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Climate change and water security in the northern slope of the Tianshan Mountains

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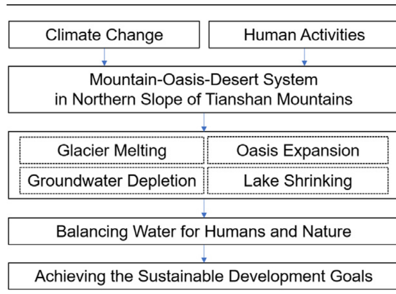
HIGHLIGHTS

- Water security is under threat on the northern slope of the Tianshan Mountains.
- Climate change and economic growth are responsible for increased water stress.
- Balancing water for humans and nature is vital in achieving SDGs.

GRAPHICAL ABSTRACT



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ABSTRACT

Water security is under threat worldwide from climate change. A warming climate would accelerate evaporation and cryosphere melting, leading to reduced water availability and unpredictable water supply. However, the water crisis in the Northern Slope of Tianshan Mountains (NSTM) faces dual challenges because water demands for fast-growing urban areas have put heavy pressure on water resources. The mountain-oasis-desert system features glacier-fed rivers that sustain intensive water use in the oasis and end in the desert as fragile terminal lakes. The complex balance between water conservation and economic development is subtle. This paper investigates changes in hydroclimatic variables and water security-related issues on the NSTM. The spatiotemporal variations in glaciers, climatic variables, rivers, lakes and reservoirs, groundwater, surface water, human water use, and streamflow were analyzed for the past four decades. The results show that temperature in the NSTM exhibited an apparent upward trend with a more significant warming rate in the higher altitude regions. Glacier mass loss and shrinkage was strong. The average annual streamflow increased from 1980-1989 to 2006–2011 at most hydrological stations. The monthly dynamics of surface water area showed notable variability at both inter-

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annual and seasonal scales, revealing the impacts of both natural and anthropogenic drivers on surface water availability in the region. The terrestrial water storage anomaly showed a decreasing trend, which might be related to groundwater pumping for irrigation. Human water use for agriculture and industry grew with the increase in cultivated land area and gross domestic product (GDP). The increased agricultural water use was strongly associated with the expansion of oases. It is unclear whether water availability would remain high under future climatic and hydrological uncertainties, posing challenges to water management. In the context of rapid urban growth and climate change, balancing water for humans and nature is vital in achieving the Sustainable Development Goals (SDGs) in NSTM. This study provides a baseline understanding of the interplay among water, climate change, and socio-economic development in NSTM. It would also shed light on wise water management under environmental changes for other rapidly developing mountain-oasis-desert systems worldwide.

1. Introduction

In the context of socioeconomic, human health, and environmental needs, water scarcity appears in specific regions or times when human water demand may exceed water availability (Gleick and Cooley, 2021). Water scarcity is strongly related to climate change, i.e., anthropogenic or natural changes in temperature, precipitation, solar radiation, humidity, etc., which directly or indirectly affect water availability. Water scarcity would aggravate future climate change in some regions (Schewe et al., 2014), which may significantly impede regional development and achievement of the sustainable development goals (SDGs) (United Nations, 2022). Thus, understanding water scarcity and climate change are necessary for sustainable water management towards better socioeconomic development.

The Northern Slope of the Tianshan Mountains (NSTM) is a vital region linking China and Central Asian countries along the "Belt and Road". The gross domestic product (GDP) in the NSTM represented 62.2% of Xinjiang's GDP (Fang et al., 2019). Two scientific expeditions were conducted in Xinjiang in the 20th century to investigate natural resources such as water, land, and vegetation and their capacity for supporting regional development (Zhou and Shi, 1986). The NSTM has undergone increasing socioeconomic development during the past decades, which has brought significant pressure on water resources in this region (Fang et al., 2019). Meanwhile, climate change has also considerably impacted water resources in the region (Zhang et al., 2009; Xu et al., 2010). Increased water consumption induced by the continual expansion of agriculture and industry (WRDXJ, 2020) further aggravated water shortages. It has led to water security issues that restrict socioeconomic development and impair ecosystem service functions in the NSTM (Chen et al., 2005).

Climate change is a key factor in the changes in regional water scarcity conditions (Gosling and Arnell, 2016; Liu et al., 2019). Climate change-induced changes in the hydrological cycle and increases in water demand are projected to exacerbate water scarcity in many regions of the world (Tang, 2020; Liu et al., 2022). The total area of the glaciers in the Tianshan Mountains has decreased by 11.5% from 1960 to 2011 (Wang et al., 2011), and the loss rate of most glaciers has accelerated since the 1970s (Liu and Liu, 2016). Climate change and regional human activities have significantly impacted the permafrost (Waller et al., 2012; Schuur et al., 2015). Previous studies have found that the permafrost in the headwaters of the Urumqi River was increasingly degraded. Specifically, the thickness of the permafrost active layer is increasing (Wang et al., 2017).

Socioeconomic development often causes a dramatic rise in water demand and thus is an essential driver of the increasing water scarcity in many regions of the world (Hanasaki et al., 2013; Haddeland et al., 2014; Veldkamp et al., 2017). It can contribute to water scarcity more than climate change in some regions (Reynard et al., 2014). Socioeconomic development in recent decades has placed significant pressure on Xinjiang's water resources. The water resource exploitation rate was 65.9% in Xinjiang, which is higher than the internationally recognized warning level of 40% (Han and Jia, 2022). With the most rapid economic development and urbanization in Xinjiang, the NSTM experienced a rapid expansion in the urban area, agriculture, and industry, which led to a sharp increase in water demand from all sectors and a widening gap between available water resources and water demand (Yang et al., 2012; H. Deng et al., 2015). During the past two decades, total water use in the NSTM has increased by nearly 15% (WRDXJ, 2020). The exploitation of groundwater resources and disproportionally high water consumption for agricultural production could lead to a high risk associated with water scarcity on the NSTM in the context of global climate change (Shang et al., 2016). With the current water use efficiency, the available water resources may not be able to support NSTM's sustained economic development (Dai et al., 2017).

Hydroclimate changes bring new challenges and uncertainty to the use of water resources in the NSTM, given that the impacts of such changes on water scarcity and socioeconomic development are not well understood. Although previous studies have analyzed changes in a single or limited number of hydroclimatic variables in the NSTM, few have examined all of the significant hydroclimatic variables and water security-related factors. This paper presents a comprehensive analysis of the changes in hydroclimatic variables in the NSTM over the past four decades and provides a larger picture of water security conditions for sustainable development in the context of climate change. This is expected to provide helpful information to SDG 6.4 concerning alleviating water scarcity and improving the sustainability of regional development.

2. Materials and methods

2.1. Study area

The northern slope of the Tianshan Mountains is situated between 42°36′N–47°60′N and 79°42′E–96°36′E, with an area of more than 90,000 km^2 (Fig. 1(a)). It is an elongated area along the Tianshan Mountains and encompasses eight cities and regions, including Hami, Urumqi, Changji, Shihezi, Kuitun, Karamay, and Tarbagatay Prefecture and Bortala Mongol Autonomous Prefecture.

The topography of this region is complex (Fig. 1(a)). The maximum elevation is 5,231 m, and the minimum elevation is 159 m. The height increases from the north to the south, with the high elevation mountainous area accounting for only 19% of the area, while the low elevation hills and plains cover 73% of the NSTM. The grassland was the largest land use type in the NSTM, accounting for about 46% of the total area (Fig. 1(b)).

2.2. Data sources

Land use and daily meteorological datasets (including temperature and precipitation) were downloaded from the Resource and Environment Data Cloud platform of the Chinese Academy of Sciences (http://www.resdc.cn). The spatial resolution of land use data was 1 km, and the map scale of soil types was 1:100,000. The change in cultivated land area in the past 40 years was analyzed by combining land use data from the *Xinjiang Statistical Yearbook*. Changes in agricultural water use from 1980 to 2020 were derived from the Xinjiang Water Resources

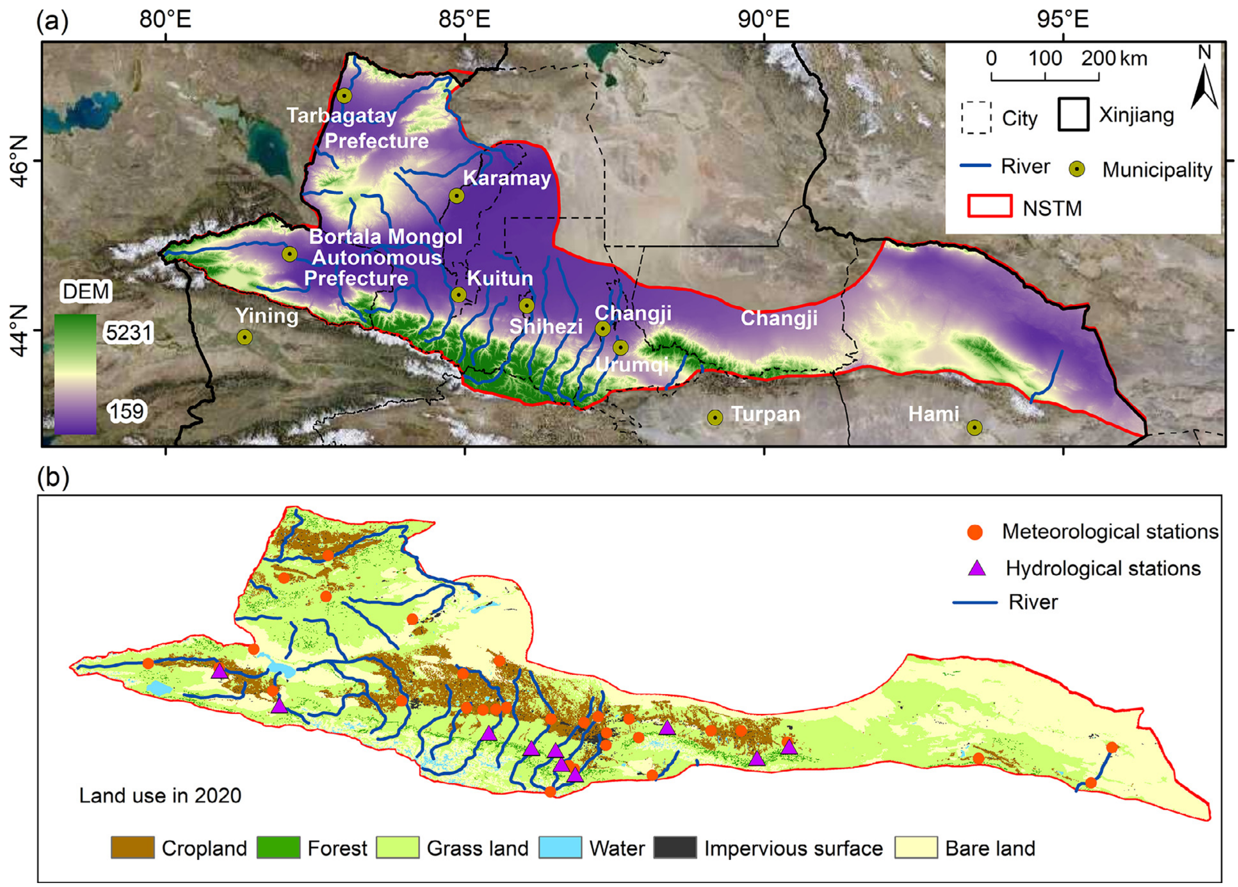

Fig. 1. Northern slope of the Tianshan Mountains (NSTM) (a) altitude, rivers, and cities; (b) land use, meteorological stations, and hydrological stations.

Bulletin. Industrial water use from 2007 to 2020 was obtained from the Xinjiang Bureau of Statistics (XBS) (XBS, 2022).

Temperature and precipitation observations are daily datasets derived from national surface meteorological stations during 1990–2020, provided by the Resource and Environment Science and Data Center, Chinese Academy of Sciences (available at https://www.resdc.cn/data.aspx?DATAID=282). Observations from 31 meteorological stations in NSTM (Fig. 1) were selected to evaluate the climate change in the study area.

The glacier data used in this study includes continuous *in-situ* observations or short field survey data of individual glaciers, multi-source remote sensing images, topographic maps, the first and second Chinese Glacier Inventory, and the published literature (Wang et al., 2014; P. Wang et al., 2016; P. Wang et al., 2020; C. Xu et al., 2019). The field survey data of individual glaciers provide a reliable basis for studying glacier changes despite their short observation duration. All monitoring and survey data of glaciers are from investigations conducted by the Tianshan Glaciological Station, including the location of the glacier boundaries, mass balance, ice thickness, surface velocity, ice temperature, and streamflow. The glacier change can be determined by comparing current glacier data with previous studies (Li et al., 2020; Wang et al., 2014; P. Wang et al., 2016).

The 0.5°×0.5° long-term terrestrial water storage data reconstructed by Li et al. (2021) was used to analyze the trends in terrestrial water storage anomalies in the study area from March 1990 to February 2020. The list of reservoirs was adopted from Deng (2020). Locations and capacities were collected from the local hydrology bureau. Observed monthly streamflow data from ten hydrological stations (Fig. 1) in the NSTM were obtained from the *Xinjiang Hydrological Yearbook*. The data cover the periods of 1980–1989 and 2006–2011. It should be noted that the streamflow data during 1990–2005 and after 2012 are unavailable.

2.3. Methods

Statistical analysis approaches were applied to most hydroclimatic variables to examine spatiotemporal changes. Specifically, climatic tendencies of the temperature and precipitation at each station in the past 30 years were calculated by the least squares method to represent the temporal and spatial characteristics of their annual variations during 1990–2020. Multi-year mean streamflow at each station was calculated and compared for the two periods. The mean seasonal streamflow was examined by calculating the mean monthly streamflow and comparing the difference between the two periods.

The long-term changes in the area of lakes and reservoirs were quantified using high-resolution (10–30 m) satellite imageries. Specifically, Zhao and Gao (2018) developed the method to retrieve changes in surface water extent, including rivers and lakes on the northern slope of the Tianshan Mountains, from 1990 to 2020. Such a method leveraged the widely used Global Surface Water Database (GSWD; Pekel et al., 2016), which applied a supervised classifier on millions of Landsat images to obtain the global monthly water area for the past three decades. However, the accuracy of the monthly water classification images from GSWD is compromised by contamination of Landsat imagery from multiple sources, including cloud, cloud shadow, terrain shadow, and sensor errors. Based on satellite-derived altimetry information, the method developed by Zhao and Gao (2018) repairs the contaminated water areas allowing high-quality area estimations. Furthermore, to derive a continuous monthly time series of water area, the gaps in the area time series for rivers and lakes (caused by partial coverage of GSWD) were filled in using linear interpolation.

Regional water scarcity is often determined by the status of water availability and demand during a specific time. Water availability is affected by several hydroclimatic components and some water projects

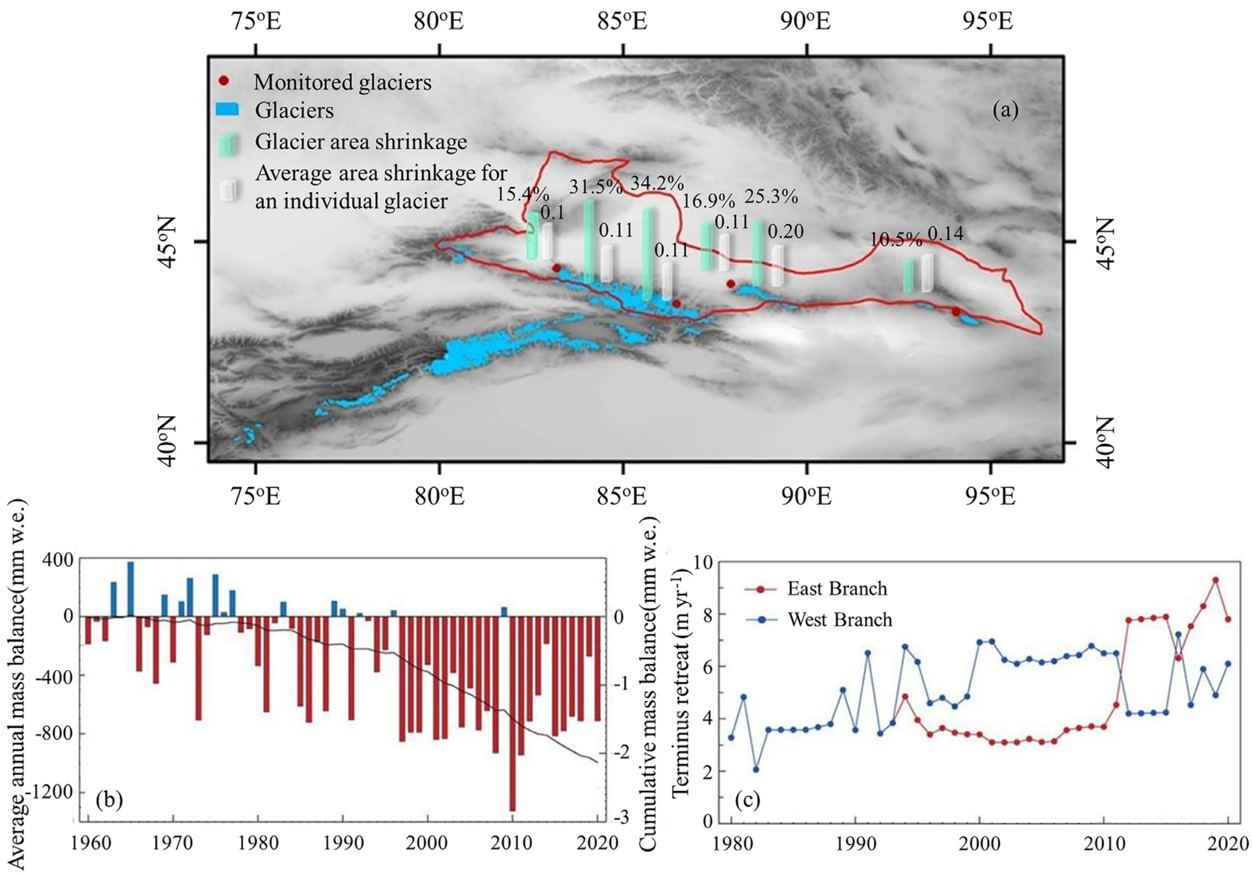

Fig. 2. (a) Spatial changes of glaciers in the Chinese Tianshan Mountains over the past 40 years; (b) annual mass balance changes from 1960 to 2020 in Urumqi Glacier No. 1 (UG1); (c) terminus changes from 1980 to 2020 of UG1. w.e. means water equivalent.

on the NSTM. The variations of hydroclimatic features determine the upper boundary of the water stock and flow on which human demand depends. The water stock could be adjusted by the water projects such as reservoirs to make the water use more efficient and mitigate the impacts of flood and drought on humans and croplands. In this study, we show the changes in each hydroclimatic component and water use to better understand the water security issue in this region.

3. Results

3.1. Glaciers

According to the Second Chinese Glacier Inventory, in the Chinese Tianshan Mountains, there were 7,934 glaciers covering an area of 7,179.77 km^2 in 2008, that accounted for 16.3% of the total number and 13.9% of the total area of glaciers in China. The ice volume was approximately 707.95 km^3 which was equivalent to about $6{,}808 \times 10^8$ m^3. However, in the NSTM, there were only 3,069 glaciers with a total area of 1,635.60 km^2. It is estimated that the annual runoff of glacier meltwater in this region was about 16.9×10^8 m^3, accounting for about 13.5% of the total runoff in the region. Many large glaciers with areas larger than 5 km^2 were distributed in the Manas, Khorgos, and Anjihai Rivers, with the glacial melt water accounting for 35%–53% of the river runoff.

By comparing high-resolution remote sensing images with topographic maps, the total area of 1,543 selected glaciers in the Chinese Tianshan Mountains was estimated to have shrunk by 11.4%, with an average value of 0.22 km^2 for an individual glacier over the past 40 years (Fig. 2(a)). The reduction rate in glacier areas varied from 8.8% to 34.2% in different regions, with the average shrinkage of an individual glacier ranging from 0.10 to 0.42 km^2. The average terminus retreat rate went from 3.5 to 7.0 m yr^{-1}. From 2010 to 2018, the glacier area shrinkage was approximately 1.4%, and the volume loss was 5.1%.

The average annual mass balance of the Urumqi Glacier No. 1 at the headwaters of the Urumqi River (UG1) was −350 mm yr^{-1} from 1960 to 2020 (Fig. 2(b)), showing an accelerated melting trend, which is consistent with the overall changes of global reference glaciers with the rate of −440 mm yr^{-1} (Zemp et al., 2019). Due to the intense ablation in 1993, the glacier separated into the East and West branches. From 1994 to 2020, their retreat rates were 5.0 m yr^{-1} and 5.7 m yr^{-1}, respectively (Fig. 2(c)).

3.2. Climatic variables

Based on the observed data from 31 meteorological stations, the annual average air temperature in the study area was 0.7 °C from 1991 to 2020, and the average temperature in summer and winter was 22.4 °C and −11.2 °C, respectively. The climate was colder in the middle region and warmer in the east and west regions (Fig. 3), which was affected by the latitude, altitude, and topography. The annual average temperature in Tianchi station was the lowest (2.5 °C), and that in Naomao Lake station was the highest (11.5 °C). In the past 30 years, 25 stations had a significant warming trend ($P < 0.1$), and the Shisanjianfang station had the fastest warming rate (1.2 °C/10yr). Moreover, the Changji station was the only station that showed a cooling trend, although this was non-significant ($P > 0.1$) (Fig. 3). The temperature rise on the NSTM is more significant than in some southern regions of Tianshan Mountain, e.g., the Kaidu River basin showed 1.82 °C/50yr (X. Deng et al., 2015).

The annual average precipitation in the study area from 1991 to 2020 was 233 mm. The climate was wetter in the middle region and the driest in the east region. The minimum and maximum annual precipi-

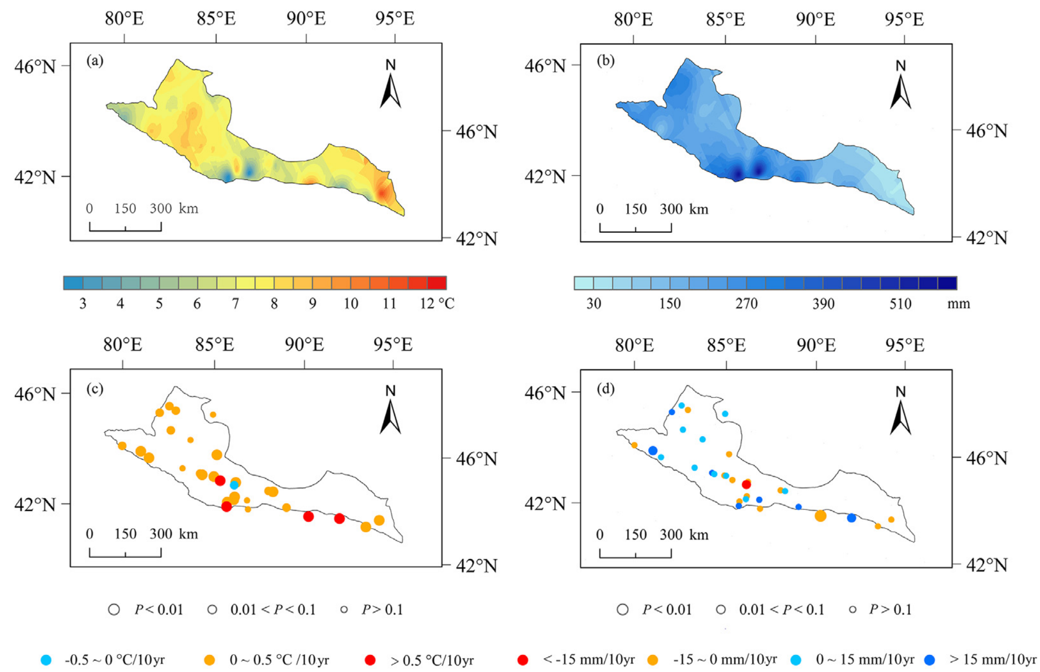

Fig. 3. Spatial distributions of annual temperature and precipitation means from 1991 to 2020. (a) and (c) indicate the characteristics of temperature; (b) and (d) indicate those of precipitation.

tation were at the Naomao lake station with 24.8 mm and the Tianchi station with 572 mm, respectively. The Shisanjianfang and Changji stations had significant drying trends of 7.9 mm/10yr and 18.7 mm/10yr ($P < 0.1$), respectively. The Barkol and Bole stations exhibited significant wetting trends with 21.9 mm/10yr and 22.2 mm/10yr ($P < 0.1$), respectively. However, there were no significant trends at the other 27 stations. This is consistent with a previous study that showed no considerable precipitation trends at most stations (Xu et al., 2018). In addition, precipitation in the NSTM mainly occurs in spring (65.4 mm) and summer (93.2 mm), which accounts for 68% of the average annual precipitation. Meanwhile, the average precipitation in the autumn and winter is 47.4 mm and 26.8 mm, respectively, which accounts for 32% of the average annual precipitation.

3.3. Rivers, lakes and reservoirs

Water body (including lakes and reservoirs) surface areas showed an increasing trend with a rate of 12 km^2 yr^{-1} from 1990 to 2020 in the NSTM. The long-term transition of the surface water extent had shown a large spatial heterogeneity (Fig. 4(a)). The three largest lakes (i.e., Sayram, Ebinur, and Manas Lakes) accounted for 50% of all surface water over the past 30 years. By contrast, the rivers and lakes in the Eastern River and the Bayi Basins (Fig. 4) accounted for only 6% of total surface water, although these two basins covered 31% of the study region. From 1990 to 2020, surface water extent showed large variability at inter-annual and seasonal scales (Fig. 4(b)–(g)).

There are 22 reservoirs ranked as large and medium-sized reservoirs in the NSTM (Fig. 5). Most of these reservoirs were constructed in the middle part of the NSTM, including the Hutubi, Manasi, Santunhe, and Urumqi Rivers. The total capacity of reservoirs in the NSTM has risen gradually, reaching 13.17×10^7 m^3 in 2022 (see the inset in Fig. 8). Reservoirs under construction were not included, i.e., Jiergelede Reservoir (with a storage capacity of 6.11×10^7 m^3) and Louzhuangzi Reservoir (with a storage capacity of 7.37×10^7 m^3).

However, reservoir silting had not been considered in reservoir operation. A reasonable estimation of available reservoir capacity after siltation for all reservoirs would benefit reservoir operation and irrigation management in the NSTM. China's annual average reservoir siltation rate (annual average siltation of reservoirs over the total reservoir capacity) reached 2.3% (Jiang, 1997). Moreover, reservoir silting in semi-arid areas was much more severe, and almost one-third of reservoir capacity had been deposited by sediment in reservoirs in Xijiang. The Kensiwate and Toutun Reservoirs are good examples of the influences of sedimentation. The Kensiwate Reservoir is located on the Manasi River, which is a mountain stream with an erosion modulus of 726.1 t/km^2 (Gao, 2016). The annual runoff was 12.21×10^8 m^3, while the annual transportation of suspended sediment load and bedload were 3.27×10^6 t and 4.5×10^5 t, respectively (Gao 2016). Thus, sediment silted in the Kensiwate Reservoir was 7.08×10^6 m^3 yr^{-1} (Table 1). The Toutun Reservoir was located on the Toutun River, and sediment silted in the reservoir was approximately 6.42×10^6 m^3 yr^{-1} (Table 1).

3.4. Terrestrial water storage and groundwater

Several studies have reported groundwater depletion. In Changji City, the water table has decreased by 2 m to 6 m from 2010 to 2019, while in some parts of Shihezi City and Manus and Hutubi Counties, the water table has decreased by more than 5 m from 2016 to 2020 (Xue and Guo, 2021; Ding et al., 2022). The terrestrial water storage anomaly (TWSA) can also partly indicate groundwater changes in plains where precipitation does not show significant trends. TWSA shows a significant decreasing trend in the NSTM (Fig. 6), one of China's three most declining regions (Deng et al., 2021). The decreasing rate in the Ebinur Lake Basin and its sub-river basin in the middle is the highest. The same trend was found in the study of Deng et al. (2021), which used the latest RL 06 mason Gravity Recovery and Climate Experiment (GRACE)-derived gridded monthly global water height anomalies from April 2002 to March 2020 from both the Center for Space Research (CSR) and Jet Propulsion Laboratory (JPL).

From south to north, documented data (L. Wang et al., 2021) collected from the Manas catchment in the middle of NSTM show that the hydraulic head of groundwater displays a prominent decreasing trend moving from piedmont plains, oasis plains, oasis-desert transition zones, and finally to deserts, following the topography. However, the amplitude of the seasonal change during the observation period from 2010 to 2014 in the oasis plain and the oasis-desert transition zone is much

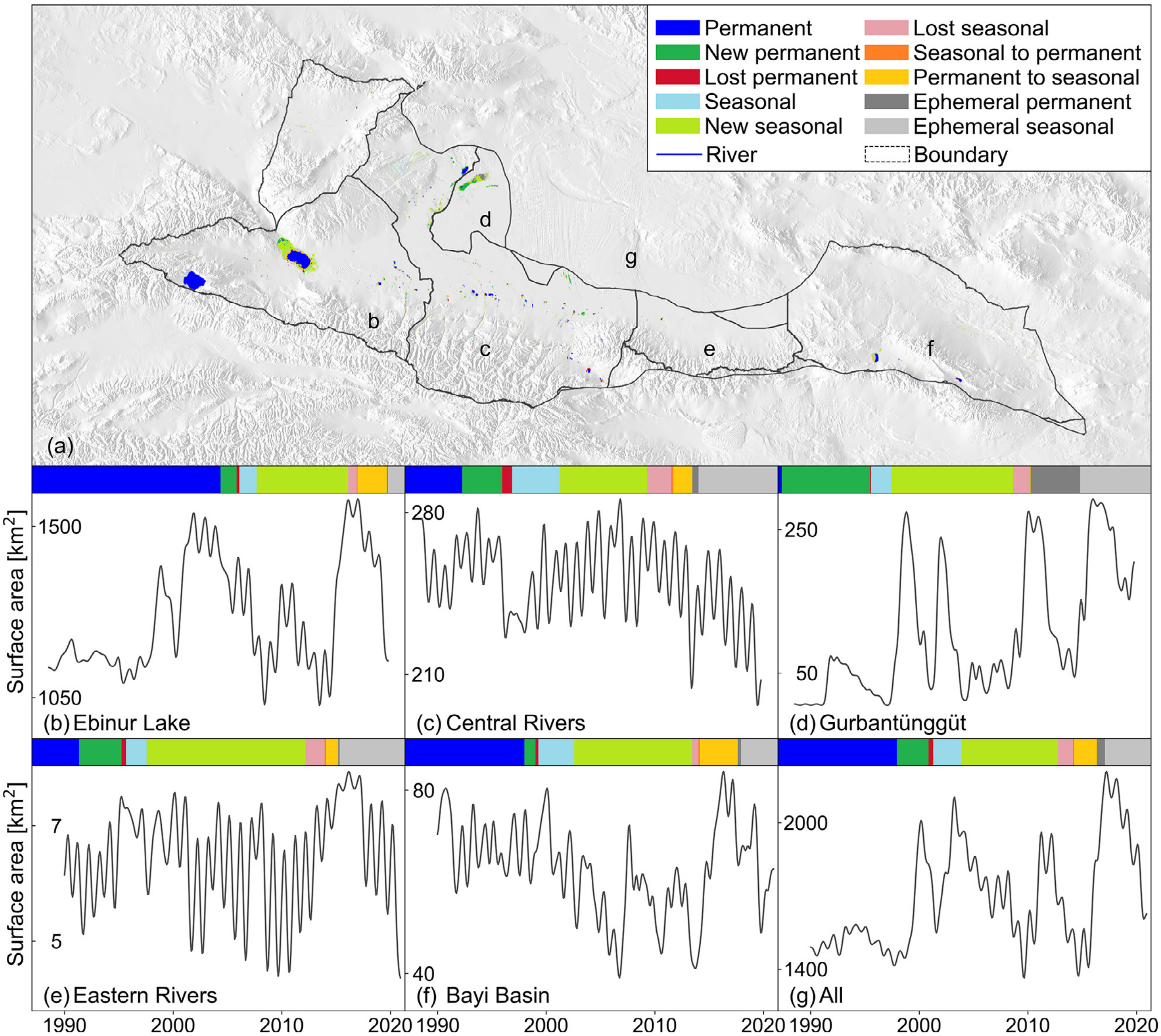

Fig. 4. Long-term transition of surface water extent and monthly dynamics for the major river basins. (a) Transitions in surface water between 1990 and 2020; (b–f) Monthly water body surface area dynamics for each river basin; (g) Monthly water body surface area dynamics for the entire study area. The transition categories are defined following Pekel et al. (2016).

higher than that in the piedmont plain, reflecting the active agricultural irrigation regime in the latter region. The highest amplitude is from the desert foothills of the Tianshan mountains, i.e., the oasis-desert transition, or the transition from cropland to bare land in Fig. 1, where the groundwater was pumped from the intermediate aquifers. Generally, the changes in the hydraulic head of the groundwater in wells located in the intermediate aquifer are larger than the changes in the deep and shallow groundwater, indicating that there is heavier use of the intermediate aquifer. From the investigation in this basin, human activity may have produced non-negligible influences on the terrestrial water resources, including groundwater. However, further study and more data are needed for the whole area.

3.5. Water use by industry and agriculture

In the past 40 years, the cultivated land area in the study area increased continuously, increasing from 9.3% in 1980 to 13.4% in 2020, with an increase of 9,182 km^2 (Fig. 7(a)). The growth rate from 2010 to 2020 was the fastest, with a rise of 27.4%, which was higher than the sum of the growth rates for the 30 years from 1980 to 2010. The total agricultural water consumption first increased and then decreased, showing an overall increasing trend. After 2010, agricultural water consumption increased by 59.29×10^8 m^3 compared with 2010 (an increase of 38.7%), the essence of which was that the arable land area increased significantly after 2010.

Table 1
Typical reservoir siltation on the northern slope of the Tianshan Mountains.

Name	Period	Preliminary Capacity (10^8 m^3)	Capacity after deposition (10^8 m^3)	Silted Sediment (10^8 m^3)	Ratio (%)
Kensiwate Reservoir	2010–2020	1.1013	1.0305	0.0708	6.4
Toutun Reservoir	1981–2006	0.2030	0.1388	0.0642	32.0

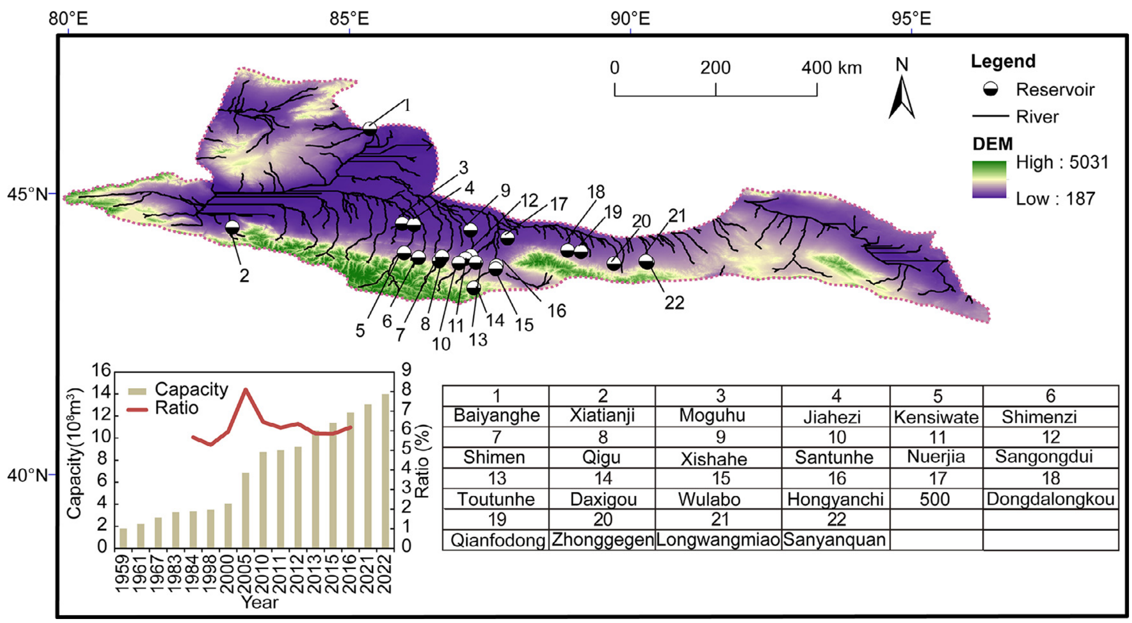

Fig. 5. Reservoirs in the northern slopes of the Tianshan Mountains (NSTM). Reservoir data is based on Deng (2020). Temporal variation of total storage capacity of reservoirs in the NSTM and their ratios to that in Xinjiang are also shown in the inset.

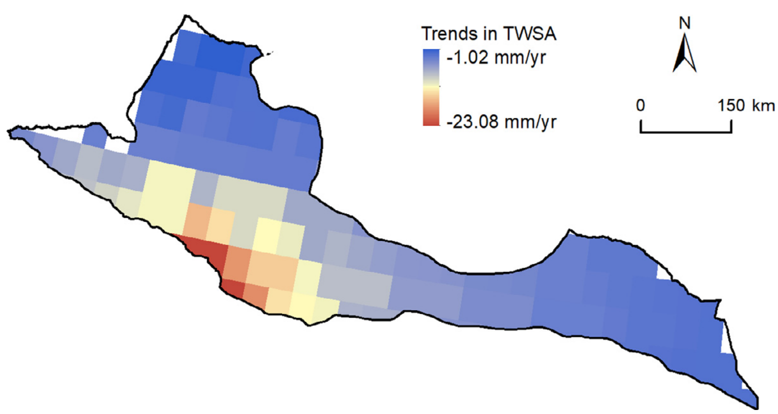

Fig. 6. Trends of terrestrial water storage anomaly (TWSA) from March 1990 to February 2020.

The industrial water use in Xinjiang in the past 15 years is shown in Fig. 7(b). From 2006 to 2014, withdrawals for industry increased continuously with increasing GDP. In 2015, limited by the water resources supply, government policy encouraged the manufacturing industry to use recycled water and improve water use efficiency. Industrial water use declined after 2015, although there was a peak in 2017. It is expected to decline and remain relatively stable due to the deflation policy of water withdrawals.

3.6. Streamflow

Streamflow was generally larger in the central and western NSTM while smaller in the eastern NSTM for the 1980–1989 and 2006–2011 periods (Fig. 8). The annual average streamflow at the Kenswat (Manas River) was the largest among the ten stations, with 37 m^3/s and 42 m^3/s from 1980-1989 and 2006–2011, respectively. Streamflow at the Yuejinshuiku station was the smallest, with 1.5 m^3/s and 2.6 m^3/s for the two periods. The average annual streamflow increased from 1980-1989 to 2006–2011 for most stations, except for slight decreases at the Jingheshankou (−4%) and Nianpanzhuang (−5%) stations. However, only the change (29%) at the Baiyanghe station (Baiyang River) was statistically significant at the 95% level. Large increases were also found in the other two eastern rivers, i.e., 74% at the Yuejinshuiku (Mulei River) station and 14% at the Kaikenhe (Kaiken River) station. In contrast, small relative changes were found in the central NSTM, such as the Yingxiongqiao (Urumqi River), Zhicaichang (Toutun River), and Nianpanzhuang (Santun River) stations. The western rivers generally showed moderate changes in average annual streamflow, e.g., increases of 10%, 15%, and 15% were found at the Bole, Shimen, and Kenswat stations during the two periods, respectively. A previous study showed that streamflow in the Toutun River during the 1980s was lower than the long-term average value (Li et al., 2007). This may be because streamflow during 2006–2011 was more significant than that in the 1980s in most rivers.

The multi-year average monthly streamflow at stations in the NSTM is shown in Fig. 9. The seasonality of streamflow was different across the rivers. Streamflow was generally highest in the summer months for all stations except the Bole station. The eastern rivers, represented by the Yuejinshuiku and Kaikenhe stations, had high streamflow in May, June, and July, while the major rivers had high streamflow in June, July, and August. The Bole station had a different seasonal pattern from others by showing high streamflow in winter. The summer streamflow accounted for large proportions of total annual streamflow except for the Bole station, where summer streamflow accounted for less than 20%. Specifically, summer streamflow accounted for ~50%–60% in the eastern rivers and 60%–70% in central and western rivers. The changes in

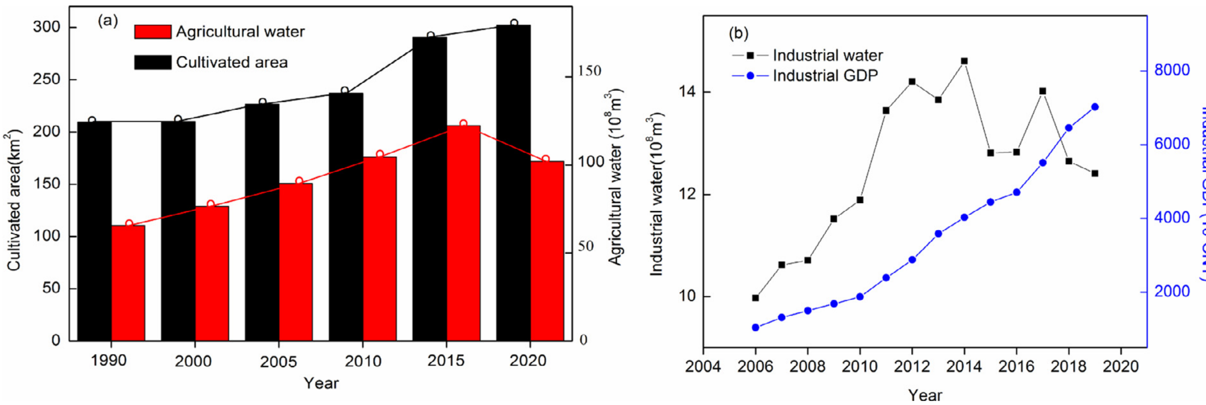

Fig. 7. (a) Change of cropland area and agricultural water consumption in the northern slope of the Tianshan Mountains; (b) change of industrial water use and GDP in Xinjiang.

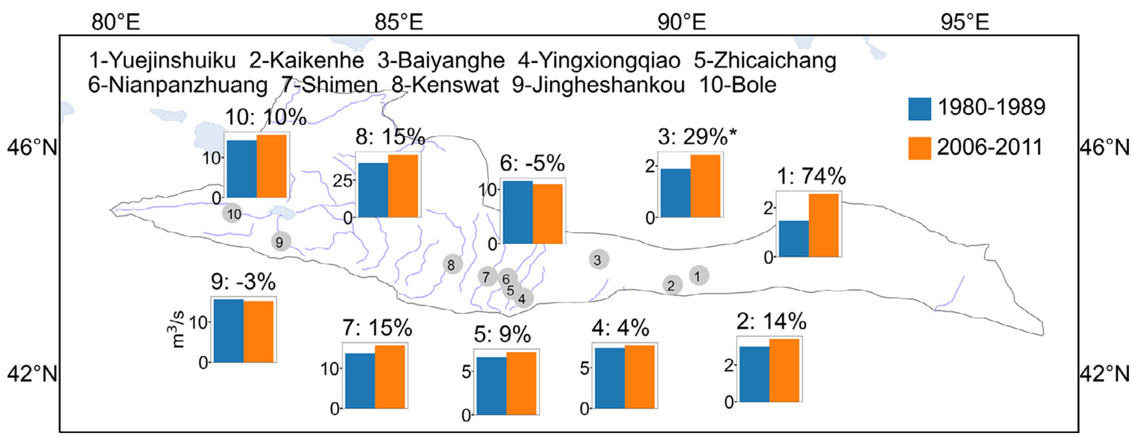

Fig. 8. Annual streamflow at stations for 1980–1989 and 2006–2011. Hydrological stations are numbered with names provided at the top of the map. The annual streamflow is shown as bar charts for each station with station numbers and relative changes (%). The asterisk indicates that the relative change is statistically significant at the 95% level.

average monthly streamflow between the two periods were generally similar to the average annual streamflow but differed across months. The changes in summer streamflow contributed the most to the changes in average yearly streamflow from 1980-1989 to 2006–2011, e.g., at the Baiyanghe, Shimen, Kenswat, and Jingheshankou stations. Streamflow decreased in June at the Yuejinshuiku and Kaikenhe stations and increased in other months for the former and spring for the latter. Streamflow decreased in July and August and increased in other months at the Bole station, likely due to water management activities.

4. Discussion

The results show that the water security issue is getting more severe due to climate change and human activities on the NSTM during the past decades. Water availability may increase to some degree, but precipitation shows no significant trends in this region. This suggests that increased water resources might be from the increasing meltwater of glaciers and permafrost due to the temperature rise. Considering that glacier stock is nonrenewable on the decade timescale and the climate is likely to be warmer in the future, water security is a significant challenge to NSTM's socio-economic development and ecosystem health, where meltwater is a crucial water source. On the other hand, human water use has dramatically increased, and agricultural land has expanded during the past decades, which has aggravated water scarcity and groundwater depletion and significantly increased water use competition between sectors. This could impede the sustainability of NSTM's socio-economic development and water security.

This study is a preliminary assessment of hydroclimatic changes and their potential impact on water security. Hydroclimatic changes and how they would impair regional sustainability is not well documented in this study due to data unavailability, e.g., the status of groundwater depletion, the contribution of different hydroclimatic components and human water use to water security, and the impact of water scarcity on socio-economic development on the NSTM. It should also be noted that the analysis for individual hydroclimatic components is subject to considerable uncertainty due to limited observations on the NSTM. A quantitative assessment of water security and the relative contribution of individual components is needed to better understand the relation between the hydroclimatic variables and water security. Furthermore, an in-depth investigation of future hydroclimatic changes and water security is critical under climate change. The uncertainties and limitations of hydroclimatic data and associated analysis are discussed below.

The changes in glaciers presented in this study are consistent with previous research (e.g., Wang et al., 2011). The glacier melt may significantly contribute to decreased terrestrial water storage (Rodell et al., 2018). In the past 30 years, climate warming has changed the pattern of glacier accumulation/ablation in mountain areas, resulting in variability and uncertainty of water resources assessment in mountain areas and bringing new challenges to evaluating and utilizing water resources in a changing environment. The same is true for permafrost. Meanwhile, glacier measurement and research methods are still limited. Therefore, it is essential to conduct surveys and systematically investigate the temporal and spatial distribution and evolution of glaciers and permafrost. Thus, *in-situ* observation, remote sensing, and modeling should be com-

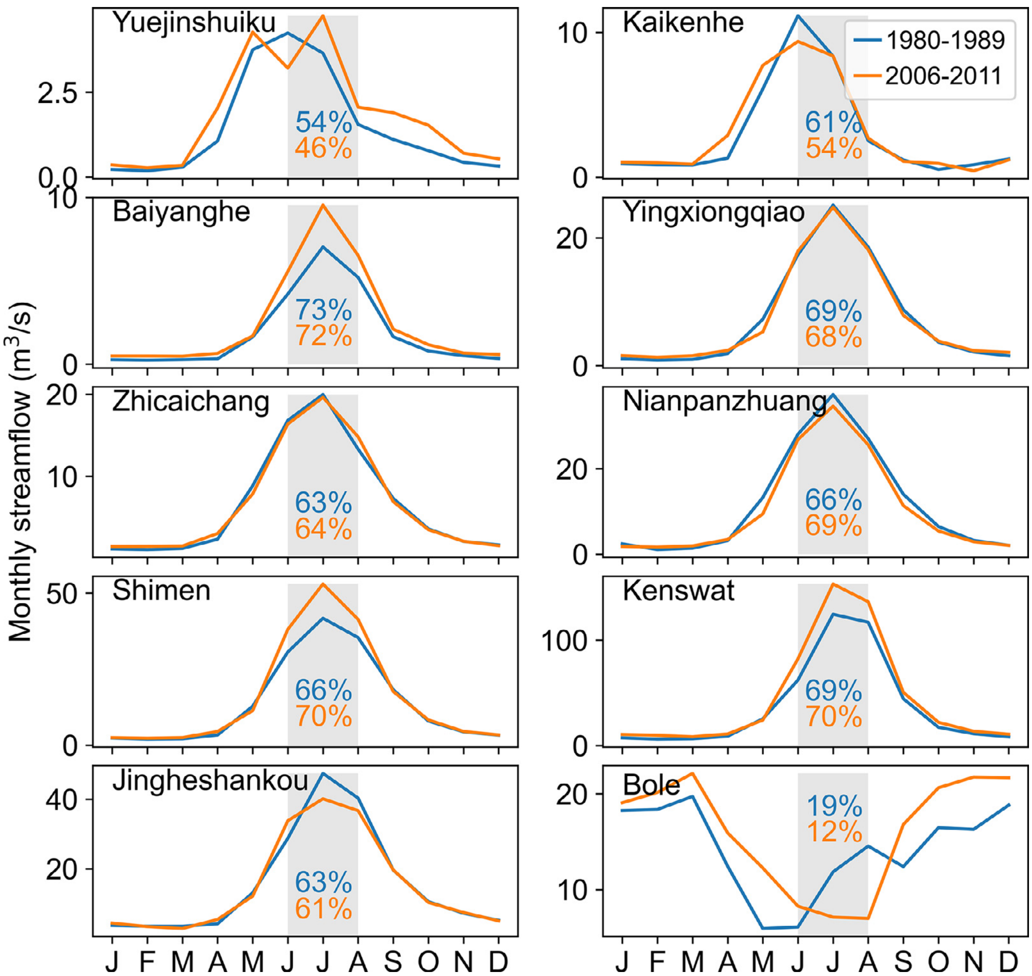

Fig. 9. Average monthly streamflow for 1980–1989 and 2006–2011. The summer months (June, July, and August) are shaded, and the percentages indicate the proportions of streamflow in the summer months to that of all months.

bined to strengthen the quantitative analysis of glacier contributions to changes in river runoff. In the future, the glaciers in Asia's high mountains will decrease by more than 30% under a global temperature rise of 1.5 °C. Further investigation is also needed to assess the future changes of glaciers on the NSTM. This could provide scientific data to understand cryosphere change's dynamic mechanisms fully, evaluate its development trends, and analyze its impact on water resources, directly contributing to the sustainable social and economic development of the NSTM.

Although a meteorological observation system has been constructed in the study area, there are few observation stations (about one meteorological station every 9×10^3 km^2), and the geographical distribution is uneven. The complex characteristics of the terrain and underlying surface in the NSTM have resulted in a poor spatial representation of the existing observation stations. Moreover, the satellite retrieval datasets have great uncertainty over the complex terrain, which severely limits the refinement of the meteorological support and hinders the development of the industries for advantageous agriculture, wind energy, and solar energy (Yuan et al., 2017; Amjad et al., 2020; Yang et al., 2020). Currently, meteorological datasets are used in weather forecasting because of their high spatial resolution and continuous spatial coverage. However, the results of multiple assimilation products have also shown that datasets in the northern slope of Tianshan Mountain are unreliable, especially for precipitation (Fan et al., 2013). Therefore, in the future, it is imperative to carry out regional vertical gradient observations, quantify the variation characteristics of meteorological variables under different altitude gradients and underlying surface conditions, and further develop meteorological datasets with high temporal and spatial resolutions.

The change in rivers and lakes is essential to understanding a region's water security. Remote sensing techniques provided an economical and efficient way to obtain these changes. The region's river and lake surface area grew from 1991 to 2020. These increases were mainly attributed to summer flooding, which was likely linked to regional water vapor transport (Bolch et al., 2012). For the central and eastern river basins, however, the lake surface area dynamics were governed by seasonal variability caused by temperature-dependent melt from glaciers and snow (Liu et al., 2020).

Traditionally, *in-situ* water level data and discharge at gauges are the primary tools to explore spatiotemporal variations of rivers and lakes. However, due to the poor weather, road accessibility, and economic conditions, many areas, including the northern slope of the Tianshan Mountains, are ungauged. For these areas, satellite remote sensing data provide us with an alternative. Compared to the Moderate Resolution Imaging Spectroradiometer (MODIS), Landsat has a much finer spatial resolution (30 m) as one of the earliest earth observation satellite missions that has accumulated long-term data for determining surface water dynamics. However, the changes could be significantly underestimated for some reservoirs and lakes because of contaminated pixels. The algorithm of Zhao and Gao (2018) used in this study overcame this difficulty and can significantly improve accuracy.

Besides MODIS and Landsat, Sentinel data from the European Space Agency also are a valuable data resource to estimate the change in rivers and lakes at even higher spatial resolutions (10 m) in all weather conditions (e.g., Zhou et al., 2021). In addition, monitoring lake storage monitoring is a better water management strategy than surface area measurement. Thus, in future work, we will translate the two-dimension surface area to three-dimension storage values by incorporating altimetric information. Despite the advanced satellite dataset, increasing *in-situ* capability and scientific expedition are essential for data validation of any remote-sensed data.

The decreasing trend in the TWSA partly confirmed groundwater depletion reported by Deng et al. (2021). Groundwater depletion and glacier mass loss may have contributed to the decreasing TWSA (Farinotti et al., 2015). The relative contribution of the driving factors of TWSA change is still not well understood and deserves further study. In addition to groundwater depletion, groundwater pollution is becoming a more serious issue. For example, the return flow from irrigation and channel leakage added risk to the security of groundwater quality (Liu et al., 2018b) through irrigation water infiltration. J. Wang et al. (2021) found that the high concentration of Na^+, Cl^-, SO_4^{2-} and HCO_3^- of shallow groundwater in the oasis plains and oasis-desert transition zone showed the high dissolution of mirabilite ($Na_2SO_4 \cdot 10H_2O$), halite and trona ($Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$) in the soil. Therefore, human activity may have an important influence on groundwater resources quantity and quality.

Agricultural water use increased with the expansion of oases. The agriculture in an oasis highly relies on surface runoff (Shen et al., 2013a, 2013b) which is charged by melt snow and glaciers and has recently increased (Ling et al., 2012a; Yao et al., 2015; Qin et al., 2016; Ling et al., 2012b). Overuse of surface water and groundwater depletion (Guo et al., 2019; H. Chen et al., 2019; Zhang et al., 2014) resulted in the government agriculture department promoting drip irrigation under plastic film to reduce evaporation (L. Wang et al., 2020). However, maintaining the sustainability of drip irrigation agriculture in Xinjiang due to soil salinity is a long-term challenge under a changing climate.

The demand for industrial water use will likely increase with economic growth (R. Xu et al., 2019). Limited by the seasonal variation of water resource supply, most industrial developments had self-supplied water systems to maintain annual production (Xu, 2013) as in the U.S. (Dieter et al., 2018). The water resources carrying capacity was lower than in other Chinese provinces, with 1/6 of water used per 10,000 GDP (Xiao, 2010). The main reason was a relatively lower-level economic structure (Fan et al., 2020). Based on the 2030 predicted low, middle, and high economic growth rates, a previous study suggests that 72.5 billion m^3 of water is necessary to support increased economic growth with a basic carbon emission situation (Li et al., 2019). However, industrial water use is expected to decline and remain relatively stable in the near future due to the limited water resources and government policy implemented in 2015 that encouraged water recycling.

Understanding the contribution to changes in streamflow would help water management under a changing climate. The sources of streamflow often include meltwater from glaciers and snow, groundwater, and precipitation on the NSTM. The contribution of these components to streamflow varies across the mountain rivers and is not yet conclusive. For example, different primary sources (glacial melt or groundwater) of streamflow in the Urumqi River were reported (Sun et al., 2016; Liu et al., 2020). Identification of the driving factors of the changes in streamflow is often complex as streamflow is affected by climate, human activities, and other hydrological factors. In this study, slight increases in streamflow are found in most rivers, which is consistent with previous studies (e.g., Zhang et al., 2010; Y. Chen et al., 2019); however, the limited streamflow data may impair the robustness of the analysis. Climate change plays an essential role in streamflow change in most rivers. In the context of global warming, the glacier meltwater and snowmelt may be the primary drivers of the changes in streamflow in some rivers, while increased evaporation due to the warming climate often results in decreased streamflows (Lei et al., 2012; L. Wang et al., 2016). A case study of the Urumqi River suggested that land use change may cause a decrease in streamflow (Yan et al., 2016). However, further investigations with more streamflow data are needed to provide a more robust analysis of changes in streamflow and a better understanding of the mechanisms underlying the changes, e.g., the relative contributions of the changes in climate variables and human activities.

5. Conclusions

This paper investigated changes in hydroclimatic variables and related water security factors on the Tianshan Mountains' northern slope. The spatiotemporal variations of glaciers, climatic variables, rivers, lakes, reservoirs, groundwater, surface water, human water use, and streamflow were analyzed. The results show that glaciers in the NSTM continuously underwent mass loss and shrinkage with increasing temperatures, while no significant trend was observed in annual precipitation. The average yearly streamflow increased from 1980-1989 to 2006–2011 for most stations which might be attributed to increasing meltwater. The region's natural and anthropogenic drivers impact the surface water area. The terrestrial water storage anomaly showed a decreasing trend, probably related to groundwater pumping for irrigation. The human water use that grew with the expansion of the cultivated land and rising GDP, such as agricultural and industrial water uses, is a significant driver impacting on water security in this region.

The NSTM has already faced severe water scarcity even though water availability (e.g., the streamflow) over the past few decades was relatively high. It is unclear if water availability will remain high in the future given climatic and hydrological uncertainty, which poses new challenges to water management in this region. In the context of rapid urban growth and climate change, balancing water for humans and nature is vital in achieving the SDGs. We highlight the necessity of conducting an in-depth investigation regarding the impacts of climate change and human intervention on water resources and developing wise water management strategies to promote sustainable development in this region.

Declaration of Competing Interest

The author declares that no known competing financial interests or personal relationships influenced the work reported in this paper.

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