Climate and Cryosphere Cause Water Yield Regime Shifts in ~~Water Yield over~~ the Upper Brahmaputra River basin

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Abstract. Although evidence of hydrological responses to climate is abundant, ~~changes in~~ the reliable assessments of water yield (WY) ~~in mountainous regionsdue to climate change and intensified cryospheric melt remain unclear, mainly because of limited observations and large uncertainties in cryosphere-hydrological modeling. In this study, we used annual runoff observations and a high-resolution precipitation dataset to examine the long-term changes in WY in~~ over mountainous regions, such as the Upper Brahmaputra River (UBR) basin, ~~as represented by six sub-basins from the stream head to downstream. We found that WY generally increased~~ remain unclear due to intensified cryospheric changes. Based on multi-station runoff observations, we examine long-term WY changes during 1982–2013 ~~, but regime shifts were detected~~ in the UBR basin, and find there are in general hydrological regime shifts in the late 1990s~~. Moreover, the direction of the changes in WY reversed from increasing to decreasing in recent years despite the magnitude of the changes continually increasing from less than~~ ; magnitude increases in WY range from $\sim$10% to ~~80.5%. Furthermore, we used~~ $\sim$80%, while its directions reverse from upward to downward after the late 1990s. Then, the double mass curve ~~technique~~ (DMC) technique is used to assess the effects of climate, vegetation, and ~~the~~ cryosphere on WY ~~. The results showed that the~~ changes. Results show that climate and cryosphere together ~~contributed~~ contribute to over 80% of ~~the magnitude increases in WY over~~ magnitude increases of WY in the entire UBR basin~~. However, the combined effects were~~ , in which the role of vegetation is nearly negligible. The combined effects, however, are either offsetting or additive, ~~further~~ leading to slight or substantial magnitude increases, respectively~~, in which the role of vegetation was nearly negligible. Nevertheless, we found that meltwater from the cryosphere had the potential to alleviate the loss of water availability, which mainly resulted from reduced effective precipitation in most regions~~. Climate change, particularly precipitation decrease leads to the downward WY trend in recent years, while melt waters under global warming may alleviate the water shortage in some basins. Therefore, the combined effects of climate and cryosphere ~~changes~~ on WY should be considered in ~~ecological restoration and~~ future water resources management over mountainous basins, particularly involving co-benefits ~~for~~ between upstream and downstream regions.

1 Introduction

Water yield (WY) in ~~mountains~~ mountainous watersheds is crucial for sustaining fragile ecosystems in ~~the~~ headwaters, supplying valuable freshwater resources to downstream lowlands, and balancing co-benefits between ~~the~~ upstream and downstream areas, especially for large transboundary river systems (Viviroli et al., 2011). In mountainous ~~regions, changes in WY~~ watersheds, WY changes have been commonly, but separately, attributed to climate ~~changes~~ (Dierauer et al., 2018; Song et al., 2021), vegetation (Goulden and Bales, 2014; Zhou et al., 2021), and ~~the cryosphere (such as glacial snow melt; see Kraaijenbrink et al. 2021). These changes~~ glaciers and snow melting (Huss and Hock, 2018; Biemans et al., 2019). These are expected to alter the spatial and temporal distribution of water resources (Tang et al., 2019) and further threaten ~~the~~ water supply and food security downstream (Biemans et al., 2019). ~~Despite some in situ observations and runoff estimates from state-of-the-art remote sensing technology, the total river runoff for the Third Pole~~The Qinghai-Tibet Plateau (QTP, see Figure 1a), which is also known as ~~the~~ “Asian Water Tower~~,~~”~~has never been reliably quantified, and its responses to climate change remain unclear (Wang et al., 2021a). Therefore, comprehensively assessing the impacts of the climate, vegetation, and cryosphere on long-term changes, particularly in magnitude and direction, in WY in this region is of great importance for the sustainable development of water resources and ecological environment (Yao et al., 2019).~~

~~The Qinghai-Tibet Plateau (QTP), regarded as the center of the Third Pole, is one of the most sensitive and vulnerable mountainous regions to environmental changes (Kang et al., 2010; Yao et al., 2010, 2019) and~~ , supplies water resources for major rivers in Asia, such as Brahmaputra, Salween, Mekong, Yangtze, Yellow, and Indus Rivers ~~. Changes in WY in this region are a crucial factor in~~ (Kang et al., 2010; Yao et al., 2010, 2019). As such, WY changes over this region significantly affect the use of water resources, prevention of natural disasters, and protection of aquatic functions for the livelihoods of approximately two billion people ~~in the area (Immerzeel et al., 2010).~~ (Immerzeel et al., 2010). While, total river runoff has never been reliably assessed, and its responses to global warming remain unclear, despite some in-situ observations and runoff estimates from state-of-the-art remote sensing technology (Wang et al., 2021a). Therefore, comprehensively assessing the impacts of climate, vegetation, and cryosphere on long-term WY changes, particularly magnitude and direction, is of great importance for the sustainable development of water resources in the QTP (Yao et al., 2019).

In recent years, changes in ~~the~~ climate, vegetation, and cryosphere have ~~significantly affected the WY over the QTP(Bibi et al., 2018)~~ affected WY in the QTP. For example, Fan and He (2015) highlighted the ~~effects of precipitation on the direction of change in WY over~~ important role of precipitation in WY increases in the Salween and Mekong River basins. Li et al. (2020) ~~determined~~ found that elevated precipitation and ~~warming-induced changes in glacial snow patterns~~ cryosphere changes both contributed to ~~the magnitude of the increase in WY for~~ substantial WY increases in the Tuotuo River ~~(a headwater of the Yangtze River)~~basin. Similarly, Lutz et al. (2014) projected that increased precipitation near the Salween and Mekong Rivers and accelerated meltwater near the Indus River caused ~~major changes in WY . Moreover, the role of vegetation in mountain water resourcesis important.~~ significant WY changes. Vegetation has also been proven to be vital for mountainous water resources; Li et al. (2017) showed that ~~increased evapotranspiration~~evaporation, mostly due to grassland restoration, decreased ~~the~~ WY in the Yangtze River basin, while Li et al. (2021) suggested that vegetation greening ~~was mainly linked to the positive WY trend~~

may change the seasonality of water resources and increase WY during the dry season ~~over the Brahmaputra River~~in the UBR basin.

Although a growing body of evidence has shown that WY is affected by climate, vegetation, and cryosphere in the QTP, most studies ~~have focused on individual sub-basins and have not considered~~ focus on individual basins, and also do not consider these three aspects together~~throughout this large and understudied region (Dierauer et al., 2018; Goulden and Bales, 2014; Kraaijenbrink et al., 2~~ ~~. Therefore~~. As such, previous results may not fully reveal the spatial ~~variability in the region~~variabilities in WY. Of specific interest is the Upper Brahmaputra River (UBR, see Figure 1a) basin, which covers an area of over 198,636 km^2 ~~(Table S1)~~ and has large gradients in elevation, climate, and vegetation (Li et al., 2019b). ~~Therefore, providing~~ Hence, it is imperative to provide a comprehensive, spatially differentiated study ~~of the WY changes in the UBR basin that considers the joint effects of the~~ considering the effects of climate, vegetation, and cryosphere ~~is imperative~~on WY changes in this region. However, studies of WY changes in ~~this region~~ the UBR basin are significantly hindered by the sparse network of hydrological observation stations (Li et al., 2019b; Wang et al., 2021a; Yao et al., 2019), which leads to large uncertainties in ~~WY forecastsand, thus~~river flow forecasts, and thus water resources assessments. ~~In addition~~Also, current precipitation estimates are highly uncertain owing to the complex topography of ~~the~~ this region, which limits the ability to accurately model the relationships between precipitation and runoff (Sun and Su, 2020). Lastly, the present ~~limited understanding of WY responses to the joint interaction of the~~ inadequate understanding of hydrological responses to complex interactions among climate, vegetation, and cryosphere ~~has become the biggest challenge for developing accurate physically-based cryosphere-hydrological models (Pellicciotti et al., 2012). Nevertheless~~limits the application of hydrological models in these mountainous watersheds (Pellicciotti et al., 2012). While, long-term ~~runoff data and~~ observed runoff records and recent high-resolution ~~satellite records of climate and vegetation cover provide a potential pathway for determining their relationships using statistical~~ precipitation datasets give a pathway for using statistical methods to estimate runoff responses to warming in the UBR basin.

~~In this study , we collected annual runoff data for 1982–2013 from six hydrological stations to~~ Hence, this study here jointly assesses historical WY responses to climate warming and associated environmental changes in the UBR basin. To do this, we collect multi-station runoff observations and detect long-term ~~changes in the WY over the~~ WY changes during 1982–2013 in the UBR basin. ~~In addition, a modified~~ And then, we use the double mass curve (DMC) ~~method was implemented to assess the influence~~ to estimate the effects of climate, vegetation, and ~~the cryosphere on WY. Accordingly, the main objectives of this study were to identify the~~ cryosphere on magnitude and direction ~~of~~ changes in WY~~based on observed runoff data and quantify the contributions of the climate, vegetation, and cryosphere to these changes~~. This study ~~can provide a reference for physical-based cryosphere-hydrological modeling and important~~ is expected to provide essential information for water resources ~~and ecosystem management over~~ management in the UBR basin and other mountainous ~~regions~~watersheds.

2 Data and Methods

2.1 Study area

The Brahmaputra River (known as the Yarlung Zangbo River, or YZR, in China), a transboundary river in the southern QTP, originates in the Gyama Langdzom Glacier and flows across China, India, and Bangladesh, before emptying into the Indian Ocean. The UBR basin is located above the Nuxia hydrological station (Figure ~~1a~~1a), and its river flow has significant implications ~~for the ecology of the source region and~~ on freshwater resources of South Asia. Here, we ~~divided~~ divide the UBR basin into the headstream (HYZR), upstream (UYZR), midstream (MYZR), downstream (LYZR), Nianchu River (NCR), and Lhasa River (LSR) ~~by~~ basins by the locations of hydrological stations (~~Figure 1b and Table S1), and analyzed WY changes over these six sub-basins to reveal spatial differences~~Table 1 and Figure 1b).

The elevation gradient and the distance to the ocean in the UBR basin together contribute to a large spatial variability in ~~the climate (Sang et al., 2016; Wang et al., 2020, 2021b)~~climate (Sang et al., 2016). The annual precipitation in the HYZR basin is less than 400 mm, while that in the LYZR basin is nearly 1000 mm~~(Figure S1). Similarly~~, and similarly, the annual actual ~~evapotranspiration (AET)~~ evaporation increases gradually from upstream to downstream areas (Figure ~~S1~~S1a+b). Meanwhile, water and energy availability modulate ~~the~~ vegetation conditions (Li et al., 2019a); vegetation cover increases dramatically from the HYZR to the LYZR basin (Figure ~~S1). Furthermore, glacial snow meltwater from the cryosphere due to warming conditions has substantially affected the hydrology of~~ S1c). Additionally, cryospheric meltwater due to atmospheric warming has substantially altered hydrology conditions in this region (Cuo et al., 2019; Yao et al., 2010; Wang et al., 2021a).

Table 1. ~~Location~~ Information of ~~(~~six basins divided by the locations of hydrological stations. The column "TP" indicates the turning point using the Pettitt method, in which a ~~)~~ significant tuning point is labeled with *. Glaciers and snow area is acquired from the ~~Upper Brahmaputra River~~ land use and cover in 2000 (~~UBR~~see details in Dataset)~~basin over the Qinghai Tibet Plateau; (b~~.

Abbrevation	Full names	Station
HYZR	Headstream	Lhatse
UYZR	Upstream	Nugesha
NCR	Nianchu River	Shigatse
MYZR	Midstream	Yangcun
LSR	Lhasa River	Lhasa
LYZR	Downstream	Nuxia ~~hydrological stations; and (c) the distribution of land use types and percentage of area covered by glaciers and~~

2.2 Dataset

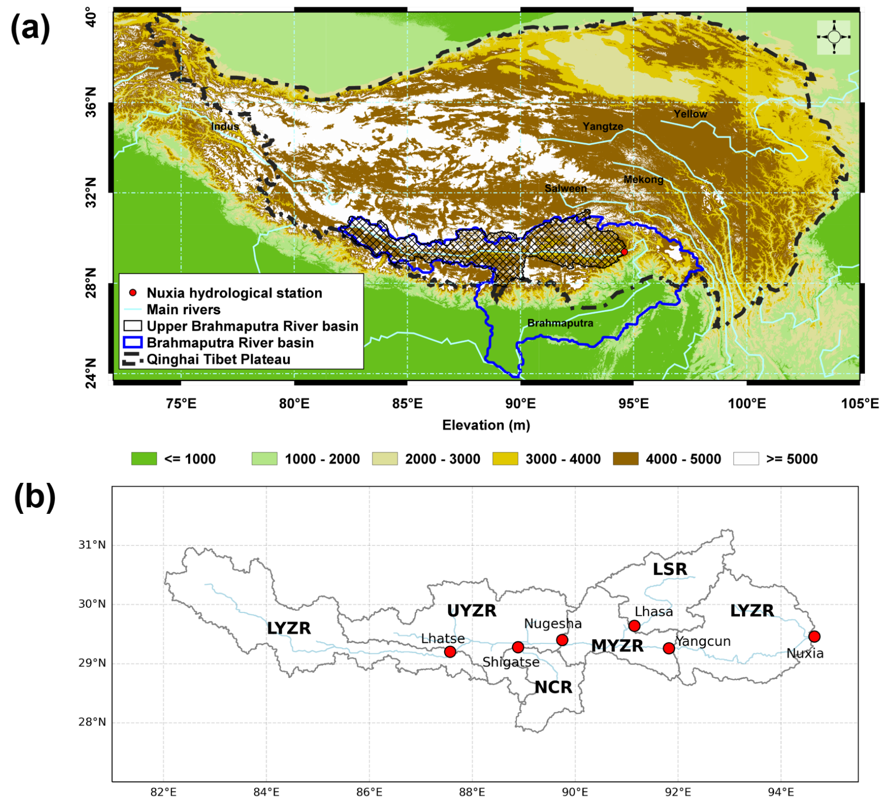

Figure 1. Location of (a) the Upper Brahmaputra River (UBR) basin in the Qinghai Tibet Plateau (QTP), which is from Li et al. (2021), and (b) six basins divided by Lhatse, Nugesha, Shigatse, Yangcun, Lhasa, and Nuxia hydrological stations.

Here we collect annual runoff observations from 1982 to 2013 and convert the river flow (m^3/s) into runoff depth (mm). Also, we acquire high-resolution climate and vegetation data in the same time range, and further aggregate these gridded data into regional annual values by considering area-weighted effects (their temporal changes are shown in Figure S2).

2.2.1 Runoff data

Annual runoff data between 1982 and 2013 used here come from six hydrological stations along the mainstream and major branches ~~, which were provided by the Hydrology and Water Resources Survey Bureau of the Tibet Autonomous Region, were used in the study. The~~ in the UBR basin. WY in the HYZR ~~was determined by the runoff observed at the Lhatse hydrological~~ is equal to runoff depth at Lhatse station, while ~~the~~ WY in other ~~sub-basins was determined~~ basins is calculated by the difference between runoff ~~observed from gauging stations located at~~ depth from the downstream station and that ~~at~~ from the upstream and branch stations. For example, WY in the MYZR basin ~~was~~ is equal to the difference between ~~the observed annual runoff in the Yangcun hydrological~~ runoff depth in Yangcun station and that in ~~the~~ Lhasa and Nugesha stations (Figure ~~1b~~1b).

2.2.2 Climate data

The most recent ~~10~~ 10x10 km gridded daily precipitation ~~dataset was obtained from Sun and Su (2020), which combined~~ data, combining topographic and linear correction approaches based on 262 rain-gauge observations, ~~and was applied~~ is developed for the UBR basin by Sun and Su (2020) and here used to estimate regional annual precipitation (P)~~in this study. Regional annual AETwas acquired from the~~ . The maximum 2 m air temperature is obtained from China Meteorological Forcing Dataset (He et al., 2020). Regional actual evaporation (AET) with a 0.25° spatial resolution is acquired from Global Land Evaporation Amsterdam Model (GLEAM) ~~products with a spatial resolution of 0.25°~~ (Martens et al., 2017). The ~~effective precipitation (eP) was regarded as a proxy for climate in this study and was calculated as the difference between P and AET, as shown in Section 2.3.2~~evaporation product has been validated in different biome types in China and shown high correlations with in-situ eddy covariance AET (Yang et al., 2017).

2.2.3 Vegetation data

The leaf area index (LAI) ~~data~~ used in this study ~~were obtained from the~~ is obtained from Global Inventory Monitoring and Modelling System (GIMMS) ~~, and spanned 1982 to 2015~~ LAI3g with a spatial resolution of 8~~km~~ ×8 km ~~. GIMMS LAI3g (Zhu et al., 2013)was~~ (Zhu et al., 2013). The product is generated using an artificial neural network trained on the Collection Terra Moderate Resolution Imaging Spectroradiometer (MODIS) LAI product and the latest version of GIMMS NDVI3g ~~(normalized difference vegetation index)~~ data for the same period, which has been proven to have an improved multi-sensor record harmonization scheme compared to other global LAI products (Forzieri et al., 2020; Gonsamo et al., 2021). ~~Note that all gridded data were aggregated to regional values over each sub-basin on an annual time scale from 1982 to 2013, considering area-weighted effects.~~

2.2.4 Land use and cover

The land use and cover in 2000 with a spatial resolution of 1x1 km is used to represent the land cover types in the UBR basin. The data is acquired from Resource and Environmental Science Data Center, and is here divided into seven primary land use types, including cultivated land, forestland, grassland, water body, urban land, unused land, and glaciers and snow (Figure S3).

2.3 Methodology

2.3.1 Trend and abruption analysis

In this study, we ~~used~~ use the non-parametric Mann–Kendall test (Kendall, 1938; Mann, 1945) to identify the ~~trends~~ trend in WY, and ~~the non-parametric~~ Pettitt abrupt detection ~~method~~ (Pettitt, 1979) to identify the turning ~~points~~ point (TP) in WY~~. The~~ , where the level of significance ~~was~~ is set at 0.05. We ~~compared the average~~ then compare the averages of WY before and after

~~each~~ the TP to reflect the magnitude ~~of WY~~ changes, and ~~compared the trends before and after each TP~~ compare the trends in two periods to reflect the direction ~~of the~~ changes.

2.3.2 Double mass curve technique

~~In a~~ The DMC used here is a plot of the cumulative data of one variable versus the cumulative data of another related variable in a concurrent period. It has previously been used to assess the individual effect of climate (Gao et al., 2011), forest disturbance (Wei and Zhang, 2010), wildfire (Hallema et al., 2018), and cryosphere (Brahney et al., 2017) on water resources. For the large and pristine ~~mountainous river basin with diverse vegetation, climatic variability, cryospheric melt , and vegetation dynamics are the three primary drivers of hydrological variation. Climatic variability is typically more dominant and can often obscure the effects of other changes on hydrology (Cong et al., 2009). The climatic effects on the annual WY must be excluded to enable quantification of the relative contributions of the cryosphere and vegetation . According to~~ UBR and other mountainous basins, climate, vegetation, and cryosphere (melt waters from glaciers and snow under warming, see Biemans et al. 2019; Huss and Hock 2018) play important roles in hydrology, and these three parts must be together considered to accurately estimate hydrological responses to warming. It is considerably hard to directly calculate the supply of melt waters to WY due to the ~~river basin water balance, the WYis determined by the difference between precipitation , evapotranspiration, and changes in soil water storage. Annual changes in soil water storage can generally be assumed to be constant and minor terms in the water balance equation (Wei and Zhang, 2010; Zhang et al., 2001); therefore, WY is mainly affected by precipitation and evapotranspiration. Furthermore, precipitation has been proven to be the dominant factor for runoff variation~~ lack of long-term glacier monitoring, while runoff observations and high-resolution climate and vegetation data make it possible to use the DMC technique, a data-driven statistical method, to estimate cryospheric contributions to WY.

The selection of climate and vegetation indices used in the DMC technique is an important issue. Previous studies have shown that effective precipitation (eP, P-AET) can reflect more information of climate on WY compared with individual P or AET, and be regarded as a reliable proxy to climate (Wei and Zhang, 2010; Zhang et al., 2019). LAI quantifies the amount of leaf area in an ecosystem and becomes an important variable reflecting vegetation structures and biophysical processes (Fang et al., 2019; Forzieri et al., 2020), and Li et al. (2021) has used LAI to investigate vegetation effects on seasonal hydrology in the UBR basin~~(Li et al., 2019b; Wang et al., 2021b; Xin et al., 2021)~~. Hence, we ~~defined the difference between precipitation and evapotranspiration as eP for WY, which was used as an integrated index for climatic variability in this study.~~

~~Unlike the traditional DMC method, where the accumulated WY from the disturbed watershed is plotted against the accumulated WY from an undisturbed watershed,~~ consider eP and LAI as the ~~modified DMC plots accumulated annual WY versus accumulated annual eP in the URB basin. Specifically, the modified DMC used in this study is a plot of the cumulative data of one variable versus the cumulative data of another related variable in a concurrent period. It has previously been used to assess the effects of climate (Gao et al., 2011), forest disturbance (Wei and Zhang, 2010), wildfire (Hallema et al., 2018), and the cryosphere (Brahney et al., 2017) on water resources. Here, we built~~ indices of climate and vegetation respectively, and use their time series as the inputs in the DMC model.

To obtain cryospheric contributions to WY, we firstly build two types of DMC plots (see Figure S4) to assess the ~~effects~~ contributions of climate (eP) ~~,~~ and vegetation (LAI), and ~~the cryosphere on WY changes over the entire UBR basin (which~~ then subtract the sum of estimated contributions from total WY deviations as cryospheric effects (results are shown in Figure ~~S2).~~ S5). The schematic diagram Figure 2 and associated mathematical formulas are shown as follows:

First, the ~~inter-annual~~ total WY deviation (~~$\Delta WY(t)$~~ $\Delta WY_s(t)$, black diamond in Figure ~~S2~~2c) can be calculated as the difference between WY after a TP (~~$WY(t)$~~ $WY_o(t)$, red point in Figure 2b) and the average WY before that TP (~~$\frac{\sum_{t=1}^{t=tp} WY(t)}{tp}$~~ $\frac{\sum_{t=1}^{t=tp} WY_o(t)}{tp}$, horizontal black line in Figure 2b), as follows:

$$\Delta WY_s(t) = WY_o(t) - \frac{\sum_{t=1}^{t=tp} WY(t)}{tp} \frac{\sum_{t=1}^{t=tp} WY_o(t)}{tp}, t = tp+1, tp+2, \ldots, 32 \tag{1}$$

Second, the regression equation (left panel in Figure 2a) between the cumulative eP ($\sum eP$) and cumulative WY ($\sum WY$) before ~~the~~ a TP can be constructed as follows:

$$\sum WY = a_1 \sum eP + b_1 \tag{2}$$

Similarly, the regression equation (right panel in Figure 2a) between the cumulative LAI ($\sum LAI$) and cumulative water yield ($\sum WY$) before ~~the~~ a TP can be constructed as follows:

$$\sum WY = a_2 \sum LAI + b_2 \tag{3}$$

Third, WY ~~changes caused~~ driven by climate ($WY_c(t)$, blue line in Figure 2b) can be calculated by inputting the cumulative eP after ~~the TP into Eq. 2.~~ a TP into Equation 2. Therefore, WY deviation caused by climate change ($\Delta WY_c(t)$, blue bar in Figure ~~S2~~2c) can be calculated as follows:

$$\Delta WY_c(t) = WY_c(t) - \frac{\sum_{t=1}^{t=tp} WY(t)}{tp} \frac{\sum_{t=1}^{t=tp} WY_o(t)}{tp}, t = tp+1, tp+2, \ldots, 32 \tag{4}$$

Similarly, WY ~~changes caused~~ driven by vegetation ($WY_v(t)$~~) were calculated using Eq. 3, and the~~ , tan line in Figure 2b) can be calculated via Equation 3, and WY deviation caused by vegetation (~~WY_v~~ ΔWY_v, tan bar in Figure ~~S2~~2c) can be calculated as follows:

$$\Delta WY_v(t) = WY_v(t) - \frac{\sum_{t=1}^{t=tp} WY(t)}{tp} \frac{\sum_{t=1}^{t=tp} WY_o(t)}{tp}, t = tp+1, tp+2, \ldots, 32 \tag{5}$$

~~Finally, the~~

Finally, WY deviation caused by cryosphere (~~ΔWY_s~~ ΔWY_g, red bar in Figure ~~S2~~2c) can be calculated as:

$$\Delta WY_{sg}(t) = \Delta WY_s(t) - \Delta WY_c(t) - \Delta WY_v(t) \tag{6}$$

2.3.3 ~~Attribution analysis on changes in water yield~~

~~The average~~

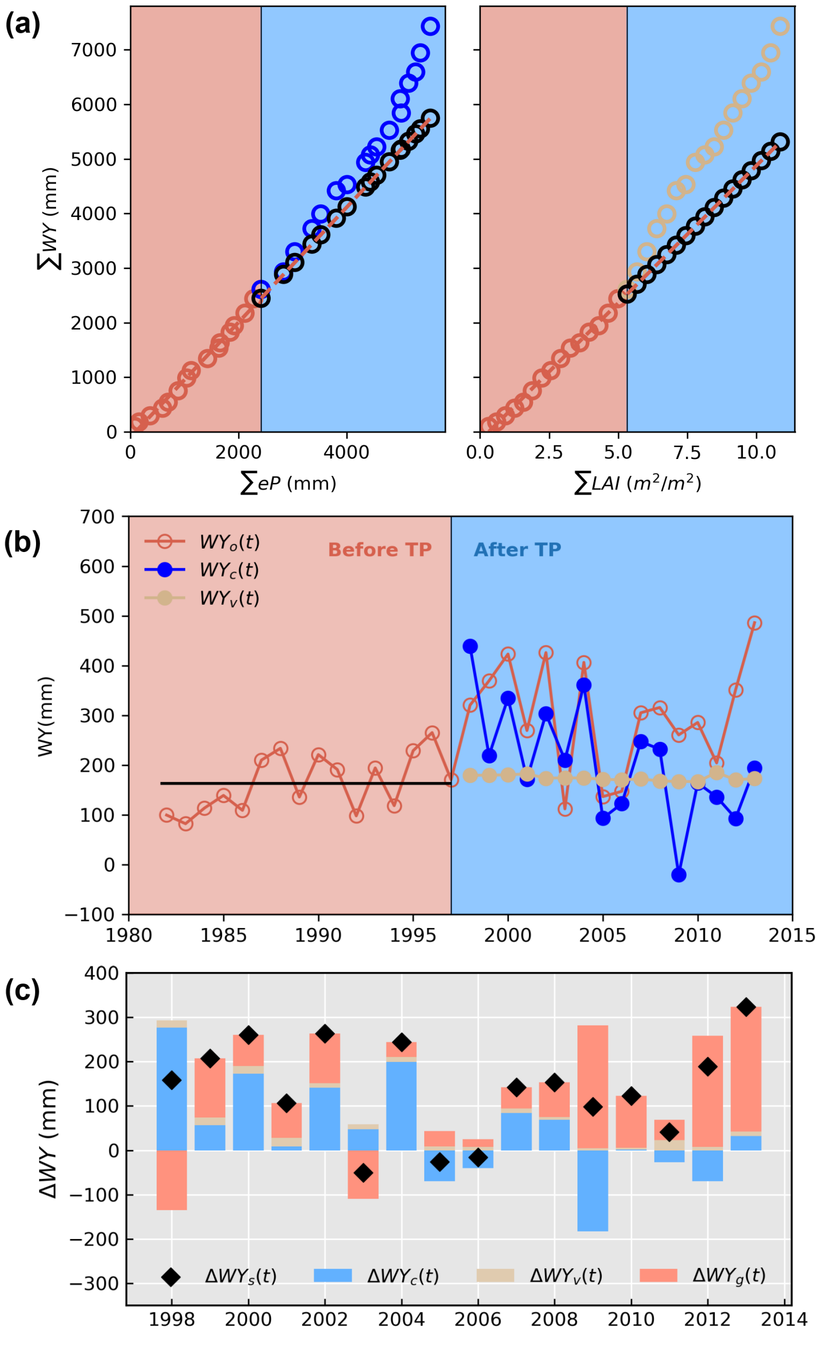

Figure 2. The schematic diagram showing how to estimate the effects of climate, vegetation, and cryosphere on ~~the magnitude of the changes in WY were~~ water yield in the MYZR basin (see details in Methodology).

2.3.3 Attribution analysis on changes in water yield

The average contributions of climate, vegetation, and cryosphere to WY magnitude changes are calculated as follows:

$$\overline{\Delta WY_c} = \frac{\sum_{t=tp+1}^{t=32} WY_c(t)}{32-tp}$$
$$\overline{\Delta WY_v} = \frac{\sum_{t=tp+1}^{t=32} WY_v(t)}{32-tp}$$
$$\overline{\Delta WY_g} = \frac{\sum_{t=tp+1}^{t=32} WY_g(t)}{32-tp} \tag{7}$$

The relative contribution (~~RC~~RC), ranging from 0 to ~~100~~1, of climate, vegetation, and cryosphere ~~changes on the magnitude~~ can be calculated as follows:

$$RC_c = \frac{\left|\overline{\Delta WY_c}\right|}{\left|\overline{\Delta WY_c}\right| + \left|\overline{\Delta WY_v}\right| + \left|\overline{\Delta WY_g}\right|}$$
$$RC_v = \frac{\left|\overline{\Delta WY_v}\right|}{\left|\overline{\Delta WY_c}\right| + \left|\overline{\Delta WY_v}\right| + \left|\overline{\Delta WY_g}\right|}$$
$$RC_g = \frac{\left|\overline{\Delta WY_g}\right|}{\left|\overline{\Delta WY_c}\right| + \left|\overline{\Delta WY_v}\right| + \left|\overline{\Delta WY_g}\right|} \tag{8}$$

~~In addition, we used~~ Additionally, we use the Pearson correlation coefficient (r) to quantify the relationships between total WY deviation (~~$\Delta WY(t)$~~$\Delta WY_s(t)$) and its components: ~~the~~ WY deviation caused by climate ($\Delta WY_c(t)$), vegetation ($\Delta WY_v(t)$) and cryosphere (~~$\Delta WY_s(t)$~~$\Delta WY_g(t)$). The Student's t-test ~~was~~ is used to detect the statistical significance of ~~Pearson's~~ the correlation coefficient at the level of 0.05.

3 Results

3.1 Long-term changes in historical water yield

The detection of long-term ~~changes in WY~~ WY changes from 1982 to 2013 ~~over~~ in the entire UBR basin is illustrated in Figure ~~2. We found that there was~~ 3. There is a great spatial variability in ~~the annual~~ WY (Figure ~~2a~~3a). The mean ~~annual WY was~~ WY is the highest in the LYZR basin (over 600 mm), followed by that ~~over~~ in the LSR basin (nearly 400 mm). However, the mean ~~annual~~ WY in the HYZR and NCR basins ~~was~~ is less than 100 mm. ~~The spatial variability in annual WY was~~ This spatial variability is consistent with that of precipitation (Figure ~~S3~~S6), which ~~was~~ is mainly determined by elevation and distance to the ocean (Sang et al., 2016). ~~WY generally increased during the study~~ In addition, WY generally increases during the period, as shown by the positive slope in Figure ~~2b, which is in agreement with previous studies on a single basin (Li et al., 2021; Lin et al., 2020; Zhang et al., 2011). However, a significant trend was~~ 3b, although the significant trend is only detected in the UYZR and MYZR basins (hatched areas in Figure ~~2b)in this study~~3b).

We ~~used~~ then use the Pettitt method to identify the ~~TPs in the WYover the entire UBR basin. The TPs mainly occurred~~ TP in WY. The TP mainly occurs during the late 1990s ~~; however,~~ (Figure 3c), but the abrupt change detected in some ~~sub-basins~~

~~was~~ basins is not statistically significant (~~Figure 2c and Table S2~~Table 1). Similarly, the cumulative anomaly curve (Figure ~~2d) showed that WY decreased~~ 3d) shows that WY decreases prior to the late 1990s and then ~~increased over~~ increases in the entire UBR basin, which further ~~complemented~~ supports the results obtained from the Pettitt method. ~~Our results agree with lake area changes in the Tibetan Plateau (Zhang et al., 2017) and climate shifts in the UBR basin (Li et al., 2019b).~~

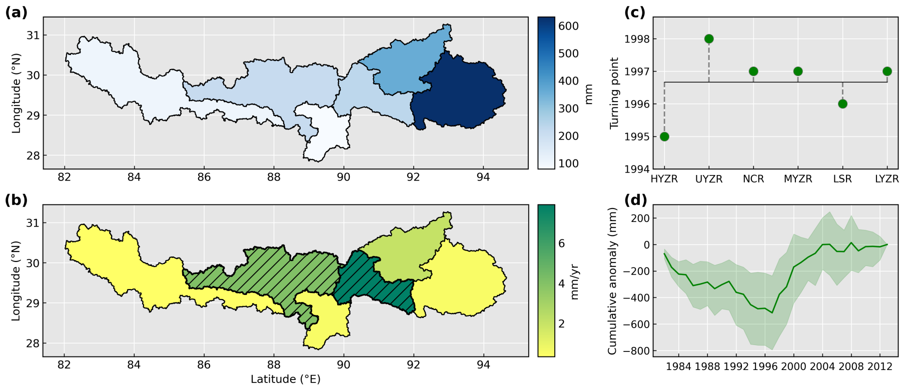

Figure 3. Long-term water yield changes ~~over~~ in the six ~~sub-basins~~basins, covering the entire UBR basin. (a) The mean annual values by averaging water yield from 1982 to 2013. (b) The temporal ~~variation~~ trends detected by the Mann-Kendall Sen's slope method. The black hatching represents statistically significant ($p < 0.05$) trends. (c) The turning points (TP) ~~as~~ detected by the Pettitt method. (d) The cumulative ~~water yield~~ anomaly ~~(CA)~~ curve of water yield. The solid green line represents the ensemble expectation of ~~the~~ cumulative ~~water yield~~ anomaly curves of water yield for the entire UBR basin (green shading).

3.2 Regime shifts in historical water yield

Based on the ~~TPs, we divided the study~~ TP, we divide the period from 1982 to 2013 into before and after TP periods, and ~~analyzed~~ analyze the magnitude and direction ~~of the WY changes over~~ changes in WY in the entire UBR basin. Figure ~~3 shows that the WY increased~~ 4a shows that WY increases from 9.5 to 130.9 mm, with a high spatial variability. The slight increase observed in the HYZR and LYZR basins ~~accounted~~ accounts for less than 10% of the mean ~~annual water yield~~ WY before the TP~~. Nevertheless, a substantial increase in WY~~ , while a substantial WY increase of 61.6% and 80.5% ~~was~~ is found in the UYZR and MYZR basins, respectively. In addition, ~~higher standard deviations were detected for WY~~ a higher variation is detected after TP, suggesting a more dramatic variability in ~~the entire UBR basin in later~~ recent years.

For the direction ~~of the WY changes , we found that the change in WY was~~ changes in WY, we find that the trend is positive before the TP~~but became~~ , but become negative afterward in most ~~sub-basins. A significant decreasing trend was detected after the TP~~ basins (Figure 4b and S2). The significantly decreasing trend is detected in the UYZR, NCR, and LSR basins. In contrast, although the WY in the MYZR basin ~~increased~~ increases during two periods, the rate ~~of increase had~~ has slowed, as the positive trend after the TP (3.64 mm yr^{-1}, $p > 0.05$) ~~was~~ is less than that before the TP (8.95 mm yr^{-1}, $p < 0.05$). Overall, ~~we found that regime shifts in the WY occurred~~ WY regime shifts occur in the late 1990s ~~over~~ in the entire UBR basin; the magnitude ~~of the WY changes generally increased, while~~ generally increases, but the direction of ~~the changes~~ WY has reversed or slowed.

~~Water yield regime shifts over the entire UBR basin. (a) Magnitude of the water yield changes. The error bars represent the standard deviation of the water yield before (light green) and after turning point (TP) (green). (b) Direction of the water yield changes. The black hatching represents a statistically significant (p < 0.05) trend.~~

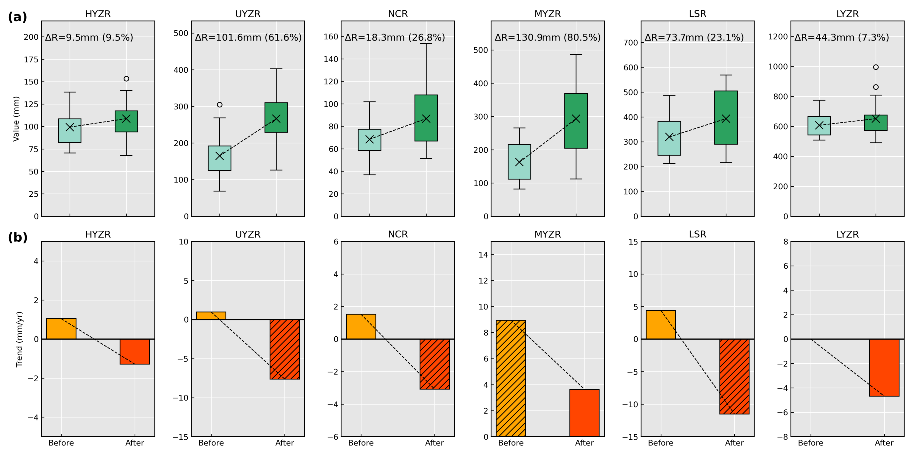

Figure 4. Water yield regime shifts in the entire UBR basin. (a) Magnitude of water yield changes. Black "x" signals show the mean of water yield in each boxplot. (b) Direction of water yield changes. The black hatching represents the statistically significant trend ($p < 0.05$). The color of boxes represents the period before (light color) and after (dark color) the turning point (TP).

3.3 Attribution analysis on magnitude increases in water yield

As shown in Figure ~~4, we quantified~~ 5, we quantify the contributions from climate (eP), vegetation (LAI), and ~~the cryosphere on the~~ cryosphere on WY magnitude increases ~~over~~ in the entire UBR basin. We ~~found that the changes in the cryosphere contributed~~ find that cryosphere changes, on average, contribute to over half of ~~the magnitude~~ WY increases in the HYZR, UYZR, NCR, and MYZR basins. However, climate ~~played~~ plays a more important role in ~~the magnitude increase~~ WY magnitude increases in the LSR and LYZR basins, with average relative contributions of 55.4% and 46.0%, respectively. In contrast to the dominant roles of ~~the~~ climate and cryosphere, vegetation ~~had~~ has a consistently positive contribution to ~~the magnitude increases in WY over the entire UBR basin, although the relative contributions of 5.6% in the HYZR basin and 19.9% in the LYZR basin were~~ WY increases, although its relative contribution is much less than those from ~~the changes in the~~ climate and cryosphere.

~~The climate~~ Climate and cryosphere – two important factors ~~influencing the magnitude change in~~ affecting WY – together ~~contributed~~ contribute to over 80% ~~to the magnitude increases over~~ average magnitude increases of WY in the entire UBR basin; however, they ~~played~~ play both additive or offsetting roles (Figure ~~4~~5), resulting in slight or substantial WY increases (Figure ~~3~~4a). For example, although ~~the cryosphere change resulted in~~ cryospheric loss contributes to average increases of

28.3 mm and 30.3 mm in the HYZR and NCR basins (black "x" signals in Figure 5a+c), the negative contributions from climate offset a considerable part of these increases~~resulting in the slight increase~~ , leading to slight increases after the TP in these regions. ~~Additionally~~Similarly, the positive contribution from climate ~~offset~~ offsets the negative contribution from ~~the~~ cryosphere in the LSR and LYZR basins, which ~~resulted in a similar slight increase in WY . However~~also results in a slight mean WY increase. In addition, the additive effects from ~~the~~ climate and cryosphere ~~change~~ lead to substantial increases in WY from 162.6 mm to 293.5 mm in the MYZR basin and from 164.9 mm ~~or~~ to 266.5 mm in the UYZR basin (Figure 4a).

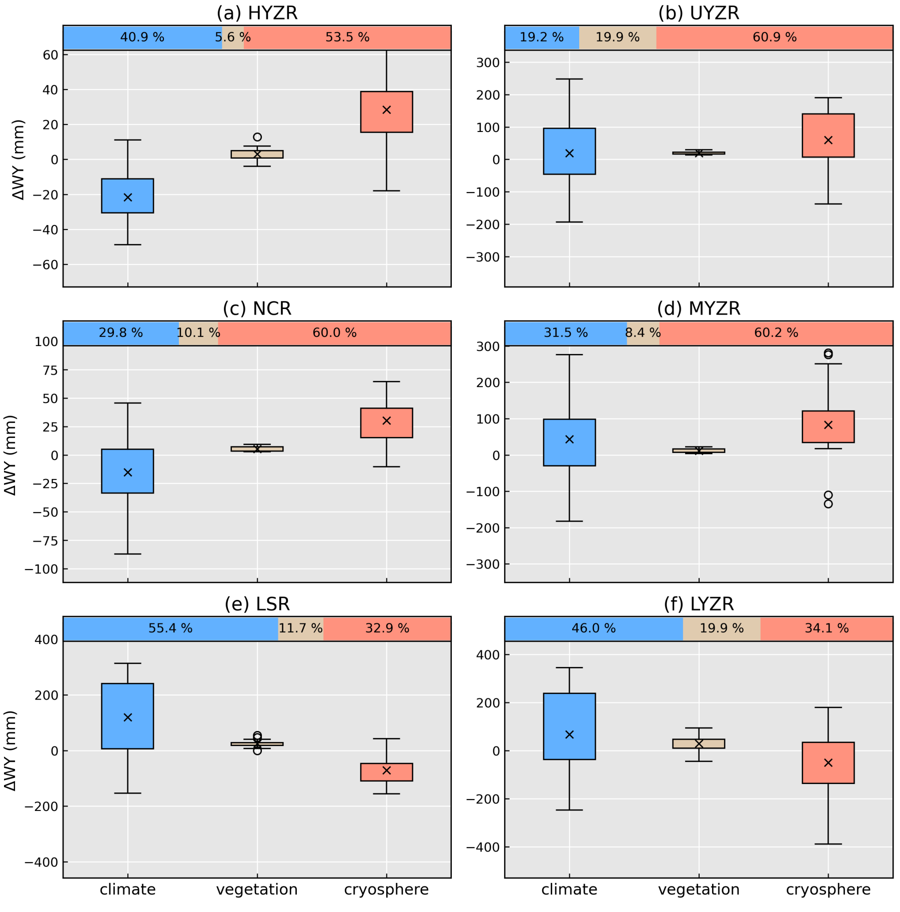

Figure 5. Attribution analysis of ~~the~~ magnitude ~~increase~~ increases in ~~the~~ water yield due to climate (ΔWY_c, blue ~~bar~~box), vegetation (ΔWY_v, tan ~~bar~~box), and ~~the 240~~ cryosphere (ΔWY_g, red ~~bar~~box), and their relative contributions (the bar with colors on the top) in each basin. ~~The error bars represent~~ Black "x" signals show the ~~standard deviation~~ mean of ~~the~~ water yield ~~changes caused by the various drivers~~ deviations (see Figure ~~S2~~S5) in each boxplot.

3.4 Attribution analysis on direction shifts in water yield

~~In this study,~~ Pearson's correlation coefficient ~~was~~ is applied to determine the role of ~~the~~ climate, vegetation, and cryosphere in the reversed or slowed WY trend after the ~~TPs~~TP, as shown in Figure ~~3b. The climate played a dominant positive role in influencing the direction of the WY changes after the TP in most sub-basins (Figure 5), which was supported by correlations ranging from 0.41 (LYZR basin)~~ 4b. Results in Figure 6 show that, although the correlation varies greatly across basins ranging from 0.11 to 0.93 ~~(LSR basin). However, the changes in WYinduced by the cryosphere instead determined the decreasing trend in WY over the HYZR basin ($r = 0.76$,~~ after the TP, climate typically is positively associated with total WY, in which the correlation is significant in half of basins ($p < 0.05$)~~. Compared to the significantly positive~~, again revealing the major role of climate ~~, however, cryosphere-induced changes in WY in the UYZR, NCR, and LSR basins exhibited a negative correlation with the decreased WY after the TP. This suggests that meltwater from the cryosphere alleviated the loss of water resources in these regions. In addition, this effect was also detected in the MYZR basin, and together with that of climate, contributed to the increasing trend in the WY in this sub-basin. Despite~~ in the hydrological trends in the entire UBR basin. Further analysis shows that, precipitation is much more important, because it exhibits the stronger reverse in trend compared with that in actual evaporation (Figure S7), which is also similar with direction changes in WY (Figure 4b). Additionally, despite the weak contribution ~~from vegetation compared to that of the other two drivers (Figure 4~~of vegetation (Figure 5), its positive role in WY ~~decline after the TPs was~~ changes is more apparent in the drier ~~sub-basins~~ basins (such as ~~HYZR, UYZR ,~~ UYZR and NCR), ~~whereas the correlation was~~ while the correlation is negative in the relatively humid LYZR basin.

4 ~~Discussion~~

~~The changes in water yield can primarily be attributed to climate change and the cryosphere; nevertheless, they are affected by a complex variety of factors (Liu et al., 2020; Harris et al., 2017), such as vegetation, snow cover, permafrost, hydrology, and soil properties. Accurate monitoring of cryospheric processes is essential for understanding the changing composite interactions in alpine regions and predicting regional responses to climate warming (Yao et al., 2019). Although some in situ observations have included more physical variables, such as soil moisture and temperature monitoring networks in Naqu and Pali (Chen et al., 2017) and observations of snow and glacial melt runoff in glacier-fed basins (Zhang et al., 2016), there remain large unassessed areas in the UBR basin. The harsh climate and environmental conditions in these regionsremain quite challenging to accurate cryosphere-hydrological modeling. In this study, with the support of the Hydrology and Water Resources Survey Bureau of the Tibet Autonomous Region, we collected long-term runoff-gauge data throughout the UBR, examined historical water yield changes, and provided a useful alternative statistical method to physical modeling approaches that can be applied to large-scale alpine river basins to quickly partition the effects of climatic and cryospheric changes on the hydrological regime. Nevertheless, further numerical modeling tools with coupled cryospheric and hydrospheric processes and comprehensive observational data (Wang et al., 2017, e.g.,) should be developed to better physically and comprehensively understand the mechanisms of~~ In contrast to positive contributions of climate, we find that WY caused by cryosphere exhibits a negative association with reduced total WY deviations in recent years in the UYZR ($r = -0.39$, $p > 0.05$) and LSR ($r = -0.36$, $p > 0.05$) basins. The negative but weak relationship indicates that melt waters from cryospheric loss may compensate for low

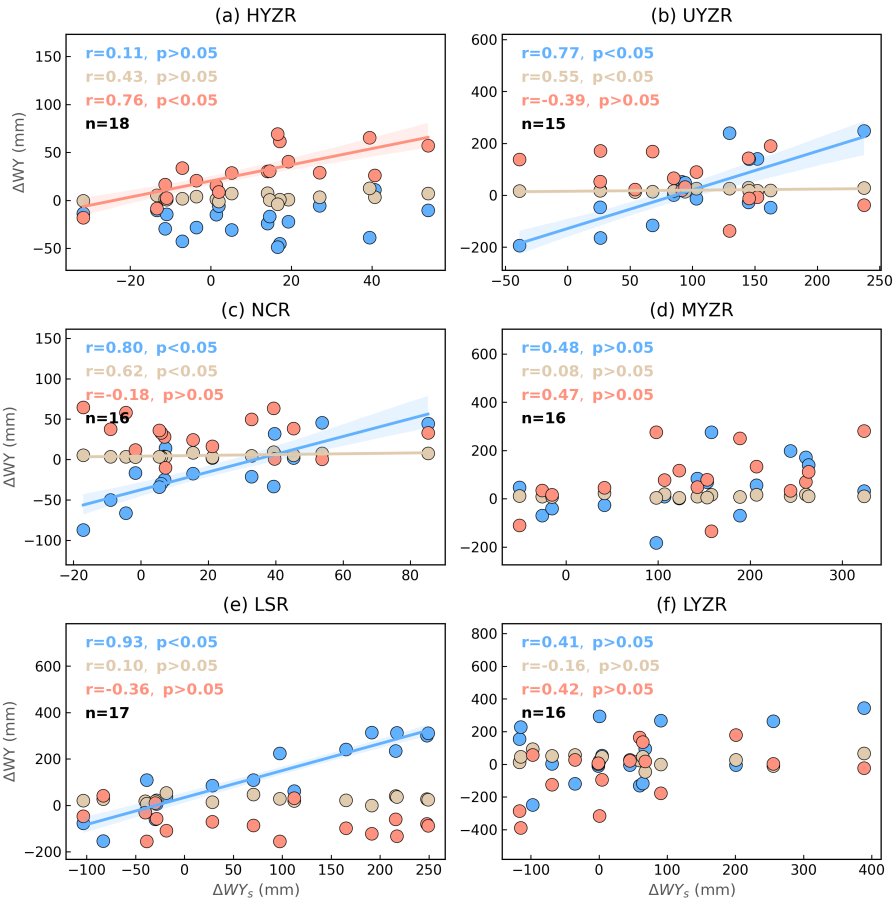

Figure 6. The ~~relationship~~ correlation between ~~the time-series~~ time series of ~~the~~ total water yield deviation (~~$\Delta WY(t)$~~$\Delta WY_s(t)$, x-axis) and its components (y-axis) ~~induced~~ caused by climate ($\Delta WY_c(t)$, blue point), vegetation ($\Delta WY_v(t)$~~(t)~~, tan point), and cryosphere (~~$\Delta WY_s(t)$~~$\Delta WY_g(t)$, red point), respectively. The ~~shading area indicates the~~ fitting line and its 95% confidence interval ~~of the fitting~~are shown only when p value < 0.05. ~~n~~ n indicates the number of years after the TP, which ~~was~~ is determined by the Pettitt method (See ~~Figure 2c and~~ Table ~~S2~~1 and Figure 3c).

flow, and even mitigate water shortage risks. Also, the compensating effect from cryosphere is much stronger in the MYZR (r = 0.47, p > 0.05), and together with climate contributions, contributes to the increasing WY trend (Figure 4). Different from other regions, however, the ~~runoff variations in the UBR basin~~HYZR basin shows a significantly positive relationship between cryospheric contributions and total WY deviations (r = 0.76, p < 0.05), indicating that cryosphere instead of climate leads to the downward trend in headwaters. This signifies that in this region, cryospheric contributions have already passed a maximum supplying to river flow, due to decreased glaciers and snow under continuous warming. The is further verified by the relationship of cryospheric contributions to total WY (RC_g) with temperature (Figure S8). In the HYZR basin, WY resulting from the cryosphere continues to increase with temperature until a maximum is reached, beyond which cryospheric contribution to total WY begins to decrease. In addition, the compensating effect of melt waters can be seen clearly in the UYZR, MYZR and LSR basins, i.e., WY caused by cryospheric loss keeps a positive relationship with the increase of temperature, further supporting the higher correlation in these basins (Figure 6).

4 Discussion

4.1 Climate and cryosphere cause water yield regime shifts

Previous studies have ~~demonstrated an increasing trend in WY over~~ indicated the increasing WY trend in the LSR (Lin et al., 2020), LYZR (Zhang et al., 2011), and UBR basins (Li et al., 2021). ~~In this study, we provided further evidence of~~ Here, we not only provide further evidence on the long-term ~~trends in~~ trend of WY changes in the above regions, ~~and, furthermore, conducted trend analysis for~~ but also conduct trend analysis in other regions that ~~have~~ received less attention in the ~~existing literature. Our results comprehensively indicated~~ present. As such, the study comprehensively indicates a general increase in WY (Figure ~~2a) over~~ 3a) in the entire UBR basin. ~~Furthermore, we extended the duration of the runoff observations to 2013 and found that regime shifts in WY occurred~~ Further, we find that WY regime shifts occur during the late 1990s ~~over~~ in the entire UBR basin ~~. Moreover, the magnitude of WY increased (Figure 3a~~ – the magnitude in WY increases (Figure 4a), but the direction ~~of WY~~ has reversed or slowed after the ~~TPs (Figure 3b). To the best of our knowledge, these regime shifts in the WY have not been reported in previous studies~~TP (Figure 4b). The result agrees with climate shifts (Figure S2), drought changes (Li et al., 2019b) in the UBR basin, and lake area changes in the Tibetan Plateau (Zhang et al., 2017).

~~Our results indicated that the~~ Attribution analysis on WY magnitude shifts gives an emphasis on the dependency of spatial gradients of climate and cryosphere ~~were important factors for magnitude increases in WY throughout the UBR basin, but their relative contribution varies across regions. Climate explained~~ accounting for WY changes. That is, climate explains a greater increase in WY in downstream regions, while ~~cryospheric changes were~~ melt water is more important in upstream regions (Figure ~~4); this matches the relative importance of meltwater from the cryosphere to streamflow (Figure S4). According to Biemans et al. (2019), meltwater from the cryosphere is the most important water source in the upper regions of the Indo-Gangetic Plain, supplying~~ 5). This may be attributed to divergent water supply sources; Biemans et al. (2019) indicates that melt waters supply over 40% of ~~the total WY upstream but~~ river flow in the upper regions, but the contribution is less than 30% ~~downstream. The effect of vegetation on changes on WY was much less than that of the climate and cryosphere (Figure 4 and Figure S2). Additionally, offsetting or additive effects from climate and cryosphere changes were detected in this study (Figure 4), which led to either slight or substantial increase in WY in each region of the UBR basin (Figure 3a). The additive effect is beneficial for mitigating drought, but it could exacerbate the flood risks due to increased precipitation and accelerated melting of the cryosphere in the future (Immerzeel et al., 2013). More importantly, the combined effects often hinder the roles of each driver in hydrological changes, which should be considered when designing water management strategies and ecological restoration engineering (Wei et al., 2018; Zhang and Wei, 2021).~~ in the downstream in the UBR basin (Figure S9). Vegetation here does not significantly affect total river flow in the UBR (Figure 5), despite its remarkable role in seasonal runoff detected by Li et al. (2021).

~~Although climate and cryosphere together contributed to the magnitude increases in WY throughout the UBR basin, climate remained the most important factor controlling the declining WY in most regions (Figure 5). Simultaneously, significant cryosphere changes due to global warming influenced the direction of the WY changes, which is supported by glacier retractation~~ Climate, especially precipitation, still control the declining WY trend after the TP in most regions (Figure 6 and S7), may become an important factor in occurrence of turning points (Figure 3c+d). This suggests the importance of precipitation and its projections on future hydrological process in mountainous watersheds (Lutz et al., 2014). Cryospheric contribution is also important for water yield regime shifts – melt waters from glaciers and snow melting can alleviate water resources shortages, mainly caused by decreased precipitation in recent years (Figure 6+S7). This finding is also supported by observed glacier runoff data (Yao et al., 2010) and several modeling studies ~~(Lutz et al., 2014; Zhang et al., 2020; Wang et al., 2021a, b). Similarly, our study indicated that meltwater from cryospheric changes has the potential to alleviate reduced water resources in most regions (Figure 3b). However, in~~ (Lutz et al., 2014; Zhang et al., 2020; Wang et al., 2021a). However, after glacier runoff reaches a maximum, defined as "peak water" (Gleick and Palaniappan, 2010), cryospheric mass loss cannot sustain the rising melt waters with atmospheric warming (e.g. the HYZR basin ~~, the decline in cryosphere-induced WY became a more important driver of the decreasing WY trend after the TP, which was inferred from the strong positive correlation (r = 0.76, p < 0.05, Figure 5) . The meltwater from snow and glaciers in the cryosphere accounted for over 60% of the streamflow in the HYZR basin (Biemans et al., 2019) and was critical for regional ecology; however, our statistical results suggested a decreasing supply from the cryosphere after the TP in the HYZR basin, which could be important for ecological restoration in river sources and emphasizes more explicit physical-based cryosphere–hydrology modeling.~~ in Figure S8), which is in agreement with Huss and Hock (2018).

~~Effective precipitation, an integrated climatic index that was generated by subtracting the actual evapotranspiration from the precipitation, was~~

4.2 Uncertainties and limitations

This study has some limitations regarding the DMC model to partition the effects of climatic and cryospheric changes on the hydrological regime shifts in the UBR basin. The DMC method is a useful alternative statistical method to physical modeling approaches, especially in alpine river basins (e.g. UBR basin) where there is less knowledge on the complex hydrological mechanisms. While the method is still dependent on our prior understanding of hydrological responses to warming and related environmental changes, such as glaciers melting and vegetation greening. For the UBR basin, besides climate change, cryosphere (Biemans et al., 2019; Yao et al., 2019) and vegetation (Li et al., 2021, 2019a) are two major factors for hydrological changes, and the cryospheric contributions can be regarded as the deviations between total water yield and climate and vegetation contributions estimated by the DMC method. While, in some mountainous basins, human activities, such as urbanization, dam regulation and irrigation, may consume severely water resource or change seasonal runoff patterns, and thus we have to consider anthropogenic impacts into the DMC statistical model for river flow attribution. On the other hand, the DMC method applies the linear assumption between two variables, and thus it may fail to capture some nonlinear process among the interactions among water yield, vegetation and cryospheric melting in the study. Thus, with the availability of long-term in-situ observations and high-resolution remote sensing datasets in the UBR basin (Wang et al., 2022), other powerful statistical models considering nonlinear and casual structures should be applied to identify the causes of water yield changes (Runge et al., 2019).

The data used in the ~~DMC method. As shown in Figure S3, the mean annual WY of all six sub-basins showed a consistently linear relationship with the corresponding~~ study may also give rise to some uncertainties for our results. The 10x10 km precipitation product used here is generated by topographical and linear corrections based on observations. As Sun and Su (2020) pointed, while, the results of the linear correction approach highly vary with the station density. For example, the increased numbers from 4 to 10 stations in the basin will decrease the mean annual precipitation ~~, further proving the dominant role of precipitation in the spatial and temporal characteristics of the WY throughout the UBR basin. In addition, Wei et al. (2018) and Zheng et al. (2009) conducted attribution analyses of the streamflow caused by climate and land surface changes in large-scale river basins with mountains and diverse vegetation; they indicated that streamflow variation and climate variability show a linear relationship, which provides solid evidence for the assumption of a linear relationship between the WY variation and effective precipitation in the present study. Furthermore, the results prove that the effects of climate variability could be successfully separated to present aclearer picture of~~ by about 20 mm. Hence, the ~~cumulative and annual effects~~ reconstruction of precipitation dataset will rely on the density of the observed stations. Besides the topographic correction, the effects of the basin size and climate seasonality should be considered in the work of precipitation reconstruction in the UBR basin due to the complex climate and environment (Sun et al., 2019). Compared with precipitation, the estimation of evaporation may be much more challenging in high mountains. Although GLEAM actual evaporation shows the good agreement with in-situ eddy covariance records (Yang et al., 2017), its model structure does not include wind speed and solar radiation, which may affect the estimation of sublimation, and thus total evaporation (Li et al., 2019c). In addition, the coarse spatial resolution with a 0.25° spatial resolution in GLEAM may be insufficient to estimate regional evaporation in the UBR basin. However, with the help of the Second Tibetan Plateau Scientific Expedition and Research, the observation networks in meteorology, cryosphere and hydrology will be built, which is expected to benefit reliable precipitation and evaporation estimation, and make developing physically-based cryosphere-hydrological modeling possible (Wang et al., 2022).

4.3 Broad Implications for mountainous water management

Understanding the hydrological regime shifts and their causes in the high mountains are especially important in managing water resources, especially balancing the co-benefits between mountains and downstream lowlands (Viviroli et al., 2011). In the study, the combined (offsetting or additive) effects from climate and cryosphere are detected (Figure 5), and further lead to either slight or substantial increases in WY in the entire UBR basin (Figure 4a). The combined effects often hinder the roles of each driver in hydrological changes (Wei et al., 2018; Zhang and Wei, 2021), which should be considered when designing water management strategies in the large transboundary river system. For example, the additive effect may be beneficial for mitigating droughts and water shortage during droughts, but it may exacerbate the flood risks due to increased precipitation and accelerated melting of the cryosphere ~~and vegetation changes on the WY in the UBR basin~~in the future (Immerzeel et al., 2013) . In addition, our results clearly show that the melt waters from glaciers might have already surpassed the "peak water" (Figure

S8), and the associated hydrological changes will substantially affect future water resources management. Thus, the projections of the occurrence time of "peak water" will be important in managing mountainous water resources.

5 Conclusions

In this study, regime shifts in WY ~~were~~ are detected during the late 1990s ~~over~~ in the UBR basin. The ~~magnitude of the WY generally increased~~WY magnitude generally increases, but its direction has reversed or slowed ~~. We used~~ in recent years. Attribution analysis based on the DMC method ~~to assess the effects of the climate, vegetation, and cryosphere on the WY and found that the changes in the~~ shows that, the combined effects of climate and cryosphere ~~had either an~~ are either offsetting or additive~~effect, which caused either a~~, leading to slight or substantial ~~increase in the WY , whereas~~ WY increases, while the role of vegetation ~~was much smaller. Furthermore, the~~ is much weaker. The declining or slowing WY ~~after the TPs was~~ trend after the TP is mainly driven by climate in most regions, ~~and notably, meltwater from the cryosphere had the potential to alleviate reduced water resources~~while melt waters may alleviate drought and water shortage. In headwaters, however, cryospheric contributions to WY have declined due to reduced glaciers under warming. These findings suggest that the combined effects of ~~the~~ climate and cryosphere should be considered in the sustainable development of water resources~~and ecosystems, especially the~~, especially involving with co-benefits in upstream and downstream regions.

Code availability. Python scripts used to extract data, analyze data, and create figures are available upon request from Hao Li (hao.liwork@ugent.be).

Data availability. Annual runoff data during 1982 and 2013 from six hydrological stations are provided by the Hydrology and Water Resources Survey Bureau of the Tibet Autonomous Region. The 10x10 km gridded daily precipitation dataset is accessed throughout https://www.tpdc.ac.cn/. The GLEAM AET is accessed from https://www.gleam.eu/. The maximum 2 m air temperature from China Meteorological Forcing Dataset is acquired via https://www.tpdc.ac.cn/. The map of land use types in 2000 is accessed from https://www.resdc.cn/.

Author contributions. HL: conceptualisation, data curation, formal analysis, methodology, writing–original draft, writing – review and editing. LL: conceptualisation, formal analysis, methodology, writing – review and editing, funding acquisition. BYS: data curation, methodology. LW: supervision, writing – review and editing. AK: validation, writing – review and editing. FZ&DFL: software, validation. XXW: visualization. WFL&XPL: Writing – review & editing. ZXX: supervision, resources.

Competing interests. The contact author has declared that neither they nor their co-authors have any competing interests.

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