Modeling decadal snow and ice dynamics and their hydrological impacts in the Balkhash Lake Basin, Central Asia (Postprint)

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Abstract

The Balkhash Lake Basin (BLB), a vital Central Asian watershed, faces hydrological uncertainty under climate warming. This study integrated multi-source remote sensing data (Sentinel-1 snow depth, Randolph Glacier Inventory (RGI) v.7.0 glacier inventory, and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) mass balance) with a degree-day model to reconstruct decadal snow and ice dynamics across 13 sub-basins and analyzed their hydrological impacts from 1950 to 2014. The results showed that: (1) while flows from the downstream river of the BLB decreased from 1950 to 1982 due to land surface changes, runoff increased significantly after 1982 in the Ili River (18.0%) and moderately increased in most rivers in the east (1.3%-8.3%), driven by increased precipitation and glacier melt. Runoff in the Ayaguz catchment (no glaciers with the highest climate warming) declined (10.5%); (2) climate warming reduced precipitation falling as snow caused snow melt water to decline (0.03-0.22 mm/a) across the BLB, leading to downward shifts in runoff and runoff coefficient, especially in the rivers in the east. However, snow melt during April–June positively correlated with runoff coefficient, contributing to an upward shift in the Ili River Basin; and (3) meltwater from glacierized areas (<5.0% of basin area) contributed to 14.3% of total ablation water. Net glacier melt provided substantial excess flows (11.6 m3/s in the Ili River and <1.0 m3/s in the rivers in the east), generally counterbalancing the negative effect of rising potential evaporation at decadal scales and positively correlating with the runoff coefficient. Therefore, water stress in the BLB may be more severe in the future due to the accelerating glacier melt after the abrupt increase in air temperature in 2000, the continuing decline in snow melt, and the significant inter-annual variations in precipitation.

Full Text

Preamble

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Abstract

The Balkhash Lake Basin (BLB), a vital Central Asian watershed, faces hydrological uncertainty under climate warming. This study integrated multi-source remote sensing data (Sentinel-1 snow depth, Randolph Glacier Inventory (RGI) v.7.0 glacier inventory, and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) mass balance) with a degree-day model to reconstruct decadal snow and ice dynamics across 13 sub-basins and analyzed their hydrological impacts from 1950 to 2014. The results showed that: (1) while flows from the downstream river of the BLB decreased from 1950 to 1982 due to land surface changes, runoff increased significantly after 1982 in the Ili River (18.0%) and moderately increased in most rivers in the east (1.3%–8.3%), driven by increased precipitation and glacier melt. Runoff in the Ayaguz catchment (no glaciers with the highest climate warming) declined (10.5%); (2) climate warming reduced precipitation falling as snow caused snow melt water to decline (0.03–0.22 mm/a) across the BLB, leading to downward shifts in runoff and runoff coefficient, especially in the rivers in the east. However, snow melt during April–June positively correlated with runoff coefficient, contributing to an upward shift in the Ili River Basin; and (3) meltwater from glacierized areas (<5.0% of basin area) contributed to 14.3% of total ablation water. Net glacier melt provided substantial excess flows (11.6 m3/s in the Ili River and <1.0 m3/s in the rivers in the east), generally counterbalancing the negative effect of rising potential evaporation at decadal scales and positively correlating with the runoff coefficient. Therefore, water stress in the BLB may be more severe in the future due to the accelerating glacier melt after the abrupt increase in air temperature in 2000, the continuing decline in snow melt, and the significant inter-annual variations in precipitation.

Keywords

runoff trend; snow and ice dynamics; degree-day model; remote sensing; Balkhash Lake Basin Citation: GAN Guojing, WU Jinglu, YANG Ruibiao, GAO Yanchun, SHEN Beibei. 2026. Modeling decadal snow and ice dynamics and their hydrological impacts in the Balkhash Lake Basin, Central Asia. Journal of Arid Land, 18(4): 547-567. https://doi.org/10.1016/j.jaridl.2026.04.001; https://cstr.cn/32276.14.JAL.20250285

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JOURNAL OF ARID LAND 2026 Vol.

Introduction

Climate warming has caused significant hydrological changes in alpine areas worldwide by accelerating glacier melts, snow cover loss, and permafrost degradation. In the High Mountain Asia, glaciers are accelerating to melt under warming conditions (Shean et al., 2020), posing severe challenges to water resources management for 8.0$×108*peoplewhodependonseasonalglaciermeltwaterinthisarea*(*Pritchard*, 2019).*Theglaci* t/a from 1961 to 2012 (Farinotti et al., 2015). The glaciers in the High Mountain Asia are expected to lose 30.0%-50.0% of their volume by 2100 at a global climate warming range of 1.50°C-2.00°C, and the snow cover days have generally declined at an average rate of 5 d/10a since the early 21st century (Jackson et al., 2023).

Compared with glacier melt, snow melt may contribute more to streamflow, for example, the relative contribution of snow melt to river runoff can be as high as 79.0% in the Amu Darya watershed in Central Asia (Khanal et al., 2021). In the Ili River Basin, Cai et al. (2014) found that daily runoff generation mainly depended on snow melt. Snow melt water supply may decrease drastically because snow melt magnitude and timing will change considerably as the climate continues to warm (Kraaijenbrink et al., 2021). An increase in air temperature is anticipated to induce a shift in precipitation from snow to rain, altering precipitation partitioning into runoff and evapotranspiration (ET) (Chen et al., 2016). Studies have reported that annual mean runoff will decrease as the snow:precipitation ratio decreases in China (Zhang et al., 2015) and the

United States (Berghuijs et al., 2014). In addition to the annual change of runoff, Liu and Yang (2021) demonstrated that the inter-annual variability in runoff would be larger with a larger snow: precipitation ratio.

Climate change and human activities have significantly affected streamflow in arid Central Asia (Siegfried et al., 2012). The Balkhash Lake Basin (BLB) is one of the largest internal drainage areas in Central Asia. The sustainability of the economy and ecological systems in this basin is highly dependent on the streamflow of its five major rivers that originated from the Tianshan Mountains, especially the Ili River, which contributes more than 70.0% of the inflow to the lake (Kezer and Matsuyama, 2006). Air temperature and precipitation in the BLB have been reported to show significant increasing trends over the past 100 a, with the rates of 0.02°C/a and 1.71 mm/a, respectively, according to in situ meteorological measurements (Xu et al., 2017).

Discharge in all five rivers decreased from 1949 to 1986 (Kezer and Matsuyama, 2006), and natural variability in air temperature and precipitation could explain the runoff decrease in the upper reaches of the BLB; in contrast, both climate and human activity resulted in the runoff decrease in the middle and lower reaches of the BLB, such as the construction of the Kapchagay Reservoir in the middle of the Ili River. However, at a longer time scale, despite the negative effects of reservoir construction and large-scale crop expansion on streamflow, the streamflow of the Ili River is increasing, as shown by the gauge data at a middle-stream station in the Ili River from 1929 to 2014 (Thevs et al., 2017), which may be due to the increase in precipitation and glacier melt. However, whether streamflow in the other four rivers in the BLB and the upper reaches in the Ili River is increasing, and the relative contributions of precipitation and glacier melt to the decadal changes in streamflow in the BLB still remain unknown.

Although much progress has been made in understanding the hydrological cycle in the BLB, the impacts of climate change on snow melt and glacial melt in the headwaters of different sub-basins of the BLB are less understood, which is partly due to the lack of data. In recent years, the emergence of remotely sensed ice/snow data, such as the global dataset of ice thickness of all glaciers on Earth (Farinotti et al., 2019), ice mass change rates derived from digital elevation changes (Brun et al., 2017), glacier areas derived from optical remote sensing (Gul et al., 2017, 2020), seasonal snow depth derived from active microwave data (Lievens et al., 2019) and passive microwave data (Smith and Bookhagen, 2018; Jiang et al., 2022), and seasonal snow cover derived from optical remote sensing (Muhammad and Thapa, 2021), has promoted research

on the water cycle in Central Asia and the High Mountain Asia. For example, using long-term (from 1987 to 2009) snow-water equivalence (SWE) data, Smith and Bookhagen (2018) found that SWE showed an overall decreasing trend in the High Mountain Asia. Gan et al. (2022) studied the decadal changes in the water balance of the upper reaches of the Ili River Basin based on the degree-day model and found that the increase in rainfall and snow and ice melt contributed equally to the rise in streamflow from 1982 to 2014.

Ongoing climate change has induced significant fluctuation in glaciers and seasonal snow in the BLB. Glacierized areas have decreased at a relative change rate of about 0.8%/a in the BLB (Severskiy et al., 2016). However, comprehensive studies on the runoff and runoff coefficient response in the complex context of glacier retreat and the decreasing snow:precipitation ratio are still lacking. The impacts of annual and seasonal snow and ice melt on the hydrological process need further investigation at decadal scales. By constructing a long-term (from 1950 to 2014) runoff dataset for 13 sub-basins in all the five rivers in the BLB and fully constrain the snow and ice dynamics in mountainous areas using the remotely sensed snow depth, glacier distribution, and mass balance data, this study aims to: (1) quantify the decadal shifts in annual and seasonal snow melt and glacier melt in the BLB; (2) explore their corresponding contributions to decadal changes in runoff; and (3) quantify the impacts of increasing ratio of precipitation:snow on the hydrological cycle in the BLB.

Materials and methods

Study area

The BLB, which covers an area of 4.13$×105*km*2, *istransboundaryinXinjiangUygurAutonomousRegion*, *Chi*
–49°08’*N*, 73°29’–85°00’*E*). *SincethedrasticshrinkageoftheAralSea*, *BalkhashLakehasbecomethelargestlake*(
km2) in Central Asia and the fifth-largest isolated reservoir in the world (Duan et al., 2020). The elevation of the BLB ranges from 116 to 6038 m a.s.l., with glaciers distributed in the high ranges of the basin (Fig. 1 [FIGURE:1]). The glaciers mainly exist in three systems, i.e., the Zailiyskiy-Kungei, Jungar, and upper Ili glacier systems (Severskiy et al., 2016) (Fig. 1), supplying water for the headwater catchments.

1 Elevation and river networks of the study area. Note that the figure is based on the standard map (GS(2024)0650) of the Map Service System (https://cloudcenter.tianditu.gov.cn) marked by the National Platform for Common Geospatial Information Services, and the boundary of the standard map has not been modified. DEM, digital elevation model.

River networks and sub-basin extents were extracted from the digital elevation data from the Shuttle Radar Topography Mission (SRTM) at a resolution of 90 m (Jarvis et al., 2008) (Fig. 1).

The Ili River, which originates from meltwater from northern Tianshan Mountains in Xinjiang Uygur Autonomous Region, China, and drains into western

Balkhash Lake, contributes the most inflow (over 70.0%) to the lake. The other four rivers, Karatal, Aksu, Lepsy, and Ayaguz rivers, drain into eastern Balkhash Lake. The Kapchagay Reservoir, which is in the middle of the Ili River, was constructed in the 1960s and started filling in 1970. The reservoir volume is 28.14 km3, which is more significant than the long-term annual runoff of the Ili River (22.87 km3) (Thevs et al., 2017). Therefore, the filling and operation of the Kapchagay Reservoir negatively impacted the downstream streamflow of the Ili River in the 1970s. Agricultural land increased by 0.74$×$103 km2/a from 1992 to 2015 in the BLB, significantly increasing ET from irrigation (Duan et al., 2020).

Data collection and processing

To evaluate the impacts of climate change on long-term (from 1950 to 2014) snow and ice melt and the water cycle in the BLB, we collected gauge runoff data, discharge datasets from land surface models, remotely sensed seasonal snow depth data, remotely sensed glacier distribution and mass balance data, and regional meteorological data. 2.2.1 Gauge runoff data and gridded discharge datasets We collected gauge runoff data from 13 hydrological stations (Fig. 1; Table 1) in all five rivers in the BLB from the hydrological yearbook and literature (Kezer and Matsuyama, 2006; Zhao et al., 2013; Thevs et al., 2017). Seven stations are located in the Ili River: the Ushjarma (1939-1985), Kapchagay (1930-2000), Dobyn (1929-2014), and Yamate (1949-1986) stations in the mainstream, and three stations including the Tekes (1956-1979), Kunes (1960-1979), and Kashi (1953-2015) stations in the mountainous reaches. For the rivers in the east, two stations are located in the Karatal River: the downstream Ushtobe station (1939-1985) and the upstream Tekeli station (1940-1985). Two stations are located in the Lepsy River: the downstream Lepsy station (1936-1985) and the upstream Lepsinsk station (1936-1985). Runoff data were acquired from the upstream Chann station (1936-1981) in the Aksu River and from the downstream Ayaguz station (1949-1986) in the Ayaguz River (Fig. 1). Using the location of each hydrological station as the outlet of the upstream drainage areas, we extracted the extents and areas of each sub-basin using the digital elevation model (DEM) data.

It is challenging to collect long-term runoff data in Central Asia, especially since the collapse of the Soviet Union, after which many of the hydrological stations stopped collecting data.

Therefore, most of the runoff records were obtained in this study before 1986, except for those from three stations: the Kashi station (1953-2015), the Dobyn station (1929-2014), and the Kapchagay station (1930-2000). Land surface models or machine learning methods are usually used to extrapolate runoff time series in Central Asia. For example, Hu et al. (2021) retrieved the runoff of the upper reaches of the Amu Darya Basin from a machine-learning-based reconstructed gridded runoff dataset, with a spatial resolution of 0.50° from 1902 to 2014 (Ghiggi et al., 2019).

In this study, to resolve the discharge variability in upper reaches, we used the 0.25° Global Land Data Assimilation System (GLDAS; from 1948 to 2014) discharge dataset (Beaudoing and Rodell, 2019) and the 0.10° European Centre of Medium-range Weather Forecasts Reanalysis v.5.0 (ERA5-Land) discharge data (since 1950) (Muñoz-Sabater et al., 2021) to extend the annual runoff time series. 2.2.2 High-resolution snow depth data from Sentinel-1 satellites Passive microwave observations are widely used to estimate regional SWE at a typical spatial resolution of 25 km, which is not suitable to resolve the spatial variability in SWE between mountains. The Sentinel-1 satellites (Sentinel-1A started in 2014 and Sentinel-1B began in 2016) provide SAR measurements at a spatial resolution of 1 km with 6 d intervals, which is suitable for snow monitoring. Lievens et al. (2019) estimated weekly snow depth variability in the mountains of Northern Hemisphere at 1 km resolution from September 2016 to April 2019. The datasets

GAN Guojing et al.: Modeling decadal snow and ice dynamics and their hydrological···

River

Karatal Lepsy Ayaguz

Information summary of the hydrological stations

Station

Longitude

Latitude

($×$104 km2)

Glacierized area (km2)

Period

Temporal resolution

Ushjarma

75°49$ '48'' $E

44°55$ '48'' $N

Monthly

Kapchagay

76°57$ '36'' $E

44°08$ '24'' $N

Annual

Dobyn

79°26$ ‘24’’ $E

43°55$ ‘12’’ $N

Annual

Yamate

81°48$ ‘00’’ $E

43°37$ ‘12’’ $N

Monthly

Tekes

82°28$ ‘48’’ $E

43°25$ ‘12’’ $N

Monthly

Kunes

83°16$ ‘12’’ $E

43°31$ ‘12’’ $N

Monthly

Kashi

81°55$ ‘12’’ $E

43°48$ ‘36’’ $N

Annual

Tekeli

78°46$ ‘12’’ $E

44°51$’ $00N

Monthly

Ushtobe

77°58$ ‘12’’ $E

45°10$ ‘48’’ $N

Monthly

Chann

79°31$ ‘48’’ $E

45°22$ ‘48’’ $N

Monthly

Lepsy

78°19$ ‘48’’ $E

46°16$ ‘48’’ $N

Monthly

Lepsinsk

80°33$ ‘00’’ $E

45°33$ ‘00’’ $N

Monthly

Ayaguz

79°32$ ‘24’’ $E

46°59$ ‘24’’ $N

Annual

Note: DEM, digital elevation model.

showed reasonable accuracy, with spatial and temporal correlations of 0.76 and 0.77, respectively.

Therefore, the snow depth datasets were used to calibrate snow melt model parameters in each sub-basin in the BLB. To ensure data quality, we restricted our analysis to pixels that received at least three valid Sentinel-1 observations within a month. 2.2.3 Glacier extent, area, and mass balance from remote sensing In this study, the detailed distribution of the glaciers in the BLB was derived from the Randolph Glacier Inventory (RGI) v.7.0 dataset (RGI Consortium, 2023). Relative to previous version, the RGI v.7.0 dataset offers a superior representation of small glaciers. Compared with the RGI v.6.0 dataset, the number of glaciers increased by 1294, and the total glacier area increased by 40.5 km^2.

As reported by Severskiy et al. (2016), the glacierized areas in the BLB have been decreasing since the 1950s, with relative decrease rates of 0.76%/a, 0.75%/a, and 0.73%/a in the ZailiyskiyKungei, Jungar, and Ili glacier systems, respectively, from 1955 to 2008. Overall, the three major glacial systems in this basin generally exhibited a uniform shrinking trend from 1958 to 2008, indicating that the dominant role of climate warming outweighed the regional differences within the area (Severskiy et al., 2016). To reconstruct the annual glacier area time series from 1950 to 2014 for each sub-basin, we integrated two data sources: the baseline glacier area from the RGI v.7.0 dataset and the relative change rates for all three glacier systems derived from Severskiy et al. (2016).

To calibrate the ice melt parameter for each catchment, we required a baseline estimate of glacier mass change. For this purpose, we utilized the dataset from Brun et al. (2017), which provides a global estimate of glacier mass change rates from 2000 to 2016 based on ASTER-derived DEMs using the DEM differencing method. We used it specifically to calculate the mean glacier water equivalent change across all 13 sub-basins from 2000 to 2016, which served as the calibration benchmark.

2.2.4 Regional meteorological data

To run the snow and ice melt model and ET model, we derived gridded meteorological data, including the incoming shortwave radiation, incoming longwave radiation, air temperature, dew temperature, wind speed, and precipitation, from the ERA5-Land dataset (0.10° resolution and 1-h intervals) (Muñoz-Sabater et al., 2021). The ERA5-Land dataset has been successfully used in High Mountain Asia (Khanal et al., 2021; Kraaijenbrink et al., 2021). Hourly data were

JOURNAL OF ARID LAND 2026 Vol.

18 No. 4

aggregated to the daily and monthly scales used for the snow and ice melt and ET models.

2.3.1 Reconstruction of annual runoff

To reconstruct a long-term annual runoff series (from 1950 to 2014) for all 13 sub-basins, we first established linear regression models (Eq. 1) between gauge observations and the corresponding annual runoff estimates from both GLDAS-2.0 (RGLDAS) and ERA5-Land (RERA5-Land) during their common period of overlap. These models were then applied to the reanalysis data to gap-fill missing values in the gauge records, thereby generating a continuous series. We found that combining RGLDAS and RERA5-Land yielded more accurate reconstructions than using either product alone. The entire reconstruction was confined to the period from 1950 to 2014, which was fully covered by both reanalysis datasets, to ensure maximum reliability. The linear regression model is shown as follows:

R = a1 RGLDAS + a2 RERA5-Land + R0 , where R is the runoff (mm); RGLDAS and RERA5-Land are the runoff from the GLDAS and ERA5-Land datasets (mm), respectively; and a1, a2, and R0 are the regression coefficients.

2.3.2 Sublimation and melt estimation

The snow and ice dynamics were modeled at a daily scale. Additionally, to better represent the snow and ice dynamics in the BLB, we ran the models at a relatively satisfactory spatial resolution (120 m). Based on the DEM data, we downscaled the air temperature in each grid box from the 0.1° ERA5-Land grid by considering the elevation effect, i.e., air temperature decreases with height at a 6.50°C/1000 m lapse rate. Snowfall was estimated using the ratio of snow to precipitation (fs; 0≤fs$ $1), defined as the snowfall ratio to the total precipitation amount. In regional and global studies, fs is usually estimated as a function of air temperature, i.e., precipitation is classified as total snowfall (fs=1) or rainfall (fs=0) when the air temperature (Ta; °C) is below 0.00°C or above 2.00°C, respectively. When Ta is between 0.00°C and 2.00°C, fs is interpolated as 1-(Ta-0)/(2-0) (Kraaijenbrink et al., 2021). The value of snow and ice accumulated in each grid box on a specific day i (acci; mm) was determined by adding the amount of snowfall and the ablation amount of the snow and ice of day i to the previous accumulation amount of the i-1 d (acci-1; mm), as shown in Equation 2. Snow and ice ablation includes both sublimation and melt processes. $\text{acci} = \text{acci} - 1 + \text{Snowfall} - \text{Sublimtion} - \text{Melt}$.

Sublimation is a direct phase transition process from solid snow and ice to water vapor (Stigter et al., 2018). Despite its importance, an accurate estimation of sublimation is difficult. This study used a mass transfer method tested in the Tianshan Mountains (Zhang et al., 2003) to determine daily sublimation, as shown in Equation 3:

$\text{Sublimation} = \text{a}\,(1 + \text{b} \times \text{u})\text{VPD}$, where u is the near-surface wind speed (m/s); VPD is the vapor pressure deficit (hPa); and a and b are two parameters, taken as 0.26 and 0.54, respectively, which are referenced from Zhou et al. (2015). For the snow-covered (non-glacierized) land surface, the sublimation for a specific day was determined as the minimum of acci-1 plus snowfall and sublimation from Equation 3. For the ice-covered (glacierized) land surface, the sublimation for a specific day was taken as the value computed from Equation 3.

Snow melt and ice melt were estimated using the degree-day model (Hock, 2003), which only requires air temperature. The degree-day model estimates the melt rate (mm/d) of snow and ice as the product of the accumulated temperature above the threshold temperature (Tr; taken as 0.00°C) and a degree-day factor (DDF; mm/(°C • d)), as shown in Equation 4. As the sublimation, the estimated snow melt was also bounded by the accumulated snow water storage, acci-1, and snowfall.

$\text{Melt rate} = \text{DDF}(\text{Ta} - \text{Tr})$, if $\text{Ta} > \text{Tr}$.

The DDF depends on the density of the snow and ice and the characteristics of the underlying surface, thus varying significantly across space and time (Kayastha et al., 2003; Armstrong et al., 2019). In this study, we calibrated the specific DDF of snow (DDFsnow) and ice (DDFice) for each sub-basin of the BLB. For DDFsnow, we ran snow melt models from 2016 to 2019, with DDF values taken from 0.5 to 20.0 mm/(°C • d) with an interval of 0.5 mm/(°C • d). By comparing the modeled snow depth and the remotely sensed snow depth from September 2016 to April 2019 (Lievens et al., 2019), we took the optimized value of the DDFsnow of each sub-basin as the value when the correlation coefficient (r) reached its maximum, and the mean bias reached its minimum.

The correlation coefficient and the mean bias are statistics based on all grid cells within each sub-basin. Similarly, the DDFice of each sub-basin was taken by matching the mean change rate of the glaciers from the ice melt model from 2000 to 2016 with that derived from the dataset of Brun et al. (2017) in the same period. 2.3.3 Complementary relationship model for estimating ET In arid and semi-arid areas, ET is a significant consumption term of water (Gan et al., 2019a; Bu et al., 2021). Therefore, we needed ET estimates to evaluate decadal water balance closure in the BLB. For this purpose, we used a complementary relationship (GCR) model (Brutsaert, 2015; Gan et al., 2021a) based on meteorological data, to estimate monthly ET (mm/month), as shown in Equation 5.

ETpo ETa = 2ETpa − ETpo , ETpa where ETpo and ETpa are the evaporation rate (mm/month) of a large uniform saturated surface (Gan et al., 2020) and the evaporation rate (mm/month) of a small saturated surface surrounded by a non-saturated environment (Gan et al., 2019b), respectively. ETpo and ETpa can be calculated using meteorological data, using the Priestley-Taylor equation (Priestley and Taylor, 1972) and the Penman equation (Penman, 1948), respectively. 2.3.4 Runoff trend detection and attribution analysis Trends in the runoff and meteorological conditions were analyzed using the Mann-Kendall (MK) method (Mann, 1945; Kendall, 1948). A positive/negative Z value from the MK test indicates an increasing/decreasing trend at the 0.10, 0.05, and 0.01 significance levels when the absolute values of Z are larger than 1.64, 1.96, and 2.58, respectively. The MK method was also used to detect abrupt change points in the meteorological and runoff time series. To more clearly reveal the relative importance of different factors in different periods, we further divided the time series into four periods using the years 1962, 1982, and 1994 as cutting points because (1) both runoff and precipitation showed abrupt changes around 1962 and 1982; (2) change points in the fs time series emerged in the early 1990s in four out of the five major river basins; and (3) air temperature in most of the area reached its minimum in 1994. The details of the MK method can be referenced from Hamed (2008) and Ahmad et al. (2015).

Furthermore, the runoff change (ΔR; mm) between different periods can be attributed as the sum of contribution of precipitation (P; mm), potential evaporation (ET0; mm), and all other factors (n) based on a Budyko-type (Budyko, 1974; Gan et al., 2021b) analytical model (Choudhury, 1999; Yang et al., 2008), as shown in Equation 6: [1 + (P / ET0)n]1/ n

Based on the elasticity method (Dooge et al., 1999), we estimated the contribution of factor x (e.g., P) to ΔR as the product of Δx (i.e., ΔP, ΔET0, and Δn) and the sensitivity coefficient of x to runoff (Eq. 7). We analytically determined the sensitivity coefficients of runoff to each variable based on the Budyko model, as shown in Equations 8-10.

JOURNAL OF ARID LAND 2026 Vol.

$\partial ET \quad \Delta R = \quad 1 - \Delta ET0 - \quad \Delta P -$

$\partial ET \; ET \quad ET0n \quad P \quad ET0n + P \; n$

$\partial ET0 \; ET0 \quad ET0 + P$

$\partial ET \; ET \quad \ln(ET0n + P \; n \;) \; ET0n \ln ET0 + P \; n \ln P \quad ET0n + P \; n$

where ∂ is the partial derivative; and ΔP, $\Delta ET0$, and Δn are the variations of P (mm), ET0 (mm), and all other factors, respectively. The contribution of Δn can be viewed as the overall impact of all possible factors other than decadal changes in precipitation and ET0, such as the change in the underlying surface due to human activities (Gan et al., 2022). If n increases with time, then the runoff/precipitation (R/P) ratio will decrease under a given precipitation condition and ET0.

In our study, we substituted precipitation with effective precipitation (Pe; mm), which is the sum of rainfall, snowfall, and net glacier melt, and we extended the usage of the Budyko model to further estimate the contributions of these three factors by taking the products of their corresponding changes between the two periods and their elastic coefficient, which is identical to that of Pe (Eqs. 8-10). In this study, ΔR was finally partitioned into the contribution of the changes in rainfall ($\Delta Rain$; mm), snowfall ($\Delta Snow$; mm), net glacier mass change (ΔIce; mm), ET0, and n, as in the following equation: $\partial ET \quad \partial ET \quad \partial ET \quad \Delta R = 1 - \Delta ET0 - \quad \Delta Rain + \quad 1 - \quad \Delta Snow + \quad 1 - \quad \Delta Ice -$

Results

Decadal changes in climate and streamflow in the BLB

The climate has substantially changed in the BLB over the past 65 a (from 1950 to 2014). The air temperature significantly ($P<0.01$) increased across the BLB at a rate of 0.01°C/a-0.03°C/a (Fig. 2 [FIGURE:2]). In contrast, precipitation exhibited no statistically significant trends in any of the sub-basins ($P>0.10$; Fig. 2). Concurrent with these climatic shifts, hydrological cycles in the BLB also changed substantially over the past 65 a. MK trend analysis revealed significant increasing trends in streamflow from 1950 to 2014 at the mid-stream (Dobyn) and upper-stream stations (Kashi and Tekes) of the Ili River. The increase rates were 2.34 m3/(s • a) at Dobyn ($P<0.01$), and 0.29 and 0.51 m3/(s • a) at Kashi ($P<0.10$) and Tekes ($P<0.10$), respectively (Fig. 3 [FIGURE:3]). Conversely, no significant long-term trends were detected at the downstream Ili River sites (Kapchagay and Ushjarma) ($P>0.10$); the streamflow at these stations declined during the 1960s—primarily due to the impoundment of the Kapchagay Reservoir—and recovered to the long-term average by the 2000s (Fig. 3a and b). Similarly, no significant trends were detected in the other four river basins (Fig. 3h-m).

Abrupt change points in runoff and precipitation time series were identified around 1982 in the Ili, Lepsy, and Aksu River basins (Fig. 3). Compared with the baseline period (from 1950 to 1982), runoff during the subsequent period (from 1983 to 2014) increased in most catchments (Table 2). For example, runoff at the Dobyn site (Ili River) increased by 30.3 mm, representing an 18.0% rise. Runoff increased by 5.4%, 1.3%, and 8.3% in the Karatal River (Ushtobe site), Aksu River (Chann site), and the Lepsy River (Lepsy site), respectively, while runoff in the Ayaguz River decreased by 10.5% (Table 2). All five rivers exhibited change points in runoff series from 1958 to 1961, which aligned with mutation points in the precipitation series (Fig. 3). In addition,

2 Annual air temperature (a–e), precipitation (f–j), and fs (the ratio of snow to precipitation; k–o) across five river basins in the Balkhash Lake Basin (BLB) from 1950 to 2014. The Z value is the trend of the Mann-Kendall (MK) test, and k is the slope in different periods. Different colors represent different periods determined by the MK test method. *, , and* represent the 0.10, 0.05, and 0.01 significant levels, respectively.

3 Annual runoff at the 13 sub-basins in the BLB from 1950 to 2014. (a), Ushjarma; (b), Kapchagay; (c), Dobyn; (d), Yamate; (e), Kashi; (f), Kunes; (g), Tekes; (h), Ushtobe; (i), Tekeli; (g), Chann; (k), Lepsy; (l), Lepsinsk; (m), Ayaguz; *, , and* represent the 0.10, 0.05, and 0.01 significance levels, respectively.

change points in runoff occurred later in the Lepsy River (1997), Karatal River and Aksu River (2002), and Ayaguz River (2005). These later shifts are potentially correlated with abrupt changes in Ta (around 2000) and fs (around 1990). Ta was generally higher and increased at faster rates

18 No. 4

runoff (R) from 1950 to 2014 River

Karatal Lepsy Ayaguz

Catchment

Rainfall (mm) Snowfall (mm) Glaciers* (mm)

ET0 (mm)

R (mm)

Ushjarma

Kapchagay

Dobyn

Yamate

Tekes

Kunes

Kashi

Tekeli

Ushtobe

Chann

Lepsy

Lepsinsk

Ayaguz

Note: Glaciers* denote the net glacier changes in water equivalent, averaged to the catchment scale.

after 2000 in four out of the five major river basins (except for the Ayaguz catchment) in the BLB (Fig. 2), which will accelerate glacier melt. fs decreased at higher rates for the rivers in the east, including their headwater sub-basins; for example, over the past 65 a, fs decreased by 6.3% and 6.9% in the upper Lepsy River (Lepsinsk catchment) and the Karatal River (Tekeli catchment), compared with the 2.0% (Tekes catchment), 4.0% (Kunes catchment), and 3.9% (Kashi catchment) decrease in the upper Ili River (data not shown).

Trends and shifts in seasonal and annual snow and ice dynamics

To compare the decadal changes in snow and ice dynamics in all sub-basins of the BLB, we first calibrated the DDFsnow and DDFice for each sub-basin. The optimized value of the DDF in each sub-basin was thus taken when r reached its maximum and bias in snow accumulation reached its minimum (Fig. 4 [FIGURE:4]). The calibrated DDFsnow ranged from 0.5 to 7.5 mm/(°C • d) in all sub-basins, and it was smaller in upper reaches and larger in the lower reaches (Fig. 4). Similarly, the DDFice for each sub-basin was determined by matching the estimated glacier ablation from 2000 to 2016 with that derived from the remote sensing dataset. The calibrated DDFice values varied from 1.1 to 2.8 mm/(°C • d) in all sub-basins, and they were more spatially homogeneous than the DDF values of the seasonal snow (Fig. 4).

With the DDF determined, the snow and ice models were run at daily scales from 1950 to 2021 using the calibrated DDF. Daily predictions were aggregated to monthly and annual scales. Figure 5 [FIGURE:5] shows the inter-annual variations in sublimation, snow melt, and ice melt in all 13 sub-basins in the BLB. Sublimation, including the sublimated water from the snow- and ice-covered areas, accounted for a large portion of snow and ice ablation water, about 30.0%–

37.0% in the upper reaches of the BLB, including the Tekes, Kunes, and Kashi sub-basins in the Ili River, and Tekeli, Chann, and Lepsinsk in the other four rivers (Fig. 5). This ratio was over 40.0% for the entire watershed for the five rivers in the BLB, especially in the Ayaguz River catchment (61.0%; Fig. 5). In comparison, snow melt accounted for 52.0%-62.0% of ablation water in all river basins in the BLB, except for in the Ayaguz River Basin. Despite the overall increase in precipitation, due to the decrease in fs, snow melt exhibited overall decreasing trends in all river basins in the BLB, at rates from 0.03 to 0.22 mm/a, except for the Tekes River Basin, where Ta increased at the slowest rate across the BLB. Additionally, snow melt decreased more slowly in the Ili River catchments than in the other four river basins (Fig. 5).

Although the glacierized area accounted for less than 5.0% of the total area of the BLB

4 Degree-day factor (DDF; a) for the snow and glaciers in all study catchments in the BLB. Figure b–g show the snow melt model performances with different DDF values. Figure b and c are the correlation coefficient (r) values during the calibration period, and d and e are the mean biases between the modeled snow water equivalent, which derived from the Sentinel measurements in the Ili River Basin (b and d) and the other river basins (c and e). The r values in Figure f (Ili River Basin) and Figure g (the other river basins) represent model performances from April to July.

5 Inter-annual variations in snow melt and ice melt at the 13 sub-basins in the BLB from 1950 to 2014. The ice melt includes the meltwater from snow that falls on the glaciers and meltwater from the glaciers themselves.

To make them comparable, we averaged all variables to the catchment scale. (a), Ushjarma; (b), Kapchagay; (c), Dobyn; (d), Yamate; (e), Tekes; (f), Kunes; (g), Kashi; (h), Tekeli; (i), Ushtobe; (g), Chann; (k), Lepsy; (l), Lepsinsk; (m), Ayaguz; (n), the pie chart shows the proportions of sublimation, snow melt, and ice melt in each hydrological station. *** represents the 0.01 significance level.

catchments, with a median value of 2.6% in all 13 sub-basins, meltwater from glacierized areas accounted for over 10.0% of ablation water from snow and ice (Fig. 5). This ratio would be much higher than 10.0% for many sub-basins if sublimation was excluded, which did not contribute to runoff. We found that the ratio of meltwater from the glacierized areas to the total amount of meltwater from both the glacierized and non-glacierized areas ranged from 0.0% to 26.8% in all 13 sub-basins, with a median of 14.3% (Kapchagay catchment) and higher than 25.0% in the Kashi and Tekes sub-basins in the upper Ili River. Such a result highlights the critical contribution of meltwater from the glacierized areas. In contrast, the Ayaguz River Basin has no glaciers, which is a possible cause for the decreased streamflow in the past 40 a under warming conditions.

The glaciers in the BLB have undergone overall negative changes since the 1950s (Fig. 6 [FIGURE:6]).

Mass balance modeling in this study showed that the glaciers were relatively stable in some of the headwater catchments in the Ili River Basin (Tekes) and the Aksu River Basin (Chann) before 1975 because air temperature was low in these two catchments. However, glaciers have lost mass in most of the catchments since 1951, and the rates of glacier loss have been accelerating (Fig. 6) as the climate warms. Net glacier melt, referring to the meltwater from the glaciers themselves (excluding the snowfall on the glaciers), provided equivalent excess flows of 10.65 m3/s in the Ili River and 0.86, 0.04, and 0.71 m3/s in the Karatal River (Ushtobe catchment), Aksu River (Chann catchment), and Lepsy River (Lepsy catchment), respectively, from 1950 to 1982. In contrast, the excess flows of glaciers increased from 1983 to 2014 to 12.62 m3/s in the Ili River and 0.92, 0.14, and 0.76 m3/s in the Karatal River (Ushtobe catchment), Aksu River (Chann catchment), and Lepsy River (Lepsy catchment), respectively. It is worth noting that such an accelerated melting rate of glaciers does not contradict the decreasing trend of the melting water supply from the glacierized areas from 1950 to 2021 in Figure 6. The result can be attributed to the fact that the meltwater volume in Figure 6 includes contributions from snowfall on glaciers, which has decreased under ongoing climate warming.

6 Modeled ice mass balances of glaciers and glacier areas at the sub-basins in the BLB from 1950 to 2021.

Glacier areas were derived from the study of Severskiy et al. (2016). (a), Ili River Basin; (b), other river basins.

Shaded areas represent 95% confidence intervals.

At seasonal scales, snow melt reaches its peak in April or May, and meltwater from glacierized areas reaches its peak in July or August; this meltwater serves as an essential water source for streamflow because seasonal snow from non-glacierized areas has usually been depleted by summer. When comparing the period from 1951 to 1982 to the period from 1983 to 2014 (Fig.

S1), it was found that seasonal snow melt underwent shifts. In the Ili River Basin, snow melt in

April and May was larger from 1983 to 2014 (Fig. S1b–e); in contrast, in the other four river basins, snow melt in spring and summer became smaller from 1983 to 2014 (Fig. S1j and n).

Relationships between decadal runoff changes and snow and ice dynamics

Compared with the period from 1951 to 1982, runoff from 1983 to 2014 increased in most of the sub-basins, except for the Ayaguz River Basin (Table 2). Meanwhile, in the latter period, snowfall decreased, and rainfall, glacier melt, and ET0 increased due to the warming climate (Table 2). The contributions of rainfall, snowfall, net glacier melt, ET0, and n to the decadal changes in the average streamflow were quantified using the elastic method with the Budyko equation. As shown in Figure 7a [FIGURE:7], the increase in rainfall played a dominant role in the rise in streamflow. In contrast, due to a decrease in fs and snow melt (Fig. 5), the changes in snowfall generally had negative impacts on streamflow, especially in the river basins in the east (Fig. 7). ET0 increased between the two periods (Table 2). Therefore, the drying effect of ET0 has led to a decrease in streamflow, as shown in Figure 7a. The net glacier melt from 1983 to 2014 increased compared with that from 1951 to 1982. Although the increase in net glacier melt was not the primary cause of the rise in streamflow in the BLB, it has generally counterbalanced the negative effect of the increasing ET0 (Fig. 7a). In contrast, without the buffering effects of glaciers, streamflow in the Ayaguz River Basin has been decreasing over the past 40 a under warming conditions.

We found that the most substantial negative impacts of decreasing snowfall occurred from 1995 to 2014, marked by abrupt decreases in fs (Fig. 7b–d). Meanwhile, our study showed that, due to the increase in air temperature, glaciers lost mass at higher rates in this period, especially in the Ili

7 Attribution of the contributions of five factors, i.e., rainfall, snowfall, glacier melt, PET (potential evaporation), and n, to the runoff change (ΔR) between different periods. (a), 1951-1982 vs. 1983-2014; (b), 1951-1962 vs. 1963-1983; (c), 1963-1983 vs. 1984-1994; (d), 1983-1994 vs. 1995-2014.

JOURNAL OF ARID LAND 2026 Vol.

18 No. 4

River Basin (Fig. 6). Therefore, the positive contribution of glacier loss was most significant in the period from 1995 to 2014 than in the other periods (Fig. 7d), even though the glacier area was much smaller in this period (Fig. 6). However, the increase in ET0 caused a considerable decrease in the streamflow in this period, which was much larger than the positive effect of net glacier melt.

In contrast, the atmospheric drying effect (ET0) favored streamflow before 1994 (Fig. 7b and c).

Compared with that in the period from 1951 to 1982, the impacts of n caused significant changes in runoff in the period from 1983 to 2014 (Fig. 7a). In general, the effects of n favored water yield in the Ili River Basin and exerted the opposite influence in the other four river basins.

In the Ili River Basin, the impacts of n were positive in most of the catchments, except for in the Kapchagay catchment, which was probably due to the construction of the Kapchagay Reservoir, whose volume (28.14 km3) was larger than the long-term annual runoff of the Ili River (22.87 km3). Additionally, the most substantial negative impacts of n occurred in the period from 1950 to 1983; the impacts of n were usually more significant in the lower reaches of the catchment (Fig. 7).

To further assess the influence of snow and glacier variations on runoff, we examined the correlation between the runoff coefficient (R/P) and indices representing snow and glacier fractions. Here, fs denotes the ratio of snow to total precipitation, while fs_{snow} melt refers to the fraction of snow melt water to total precipitation. Since snow ablation includes both melting and sublimation, fs is expected to be greater than fs_{snow} melt. At the decadal scale, catchments with higher fs or fs_{snow} melt generally exhibited a higher runoff coefficient (Fig. 8 [FIGURE:8]). The regression analysis indicated a strong positive correlation between fs_{snow} melt and R/P: for every 0.1 increase in fs_{snow} melt, R/P increased by 0.50 in the Ili River Basin (R2=0.77) and by 0.29 in the other four basins (R2=0.73) (Fig. 8b and e). Similarly, the parameter n was strongly correlated with both snow and glacier ratios. These results support the inference that greater snow melt contribution enhances streamflow. It is noteworthy that fs_{snow} melt was generally lower than fs, and fs_{snow} melt proved more effective than fs in explaining the spatial variability of R/P, given that sublimation

8 Relationship between runoff coefficient (runoff/precipitation (R/P)) and snow and ice amounts, represented by fs, the ratio of snow melt to precipitation (fs_{snow} melt), and the ratio of ice melt to precipitation (fs_{ice} melt). (a-c), sub-basins of the Ili River; (d-f), sub-basins of the Karatal, Aksu, Lepsy, and Ayaguz rivers. The black dots in b and e denote the regression lines between fs_{snow} melt and R/P in the Ili River Basin and the other four river basins, respectively.

does not contribute directly to runoff. R/P was positively correlated with fs_{ice} melt, which represents the ratio of ice melt to precipitation. In most upper catchments, such as the Kashi and Tekes catchments in the Ili River Basin, as well as the Chann and Lepsinsk sub-basins, R/P increased with fs_{ice} melt (Fig. 8c and f), indicating that, as the climate continues to warm, the runoff coefficient (R/P) may decrease as the glaciers deplete in the future.

Discussion

Impacts of snow and ice dynamics on runoff coefficient

Previous studies have reported that streamflow in all five rivers in the BLB showed decreasing trends from 1949 to 1986 (Kezer and Matsuyama, 2006), and, at a longer time scale, the streamflow in the middle stream of the Ili River increased from 1929 to 2014 (Thevs et al., 2017).

To obtain more profound insights into the hydrological responses of the BLB to climate change, long-term (from 1950 to 2014) runoff time series for 13 sub-basins in the BLB were constructed in this study. By comparing the period from 1983 to 2014 with the period from 1950 to 1982, we found that streamflow increased at all stations in the Ili River and the other four rivers in the east, except for the Ayaguz River. The increases in rainfall and meltwater from glaciers play a critical role in maintaining annual streamflow.

Snow and ice dynamics may profoundly impact the variations in R and R/P. Our analysis is based on the underlying assumption that rainfall, snowfall, and net glacier melt have equal strengths in runoff generation. However, the strengths of these three factors may differ. Changes in snowfall can impact runoff in many ways. Firstly, they affect the total amount of precipitation and, therefore, runoff generation. The results showed that changes in snowfall generally have negative impacts on streamflow (Fig. 7). Secondly, changes in snowfall induce changes in the fs, which will further alter the partitioning of precipitation into runoff and ET under given P and ET0.

The intrinsic mechanism underlying the significant correlation between fs and R/P can be explained from the perspectives of energy and water balance. From an energy perspective, a decrease in fs indicates a reduction in the proportion of snowfall relative to rainfall, leading to a decline in surface albedo. Snow exhibits a significantly higher reflectance of solar shortwave radiation compared with the other surface types, such as soil and vegetation. The reduction in reflected radiation increases the net radiation absorbed by the surface, thereby enhancing the available energy. This additional energy primarily drives the enhancement of ET processes, suppressing runoff generation. From a water pathway perspective, under high fs conditions, snow accumulated during winter melts rapidly and concentratedly in spring, resulting in a high runoff generation rate that favors surface runoff formation. In contrast, under low fs conditions, reduced snowpack leads to a slower and more prolonged melt process, allowing meltwater more time to infiltrate into the soil or evaporate, thereby reducing surface runoff (Berghuijs et al., 2014; Liu and Yang, 2021).

The results showed that both fs and fs_{ice} melt were positively correlated with runoff coefficient, indicating that the decrease in snowfall (snow melt) would have a more significant negative impact and the increase in glacier melt would have a more significant positive effect (Table 2). As the climate warms, an increase in air temperature is anticipated to induce a shift in precipitation from snow to rain, leading to downward shifts in both the multi-year R and runoff coefficient.

Additionally, water stress may become more severe, as glacier depletion in the future would negatively impact both R and R/P.

Apart from the impacts of the multi-year averaged fs, fs_{snow} melt, and fs_{ice} melt, the seasonality of snow melt and ice melt is also expected to impact seasonal and annual streamflow. For example, summer runoff has decreased in the Syr Darya watershed due to earlier snowmelt as the climate warms (Siegfried et al., 2012). In comparison, although snow melt generally showed a decreasing trend from 1951 to 2014, at the seasonal scale, snow melt during April–June was more significant in the period from 1983 to 2014 than in the period from 1951 to 1982 in the Ili River, as shown in

the Dobyn and Yamate catchments (Fig. S1c–d). Correspondingly, R/P in these two catchments also increased between the two periods. Similarly, R/P in the Ushtobe catchments decreased as the April–June snow melt decreased, indicating that the snow melt in the melting season plays a vital role in the annual runoff coefficient and, therefore, the water yield of a catchment. In short, although the overall runoff of the BLB has increased in recent decades due to the increase in P, the changes in the cryosphere have put enormous pressure on water resources. The degradation of glaciers and the decrease in fs negatively affect runoff and the runoff coefficient, especially in the eastern river basins, with fewer glaciers and more significant climate warming.

Accuracy and uncertainty analysis

This study used multiple datasets and methods to analyze the climate impacts on water balance changes in the BLB. Their suitability and uncertainty are examined in this section. This study leveraged the ERA5-Land dataset to characterize climatic drivers within the BLB. Our derived multi-year mean air temperature (6.75°C) and precipitation (342.2 mm) from 1950 to 2021 align closely with the values (6.70°C and 320.0 mm from 1936 to 2011) reported by Xu et al. (2017).

To rigorously evaluate the performance of the glacier melt model, we compared its output against the long-term record of the Tuyuksu Glacier, a benchmark in Central Asia. Our estimate of a cumulative mass balance of -22.1 m w.e. (-0.38 m w.e./a) from 1958 to 2016 shows excellent agreement with the measurement of -23.6 m w.e. by Kapitsa et al. (2020) and their geodetic estimate of -21.8 ($±2.6)mw.e.Theclosesconvergenceofthesevaluesderivedfromindependentmethods(modeling, directmeasure
decadaltimescales.Similarly, weestimatedtheablationprocessofsnowaftercalibratingthedegree−
daymodelwiththeremotelysensed1km−resolutionsnowdepthvariabilitydatafromtheSARmeasurementsofth
1satellitesfromSeptember2016toApril2019(Lievensetal., 2019).AninappropriatelylowDDFvalueleadstoafail
d)intheKashicatchmentintroducedabiasofnearly20.0mminsummersnowaccumulation.Conversely, anexces
0.18m; meanbias : −0.01m(Lievensetal., 2019))anddensity(0.15kg/m^{3}$) yielded a standard deviation of 27.0 mm. According to Severskiy et al. (2016), glaciers in the BLB consistently shrank from 1958 to 2008, dominated by climate warming, with long-term area uncertainties partly due to early data limitations (e.g., aerial survey errors of 5.0%-7.0% in the 1950s). Based on the aforementioned uncertainty ranges, we conducted an uncertainty analysis

on the simulation results of dynamic snow and ice processes. We found that although a relatively high level of uncertainty was set at the pixel scale, due to the cancellation effect when analyzing at the watershed scale, the uncertainty in the snow and ice melt processes at the watershed level is not significant, as shown in Figure 5. The uncertainty in the upper reaches of the watershed is higher than that in the lower reaches. For the net glacier ablation, the accumulation of uncertainties leads to a wider range of variation in ice mass balance, but it does not alter the overall trend of the curve (Fig. 6). It should be noted that the aforementioned uncertainty primarily refers to random error, which will be significantly reduced after integration at the watershed scale (the rate of decrease is inversely proportional to the square root of the number of pixels). Systematic error,

however, will not diminish as the number of pixels increases. Given that the mean bias of the remote sensing data of snow and ice we adopted is reportedly low, this error is consequently expected to be minor.

With actual ET determined using a complementary relationship ET model (Brutsaert, 2015; Gan et al., 2021a), which performs reasonably well in ET estimation from wet to dry conditions (Gan et al., 2019b) and in the cold and arid areas of the Tianshan Mountains (Gan et al., 2022), we found that although water cycle components (P, ET, and R) were derived/estimated from different data sources and methods, the water balance was generally closed at the decadal scale in both the Ili River and the other four basins, except for at the Ushjarma station in the downstream of the Ili River. The residue of the water balance, P–ET–R, was equivalent to 7.3% and 6.6% of P for the upstream/midstream catchments of the Ili River Basin and the catchments of the other four river basins, respectively, which is reasonable compared with the observational errors in P and streamflow measurements (Potter et al., 2005). We further used the machine-learning-reconstructed terrestrial water storage (GTWS-MLrec) (Yin et al., 2023) and global-scale groundwater model (GLOBGM) (Verkaik et al., 2024) datasets to explore long-term groundwater dynamics and their interplay with regional water cycling in the BLB (Fig. S2). The analysis reveals a consistent increase in total water storage since the 1950s, which—against the cryospheric loss due to warming—suggests a substantial contribution from groundwater and soil moisture. This result is corroborated by GLOBGM' s simulations, indicating a rise in groundwater storage across major sub-basins from 1958 to 2014. The primary driver of this accumulation is the increased P, which has enhanced runoff more strongly than ET. As a terminal basin, Balkhash' s water export relies solely on ET; thus, the positive P-ET balance explains the net storage gain. Groundwater interactions significantly modulate the basin' s hydrology. The shift in runoff trend around 1983, while P-dominated, also coincides with groundwater rebound. Increased storage supports baseflow and runoff sustainability, and partly counteracts the declining runoff coefficient caused by reduced snow fraction.

Conclusions

Analysis of reconstructed runoff from 1950 to 2014 in the five major rivers of the BLB revealed a shift from stable or declining runoff in the period from 1950 to 1982 to increased flows in the period from 1983 to 2014 in all basins except the Ayaguz River. Increased P was the dominant driver, while enhanced glacier melt largely offset runoff losses from atmospheric drying under rising temperatures. The Ili River Basin showed the highest runoff increase, supported by greater net glacier melt and smaller reductions in snow fraction. Conversely, rivers in the east exhibited smaller runoff gains—or even declines—along with greater snowpack reductions, and lower glacial contributions. Since the 1990s, despite P remaining the primary driver of runoff increases, sharp declines in snow fraction and snow melt have imposed significant negative impacts.

Meanwhile, increased ET0 from warming caused substantial streamflow reductions that exceeded the positive contribution from glacier melt, highlighting serious challenges for water resource management in the BLB with intensified atmospheric drying and loss of glacial buffer capacity.

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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JOURNAL OF ARID LAND 2026 Vol.

18 No. 4

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Figure 52

Figure 1: Figure 52

Figure 57

Figure 2: Figure 57

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GAN Guojing et al.: Modeling decadal snow and ice dynamics and their hydrological···

Appendix

Fig. S1 Monthly snow melt and ice melt at the 13 sub-basins in the Balkhash Lake Basin (BLB). (a), Ushjarma; (b), Kapchagay; (c), Dobyn; (d), Yamate; (e), Tekes; (f), Kunes; (g), Kashi; (h), Tekeli; (i), Ushtobe; (j), Chann; (k), Lepsy; (l), Lepsinsk; (m), Ayaguz. The curves represent the median values of snow melt and ice melt at a specific month within a certain period (i.e., 1951-1982 and 1983-2014). Bar represents standard deviation.

Fig. S2 Annual anomalies of water cycle components, including precipitation (P), evapotranspiration (ET), runoff (R), groundwater (Globgm), and terrestrial water storage (TWSA-CSR) in all five river basins in the BLB. (a), Ili River Basin; (b), Karatal River Basin; (c), Aksu River Basin; (d), Lepsy River Basin; (e), Ayaguz River Basin.

Figure 62

Figure 3: Figure 62

Figure 66

Figure 4: Figure 66

Figures

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