential evapotranspiration; Table 5). From P2 to P3, a 2.35 mm contribution from intensified frozen ground degradation partly offset the reduction in mean annual streamflow induced by climatic factors, attenuating regional runoff decrease to some extent. Compared with the P1–P2 period, the contribution of landscape change to mean annual streamflow change increased from 11.51% to 20.44%, whereas the impact of frozen ground degradation increased from 6.63% to 31.31% (approximate 95% uncertainty range: -72.88 – 10.30%) during P2 to P3. This implies a gradually intensifying statistical association of permafrost warming on mean annual streamflow across the YaSR since the 2000s.

Table 5. Attribution analysis of streamflow considering the contributions of frozen ground, other landscape factors, and climate changes in the Yangtze and Yellow River headwaters for the periods P1 (1961–1978) to P2 (1979–2000) and P2 to P3 (2001–2017).

Period	Headwater	ΔQ (mm)	ΔQ_c (mm)	$\Delta Q_c/\Delta Q$	ΔGFI ($^{\circ}\text{C}\cdot\text{d}$)	ΔQ_f (mm)	$\Delta Q_f/\Delta Q$	$(\Delta Q_c + \Delta Q_f)/\Delta Q$	$\Delta Q_o/\Delta Q$
P1–P2	YaSR	21.78	19.27	88.49%	−73.84	1.44	6.63%	95.12%	4.88%
	YeSR	−15.44	−2.90	18.79%	−127.77	−10.15	65.71%	84.50%	15.50%
P2–P3	YaSR	−7.51	−9.04	120.44%	−128.12	2.35	−31.31%	89.13%	10.87%
	YeSR	18.44	19.27	104.50%	−187.42	−2.56	−13.86%	90.64%	9.36%

Conversely, the YeSR exhibited a positive correlation between Q_{dev} and GFI (Figure 6b). As GFI decreased, Q_{dev} shifted from positive to negative, indicating that frozen soil loss caused actual runoff to progressively fall below the climate-only estimates. Nevertheless, this attenuating effect progressively diminished as thermal degradation advanced. As shown in Table 5, climate change alone explained merely 18.79% of the streamflow decline across the YeSR from P1 to P2, whereas frozen ground contraction accounted for 65.71% (approximate 95% uncertainty range: 50.87–80.60%). During the P2–P3 phase, however, its contribution dropped to 13.86% (approximate 95% uncertainty range: -26.33 – -1.44%), even though frozen ground degradation persisted in exerting negative forcing on streamflow as GFI further decreased by 187.42 $^{\circ}\text{C}\cdot\text{d}$. Notably, the YeSR exhibited an 18.44 mm increase in runoff during these periods, which was largely driven by climatic variability (Table 5). Meanwhile, as frozen ground continued to retreat at the basin scale, enhanced suprapermafrost flow and meltwater release likely supplemented annual runoff, which may partially offset the cryospheric deficit and attenuate the negative impact [33,40].

Taken together, the two source regions exhibit diverse hydrological associations of frozen ground degradation on hydrological regimes, likely attributable to differences in permafrost coverage, ground ice content, topographic characteristics, and bedrock permeability between the basins. Previous studies indicate that in permafrost-dominated catchments, areas with lower thermal stability (i.e., rapid GFI decline) show more immediate statistical associations on streamflow [3]. Our results further indicate that catchments covered mainly by permafrost and seasonally frozen soils show strikingly opposite statistical associations on streamflow variations in the context of climate change. In the YaSR, when persistent GFI decline within underlying permafrost surpasses a critical magnitude, sustained water release effectively recharges surface runoff, establishing permafrost degradation as a potential driver of streamflow generation. As the active layer thickens and soil water storage capacity increases, modified moisture migration pathways through soil columns facilitate surface runoff infiltration into groundwater, thereby altering winter baseflow regimes [15,40–43]. Conversely, the YeSR, which is primarily covered by seasonally frozen soils, shows more

direct streamflow decrease as ice barriers within soil pores diminish. Enhanced hydraulic connectivity between precipitation, terrestrial moisture, and groundwater recharge accelerates streamflow attenuation. As seasonally frozen ground degrades into unfrozen soils, the diminished aquitard effect tends to show limited statistical association with runoff generation mechanisms. These findings suggest that streamflow at the basin scale in both the YaSR and YeSR exhibits prominent sensitivity to frozen ground degradation as climate change advances, which inevitably modulates downstream hydrological regimes.

Figure 7 presents the correlation coefficients between Q_{dev} across the YaSR and YeSR and annual streamflow anomalies in the Jinsha, Yalong, Min, and Tuo rivers during P1, P2, and P3, respectively. Figure 7a illustrates that, owing to hydrological connectivity with the Jinsha and Yalong rivers, the YaSR exhibited pronounced positive statistical associations with streamflow from P1 to P3 in the context of extensive frozen ground degradation. Moreover, the Tuo River also exhibited an intensified positive correlation between streamflow anomaly and Q_{dev} in the YaSR from P2 to P3. By contrast, the streamflow anomaly in the Min River was negatively correlated with Q_{dev} in the YaSR. Located in the transitional zone between the Sichuan basins and the TP, where dramatic orographic lifting creates pronounced climatic gradients, the Min River has experienced a more pronounced precipitation decline since the late 1990s than the other rivers (Figure 2c). A negative streamflow anomaly was detected against the backdrop of a sharp precipitation decrease in P3, even though increased streamflow generation caused by thermal degradation in the upper YaSR might recharge the annual runoff of the Min River to some extent. Table 6 shows that, with greater values of ε_{E_0} and ε_P in the YeSR than those in the YaSR, climatic variability tends to act as a more important role in runoff dynamics in the YeSR than in the YaSR over the period 1961–2017. As a proxy indicator of regional climate variability, streamflow deviation in the YeSR caused by frozen ground degradation showed increasingly significant statistical associations with hydrological processes in the Western Sichuan basins during P3, especially in the Min River (Figure 7b). These findings suggest that frozen ground degradation in the upper Yangtze–Yellow River source regions and hydrological variability in the western Sichuan basins have shown increased statistical synchronization since the 2000s, reflecting the regional climate sensitivity of frozen ground and land surface hydrological processes.

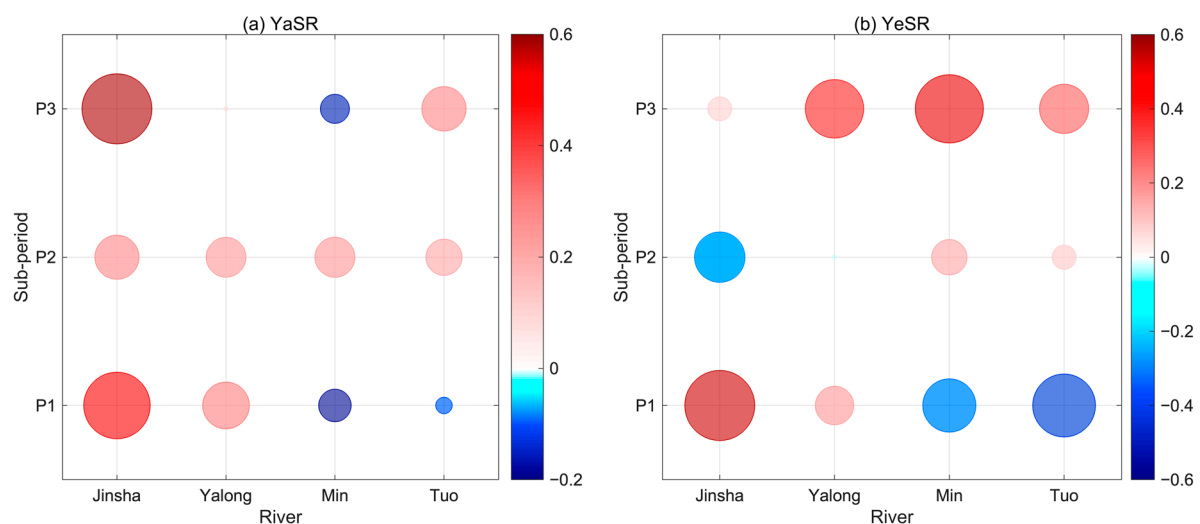


Figure 7. Correlation coefficients of Q_{dev} at (a) YaSR and (b) YeSR with the annual streamflow anomaly of the Jinsha River, Yalong River, Min River, and Tuo River for P1 (1961–1978), P2 (1979–2000), and P3 (2001–2017). The size of the circles denotes the absolute value of the correlation coefficient.

Table 6. Catchment parameter and climate elasticity of streamflow in YaSR and YeSR headwaters.

Headwater	n	φ	ε_{E_0}	ε_P
YaSR	0.83	1.02	−0.39	1.39
YeSR	1.03	1.12	−0.55	1.55

Collectively, the Jinsha, Yalong, Min, and Tuo rivers exhibit markedly heterogeneous hydrological associations with frozen-ground degradation in the upstream Yangtze–Yellow River source regions, reflecting distinct response mechanisms. The Jinsha and Yalong rivers demonstrate the strongest and most robust positive statistical associations, primarily because their headwaters originate directly within the TP and maintain established hydrological connectivity with the YaSR. This configuration allows enhanced baseflow and meltwater release from permafrost degradation to propagate efficiently downstream. By contrast, the Min River, situated in the transitional zone between the Sichuan Basin and the TP, exhibits a negative correlation with the Q_{dev} of the YaSR despite limited direct hydrological connectivity. Notably, the Min River has experienced a more severe precipitation decline since the late 1990s than the other rivers, which may locally dominate runoff variability and obscure the upstream frozen ground signal. The Tuo River shows the weakest and most inconsistent response, suggesting limited sensitivity to thermal dynamics in the upper source regions. These divergent basin-scale responses underscore that downstream statistical linkages to frozen ground degradation are strongly modulated by local geomorphology, precipitation regimes, and basin connectivity, and should not be generalized across the western Sichuan region.

4. Discussion

4.1. Comparison with Other Regional Studies

This study identified the contrasting hydrological responses to frozen ground degradation. Thermal degradation in permafrost-dominated basins (YaSR) enhanced streamflow generation while attenuating runoff in seasonally frozen ground regions (YeSR), which is consistent with findings of previous studies conducted in other cold regions. In the upper Heihe basin on the northeastern TP, Gao et al. [16] reported that frozen soil degradation intensified surface water infiltration and increased baseflow, similar to the enhanced streamflow generation observed in the YaSR. Conversely, in the YeSR, Wang et al. [33] found that seasonally frozen soil loss reduced surface runoff due to weakened aquitard effects and enhanced infiltration, paralleling the streamflow decrease in the YeSR. These regional comparisons suggest that the divergent hydrological associations of thermal degradation across the “Asian Water Tower” might be modulated by frozen ground type.

This study quantifies the contributions of frozen ground degradation to runoff change, ranging from 6.63% to 31.31% in the YaSR and from 13.86% to 65.71% in the YeSR. Similarly, Wang et al. [33] attributed approximately 32.60–87.50% of runoff change to frozen ground degradation in the YeSR using a similar Budyko framework. Nevertheless, Duan et al. [40] reported permafrost contributions of 3.10–15.80% in northeastern China using a different attribution approach. The range of estimates across studies, stemming from differences in methodology, time periods, and regional contexts, underscores the uncertainty inherent in empirical attribution methods and highlights the need for further cross-regional comparison.

4.2. Limitations and Uncertainties

Methodological constraints and data deficiencies impose clear limitations on the results of this study. While the GFI- Q_{dev} fitting provides an empirical basis for quantifying

cryospheric contributions, these empirical relationships do not necessarily imply causal relationships, as both variables may respond to common climatic drivers such as atmospheric warming and precipitation changes. The Budyko attribution framework employed here partitions runoff change into climatic and landscape components, but the exact cryospheric–climatic partitioning remains unresolved. Meanwhile, the gridded precipitation, and runoff datasets carry considerable uncertainty in topographically complex regions with sparse station networks. The soil temperature data, though homogenized, also inherit observational uncertainties from sparse station networks and complex terrain. The uniform period division, despite basin-specific change points, may obscure temporal dynamics in individual catchments. Furthermore, water withdrawal, reservoir regulation, and land use change may have also modulated streamflow changes. The absence of direct anthropogenic data represents another limitation.

It should be noted that all analyses in this study were conducted at the annual scale. Seasonal variations in these hydrological associations, which may be particularly pronounced during thawing and freezing periods, remain beyond the scope of the present work. In future studies, multilayer soil temperature observations, active layer thickness measurements, and ground ice surveys should be combined with numerical experiments to further reduce uncertainties in frozen ground contributions. Therefore, cryospheric controls on runoff generation should be incorporated into water management strategies for the western Sichuan basins in the context of climate warming and wetting.

5. Conclusions

This study quantifies the hydrological associations with the thermal dynamics of frozen ground in the Yangtze–Yellow River source regions and their downstream associations with the western Sichuan basins during 1961–2017. Streamflow across the four major rivers (Jinsha, Yalong, Min, and Tuo) of the western Sichuan basins exhibited markedly heterogeneous temporal patterns, with prevalent positive anomalies since the mid-2000s despite widespread precipitation decline. This marked decoupling between precipitation and runoff suggests that thermal degradation of frozen ground in the Yangtze–Yellow River source regions is statistically associated with altered downstream water availability since the 2000s, although a shared response to common climatic drivers cannot be excluded.

The hydrological associations of frozen ground degradation exhibit pronounced spatial heterogeneity governed by frozen ground type and degradation stage. In the YaSR, where extensive permafrost underlies the basin, relatively moderate degradation initially enhanced terrestrial water storage and streamflow generation through active layer thickening and limited meltwater release. However, as degradation intensified during P3, the potential contribution of frozen ground dynamics to streamflow increased from 6.63% to 31.31%, partly offsetting climate-induced reductions in runoff. Conversely, the YeSR (mainly covered by seasonally frozen soils) exhibited more immediate streamflow attenuation with frozen ground loss, though this negative forcing diminished as thermal degradation advanced, as evidenced by its potential contribution decreasing from 65.71% in P1–P2 to 13.86% in P2–P3.

While the YaSR exhibited statistically significant positive statistical associations with streamflows in the Jinsha and Yalong rivers via established hydrological networks, the YeSR developed increasingly significant statistical associations with hydrological variability in the Min River during P3 despite limited direct hydrological connectivity. These findings reveal enhanced statistical synchronization between the upper Yangtze–Yellow River source regions and hydrological variability in the western Sichuan basins to climate change since the 2000s. As the Asian Water Tower continues to warm, persistent weakening of aquiclude effects and enhanced hydraulic connectivity between surface and subsurface flows across

the Yangtze–Yellow River source regions are likely to alter seasonal runoff distribution and baseflow regimes, leading to heightened uncertainties in seasonal and interannual water availability projections for downstream basins.

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