Changes in Glacial Meltwater Runoff and Its Response to Climate Change in the Tianshan Region Detected Using Unmanned Aerial Vehicles (UAVs) and Satellite Remote Sensing

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Abstract: The Tianshan Mountains, known as the “water tower” of Central Asia, are the major source of water for the most part of Xinjiang and oasis region of Central Asia. However, climate warming has amplified the discharges of glacial meltwater in the Tianshan Mountains. In this study, we calculated river discharge by integrating cross-sections mapped using unmanned aerial vehicles (UAV) and water velocity data collected in the field. Multiple remote sensing images, such as Landsat and Sentinel-2 imagery, were applied to estimate the long-term discharge of 19 river sections in ungauged regions of the Tianshan Mountains. River discharge variations under climate change were also examined. Using our in-situ measured discharges as reference, the UAV derived discharge results have an NSE (Nash–Sutcliffe efficiency) of 0.98, an RMSE (root mean square error) of 8.49 m³/s, and an average qualification rate of 80%. The monthly discharge of glacial meltwater-dominated river sections showed an average decrease of 2.46% during 1989–2019. The shrinking and even disappearance of mountain glaciers (approximately −4.98 km²/year) was the main reason for the decrease trend. However, the precipitation-dominated river sections showed an average increase of 2.27% for the same period. The increase in precipitation (approximately 1.93 mm/year) was the key cause for the increase tendency. This study highlights remote sensing hydrological station technology and its application in the long-term prediction of river discharge, which is critical for decision-making regarding integrated water resource management in alpine regions.

Keywords: climate change; discharge; remote sensing hydrological station; river section; trend

1. Introduction

Climate change is a major global issue that is of great concern to the international community. Since 1950, unprecedented changes have been observed in the climate system in recent decades [1]. Glaciers respond to climate change through translating the climatic signal into observable changes in the landscape [2]. Considerable retreat of glaciers has been observed globally because of warming effects worldwide [3]. Publications relating to the accelerated retreat of glaciers in recent decades are enormous [4–9]. Continuous retreat will alter the contribution of ice and snow melt to mountain river systems, reduce water quantity in the downstream and further intensify the stress of water allocation for the oasis region [10].
In alpine regions, river runoff is mainly replenished by glaciers/snow meltwater, making them quite sensitive to both regional and global climate changes [11]. Recent climate change has magnified uncertainties of water balance in river systems. So, widespread concerns have been raised regarding the impact of climate change on river runoff in high-altitude regions and in related academic fields. In the Nepal side of the Himalayas, glaciers have changed water balance of the upper reaches of the Ganges Basin, which has a great impact on its local community owing to the high population density and extensive needs in irrigation [12]. A contrasting study conducted in the Mountains of the Himalayan and Andes area found that the river in the upper Langtang catchment (accounting for 27% of glacier area) illustrated a noticeable increase in river runoff, while there was a dramatic decrease in runoff in the Juncal catchment [13]. The loss of glacier shall increase the overall river runoff. When the loss of glacier is sufficiently large, a decline in runoff of the area of glacier cover declines sufficiently to offset any increase in ablation rate [14,15]. In some cases, even within the same mountain ranges, the runoff has reached its peak in certain catchments, but the peak is estimated to occur in 2100 in other catchments [14,16]. The decreasing of stream flows in rivers of the Himalaya region is frequently linked to the shrink of the cryosphere in corresponding regions [17–19]. Research conducted in the Swiss Alps area show significant trends between annual streamflow and glaciated area. In addition, the higher the proportion of glaciated area in the watershed, the higher the proportion of glacial melt in total runoff and its increment [20]. Multiple studies show that, in a warming climate, glaciers and seasonal snow cover have altered the hydrological processes in their watersheds, especially in alpine regions [21,22]. Consequently, water availability could become scarce in the future when glaciers and seasonal snow cover regions have shrunk to a certain limit. Our strategies for water management shall face great challenges in future.

The Tianshan Mountains are the “water tower” of countries in Central Asia [16]. The signature of climate warming is evidenced by an average temperature increase of 0.036–0.042 °C/year during the past 3 decades [23]. Warming has further accelerated glacier melting and reduced the area and depth of snow cover in this region [23,24]. The melting of glaciers and reduction in snow cover not only cause resource and environmental problems, such as changes in water resource reserves and their spatial distribution, as well as the regional water cycle, but also increase the frequency and impact of glacier disasters. Although variations in glacial/snow meltwater runoff and its relationship with climate change in the Tianshan region have been analyzed in recent years [24–26], some deficiencies remain. Studies in this region have focused predominantly on large-scale watersheds or a small number of in situ measurements, not to mention the relatively short time series. Moreover, some studies take hydrological station data as the main data source. However, hydrological stations in the Tianshan region are mostly located at the river outlets, while stations in the middle and high mountains are rare and unevenly distributed due to the harsh environment. Therefore, previous studies were limited by data, methods, time scales, etc., and could not reflect the changes in glacial/snow meltwater runoff before it was affected by human activities or the construction of hydrological stations. To advance our understanding of how climate change affects glacial/snow meltwater runoff, there is an urgent need to comprehensively reveal the long-term runoff changes in glacier/snow-fed rivers.

Remote sensing images have been widely adopted to estimate river discharges, especially for ungauged areas [27]. Remote sensing technology performs discharge calculations without field studies under complex geological conditions and harsh external conditions [28]. To date, many scholars have researched flow inversion through remote sensing [29–34]. Although great progress has been made in the method of river discharge inversion by remote sensing, existing methods are applicable to monitor only large-scale rivers, and it is difficult to obtain the discharge of small rivers.

During the last few years, the cost and maneuverability of unmanned aerial vehicles (UAVs) have undergone revolutionary breakthroughs, which have enabled the expanded
use of UAVs different fields. UAV image acquisition has the advantages of low cost, fast speed, and high resolution, and is incomparable to traditional satellite remote sensing. The UAV data collection, post-processing, and modeling techniques have been integrated into a large number of applications across many disciplines, such as agriculture [35], ecology [36], forestry [37], and archeology [38]. UAV images have also been widely applied for river monitoring, environment evaluation [39], and river discharge estimation in ungauged catchments [40].

In this study, we explore the potential of integrating UAV hydrological station technology and remotely sensed images to analyze discharge variations in mountain river sections, and how they respond to climate change in the Tianshan region from 1989 to 2019. Three important issues were investigated: (1) using UAVs to obtain image data for tributaries in the Tianshan region and establishing digital river section models to determine the shapes of the river sections; (2) coupling UAV data with multisource remote sensing data to obtain long-term river discharges; and (3) exploring the discharge variation patterns of different river sections according to the water supply of different rivers and examining their influencing factors.

2. Study Area and Datasets
2.1. Study Area

Tianshan Mountains are located in the Eurasian hinterland. The region is about 2400 km between west and east, of which 1700 km in the eastern side is located in Xinjiang Uyghur Autonomous Region, covering an area of approximately $57 \times 10^5$ km$^2$ [41]. Our study area stretches from 43 to 46° N and from 79 to 87° E (Figure 1). The climate is interactively controlled by the Siberian anticyclonic circulation and cyclonic activity [42]. Hydrological stations in the Tianshan region are mostly located at the river outlets. Because of the complex geographical conditions, stations in the middle and high mountains are rare and unevenly distributed. The Mountain region is ungauged and is a critical water source for of the Xinjiang and the oasis region of Central Asia.

![Figure 1. Monitoring sections in the Tianshan region.](image)

The elevation of the Tianshan Mountains region is 4000 m on average, and the snow/glaciers permanently existed in mountain areas. According to a latest investigation, glaciers as abundant as 7934 have been observed in this region. Those glaciers are estimated to be 7179.77 km$^2$ in area and 707.95 km$^3$ in volume [43]. The Tianshan
Mountains are the source of large quantities of rivers in Xinjiang Uyghur Autonomous Region, and their rich glaciers and snow cover are an important part of this region’s water resources. Affected by the westerly belt and terrain, precipitation in this region presents an uneven spatio-temporal distribution. Precipitation in the northern area is more than that of southern area, and precipitation in the mountainous area is more than that of plains and basins [16].

2.2. Datasets

2.2.1. UAV Data

Topographic information about rivers in the Tianshan region was collected using a DJI Phantom 4 Professional UAV (DJI, Shenzhen, China) between 8 and 15 August 2018 (Table 1). The flights were controlled intelligently after successful delineation of trajectories. The image overlap parameter was set to 90% to guarantee generation of good stereoscopic image pairs. During the UAV flights, 200–300 photos were obtained at each site for estimating topographic information and cross-sectional shape, measuring discharge velocity, and recording land use and river characteristics. The spatial resolution of the acquired UAV images was also depicted in previous studies [44]. The root mean square error (RMSE) of our UAV data was ±2.79 cm in the vertical direction and ±9.98 cm in the horizontal direction. It is considered to be feasible to apply similar UAVs for river terrain acquisition.

Table 1. Basic parameters of the UAV.

| UAV Model | Phantom-4-Pro |
|-----------|----------------|
| Camera model | FC300x |
| Sensor type | 1/2.3" CMOS sensor |
| Image size | 1.2 million (4000 × 3000) |
| Maximum aperture | f/2.8 |
| Camera focal length | 20 mm |
| Field of view | 94° |
| Maximum flight altitude | 500 m |

Through field investigation, the river system in this region was analyzed and a total of 19 river sections located at the middle- and high-altitude river outlets, were selected for discharge estimation (Figure 1). Among these, six were located in the upper reaches of the Bortala River (TS-B1, TS-B2, TS-B3, TS-B4, TS-B5, TS-B6), six were located in Wenquan County before the Bortala River enters the oasis (TS-W1, TS-W2, TS-W3, TS-W4, TS-W5, TS-W6), and the remaining seven were in the middle of the Tianshan Mountains (TS-1, TS-2, TS-3, TS-4, TS-5, TS-6, TS-7) (Table 2).

Table 2. River section information.

| Water Supply Source | Section | Location | River Width (m) | Control Area (km²) |
|---------------------|---------|----------|-----------------|-------------------|
| Glacial meltwater   | TS-B1   | 44°55'02.74",80°06'45.76" | 25.71 | 260.29 |
|                     | TS-B2   | 44°55'42.99",80°03'38.42" | 12.85 | 79.46 |
|                     | TS-B3   | 44°55'59.19",80°05'39.60" | 11.03 | 68.35 |
|                     | TS-W5   | 45°08'27.25",81°17'24.40" | 9.06  | 61.84 |
|                     | TS-3    | 43°56'40.16",85°47'44.75" | 12.46 | 3.64 |
|                     | TS-4    | 43°56'47.04",85°36'09.42" | 9.94  | 265.21 |
|                     | TS-5    | 43°59'27.51",85°18'03.05" | 7.63  | 166.55 |
|                     | TS-6    | 43°57'56.17",85°06'44.52" | 9.98  | 108.98 |
|                     | TS-7    | 44°01'27.58",84°58'34.68" | 32.25 | 1091.83 |
Table 2. Cont.

| Water Supply Source | Section | Location | River Width (m) | Control Area (km²) |
|---------------------|---------|----------|-----------------|--------------------|
| TS-B4               | 44°56′18.48″,80°12′42.14″ | 13.56     | 66.22           |
| TS-B5               | 44°57′11.48″,80°24′09.70″ | 8.88      | 82.19           |
| TS-B6               | 44°57′42.17″,80°34′35.85″ | 7.13      | 58.13           |
| TS-W1               | 45°03′06.98″,81°02′25.81″ | 2.47      | 45.54           |
| TS-W2               | 45°05′02.60″,81°02′17.34″ | 10.17     | 45.54           |
| TS-W3               | 45°03′41.95″,81°04′58.72″ | 2.42      | 23.89           |
| TS-W4               | 45°07′40.96″,81°11′39.07″ | 3.88      | 18.02           |
| TS-W6               | 45°08′46.43″,81°20′42.83″ | 6.51      | 119.34          |
| TS-1                | 43°49′53.41″,85°21′58.71″ | 17.84     | 973.86          |
| TS-2                | 43°54′02.98″,85°51′33.35″ | 43.25     | 961.48          |

2.2.2. Satellite Remote Sensing Data

The European Space Agency (ESA) launched an Earth observation mission in 2015 and named it Sentinel-2. It carries a multispectral instrument (MSI) that images 13 spectral bands in the visible, near-infrared, and shortwave infrared spectral range (SWIR) at 10–60 m spatial resolution [45]. Sentinel-2 provides mature data and processing methods for Sentinel satellites, which are widely used in ground object recognition and water area analysis. In this study, Sentinel-2 10 m resolution band 3 (green band) and band 8 (NIR band) data between March 2016 and November 2019 were used for water surface extraction, in combination with the requirements of the normalized difference water index (NDWI) for water surface calculation.

Since the first Landsat satellite was launched in 1972, the mission has collected data on the forests, farms, urban areas, and freshwater of our home planet, generating the longest continuous record of its kind [46]. Landsat series images have a spatial resolution of 30 m and provide a long-term record for nearly five decades. In this study, Landsat 5, 7, and 8 images acquired from 1989 to 2019 were used to estimate the water area and to identify the distribution of glaciers. Since the mean monthly temperature in the Tianshan region began to drop significantly in November and the rivers froze, water bodies could not be identified by remote sensing images. Therefore, based on the availability of satellite data, this study mainly analyzes the river discharge changes from March to November in the study area.

The temperature and precipitation dataset was obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF), which is operated by Deutscher Wetterdienst under the auspices of the World Meteorological Organization (WMO) [47]. It has a higher accuracy with a spatial resolution of 0.125° and should, therefore, perform better in mountainous regions with complex topography [48] (Table 3).

Table 3. The datasets used in this study.

| Dataset | Spatial Resolution | Temporal Resolution | Period | Source |
|---------|--------------------|---------------------|--------|--------|
| UAV images | 3.8–4.2 cm | / | 8 August 2018–15 August 2018 | Fieldwork (accessed on 19 September 2020) |
| Landsat | 30 m | 16-day | 1989–2019 | http://www.gscloud.cn/ |
| Sentinel-2 | 10 m | 5-day | 2016–2019 | /scihub.copernicus.eu/dhus/#/home (accessed on 19 September 2020) |
| ERA-Interim | 0.125° | daily | 1989–2018 | https://apps.ecmwf.int/datasets/ (accessed on 29 September 2020) |
3. Methods
3.1. Remote Sensing Hydrological Station and Its Algorithms

Due to factors such as the geographical environment and economic conditions, the acquisition of river information is greatly hindered in areas with limited hydrological data. Some recent studies have already focused on estimating river discharge in ungauged areas and proposed remote sensing hydrological station technology. Their method was applied to many rivers with different width [39,40]. Point clouds and digital surface elevations (DSM) were generated from UAV images. They were consequently used to estimate width, roughness, slope, and cross-section of water surface. Hydraulic methods were used to calculate river discharge [40,49]. The methodology has been applied to establish remote-sensing-enhanced monitoring of runoff in areas with poor hydrological data, such as the Ebinur Lake Basin, Tibetan Plateau, and some desert rivers, and has combined remote sensing data with hydrological and hydraulic methods to realize single-point and sequential river discharge estimation [50–53]. The accuracy of the method was verified according to the measured data from field stations and hydrological stations. The relative accuracy and Nash–Sutcliffe efficiency coefficient (NSE) were used to compare the calculated and measured discharges. Results favored our remote sensing hydrological station method for estimating river discharges in ungauged areas [53,54].

In this study, we extended the previous research to estimate river discharge using remote sensing hydrological station technology. The main methodology is as follows.
Step 1: Generate the shapes of river sections by combining the field measured water depth data and the UAV DSM data.
Step 2: Extract the elevation data, obtain the water surface widths corresponding to different water depths, and then draw the water surface width–water depth relationship curve.
Step 3: Obtain the cross-sectional shape characteristics of the target river section, and establish the digital river section model according to the corresponding relationship among discharge, water surface width and water depth.
Step 4: Estimate the river discharge and verify accuracy.

River discharge was calculated from the Manning formula. It is an empirical formula that involves water flow, riverbed, and internal factors of a riverbed [55,56] and was used by many previous studies, e.g., [57,58]. The general form of formula is:

\[ Q = V \cdot A \]  

where \( Q \): river discharge (m³/s); \( V \): water flow velocity (m/s); and \( A \): area of river cross-section (m²).

The water flow velocity is a key parameter in the Manning–Strickler formula, which was calculated using the following function [59]:

\[ V = \frac{k R^{2/3} J^{1/2}}{n} \]  

where \( V \): water flow velocity; \( k \): conversion factor (m^{1/3}/s), regarded as 1 in this study; \( n \): roughness coefficient, determined by the riverbed materials, water bank, and plants [60]; \( R \): hydraulic radius, which depends on the cross-sectional shape; and \( J \): hydraulic gradient, which describes the slope of the vertical section. The \( R \) and \( J \) values were obtained from UAV-based remote sensing [40,48].

3.2. Long-Term River Discharge Calculation Based on Satellite Remote Sensing

Although remote sensing hydrological stations can only obtain one-period river discharge based on UAV data, but provide basic river information, such as water depth, hydraulic radius, and hydraulic gradient, for subsequent work [48]. To estimate the long-term river discharge, the river width is the only unknown parameter. Landsat and Sentinel-2 time-series images were used to obtain the river width in historical time because of their higher temporal resolution of satellite images. Due to the spatial resolution constraints of remote sensing data, the spectrum of one pixel in a certain remotely sensed image is
a mixture of several materials covered by that pixel. Some rivers in the study area have small widths, and there was an error in the width directly extracted from remote sensing data. To ensure the estimation accuracy, the spectral unmixing method was used [61]. The water surface area was calculated according to the determined thresholds of water pixel area larger than 70% and land pixel area less than 30%. Then, IDL software was used to batch calculate the time series river discharge.

We used the NDWI to extract the width of the water surface. The method of NDWI is shown in Equation (3):

\[
NDWI = (\text{Green} - \text{NIR})(\text{Green} + \text{NIR})
\]

where Green and NIR are the surface reflectance of the green band and near-infrared band, respectively.

We verified the river widths measured by UAV images and obtained by the spectral unmixing method in the same period for the 19 river sections. Figure 2 shows the validation results of river widths extracted from Landsat 8 OLI and Sentinel-2 images. The two river width extraction results obtained by the spectral unmixing method were in good agreement with the river width measured by UAV images. There is a linear relationship between the calculated river width and the measured river width, and the correlation coefficients are 0.65 and 0.79 (\(p < 0.01\)), respectively, but the calculated river width was slightly higher than the measured river width. Comparing the two kinds of extraction results, the accuracy of Sentinel-2 data was higher than that of Landsat data, indicating that Sentinel-2 images have certain advantages compared with Landsat images when extracting water bodies due to its higher spatial resolution.

\[
y = 1.3585x + 5.2624 \\
R^2 = 0.6555
\]

\[
y = 1.0395x + 5.3296 \\
R^2 = 0.7998
\]

Figure 2. Validation of the calculated river width from Landsat 8 OLI (a) and Sentinel-2 (b).

Overall, due to its high spatial and elevation resolution, low-altitude remote sensing (i.e., UAV) has great advantages in monitoring small-sized rivers in ungauged areas. In terms of temporal resolution, satellite remote sensing can play an important role in obtaining river widths at different historical times. The spectral unmixing of high spatial resolution UAV with high temporal resolution satellite sensors can well realize the estimation of small-sized rivers widths with scarce data, and can capture river widths less than 10 m wide.

3.3. Accuracy Validation

To evaluate the accuracy of the discharge estimated by UAV data, we used the RA (relative accuracy), RMSE, and NSE [62] as the evaluation criteria:

\[
RA = \frac{|Q_c - Q_m|}{Q_m}
\]

where

\[
\begin{align*}
RMSE & = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (Q_c - Q_m)^2} \\
NSE & = 1 - \frac{\sum_{i=1}^{n} (Q_c - Q_m)^2}{\sum_{i=1}^{n} (Q_m - \bar{Q}_m)^2}
\end{align*}
\]
\[ RMSE = \sqrt{\left( \frac{\sum (Q_c - Q_m)}{n} \right)^2} \]  

\[ NSE = 1 - \frac{\sum_{t=1}^{T} (Q_m - Q_c)^2}{\sum_{t=1}^{T} (Q_m - \overline{Q})^2} \]  

where \( Q_m \): in situ discharge, \( Q_c \): estimated discharge, \( \overline{Q} \): mean value of the in situ discharge, \( T \): number of simulation calculations, and \( n \): total number of observations. The NSE varies from \(-\infty\) to 1, and 1 indicates the optimal status where the simulated discharge equals the in situ measurements.

4. Results

4.1. River Discharge by Remote Sensing Hydrological Station

A digital orthophoto map (DOM), an image point cloud, and a DSM were generated from the corresponding UAV images for each site listed in Table 2. The DOM records the color information (RGB) and is used to determine river sections, to analyze the environment of the riverbed, and establish a training area for the inversion of the river width. The DSM implies the terrain information of the river section in high precision. It was used to calculate the hydraulic radius and hydraulic gradient (Figure 3).

![Figure 3. (a) DOM and (b) DSM of river section TS-B2.](image)

Surface water that flows down cracks and folds in the land has eroded the ground for a long time, washed into ravines, formed streams, and finally gathered to form rivers. Valleys are the most common landforms and are formed through the erosion of rivers [63]. The water delivery capacity of the section is closely related to the shape of the section. In this study, cross-sectional shapes of every studied river section were obtained by combining the measured underwater data with the UAV data (Figure 4).

The shape of each river section was fitted using the measured water depth in combination with full cross-section and high-resolution water-based terrain data. Figure 5 shows the digital river section models for typical river sections in the study area. Based on the Manning–Strickler formula, the river discharge was calculated using the digital river section model. The roughness coefficients and river widths were determined by UAV images. The results are shown in Table 4.
Figure 4. Cross-sections of the researched river sections.

The shape of each river section was fitted using the measured water depth in combination with full cross-section and high-resolution water-based terrain data. Figure 5 shows the digital river section models for typical river sections in the study area. Based on the Manning–Strickler formula, the river discharge was calculated using the digital river section model. The roughness coefficients and river widths were determined by UAV images. The results are shown in Table 4.

Figure 5. Digital river section models of typical river sections.
Table 4. Discharge estimation results based on UAV data and validation. Qm is the in situ discharge, Qc is the estimated discharge.

| Section | Qc (m³/s) | Qm (m³/s) | RA (%) | Section | Qc (m³/s) | Qm (m³/s) | RA (%) |
|---------|-----------|-----------|--------|---------|-----------|-----------|--------|
| TS-B1   | 28.53     | 26.34     | 7.68   | TS-W5   | 1.21      | 1.07      | 11.57  |
| TS-B2   | 3.03      | 2.95      | 2.64   | TS-W6   | 1.97      | 2.25      | 14.21  |
| TS-B3   | 3.17      | 3.29      | 3.79   | TS1     | 39.15     | 40.07     | 2.35   |
| TS-B4   | 41.23     | 39.42     | 4.39   | TS2     | 54.02     | 49.29     | 8.76   |
| TS-B5   | 17.19     | 15.34     | 10.76  | TS3     | 10.43     | 11.76     | 12.75  |
| TS-B6   | 15.29     | 11.76     | 23.09  | TS4     | 3.74      | 3.96      | 5.88   |
| TS-W1   | 3.85      | 3.97      | 3.12   | TS5     | 1.02      | 1.2       | 17.65  |
| TS-W2   | 0.45      | 0.53      | 17.78  | TS6     | 2.56      | 2.95      | 15.23  |
| TS-W3   | 0.29      | 0.34      | 17.24  | TS7     | 106.05    | 95.46     | 9.99   |
| TS-W4   | 0.45      | 0.39      | 13.33  |         |           |           |        |

There are no hydrographic stations in the Tianshan Mountains, which are typical ungauged areas. The discharges measured in the field were considered as true values and used to validate the estimated river discharges. According to the “Standard for hydrological information and hydrological forecasting” (GB/T22482-2008) and previous publications [64], the threshold for the RA was set to 20%, which means that an estimation error within 20% was considered to be acceptable. Table 4 shows the measured and estimated discharges of the 19 sections and their precisions. Among these results, the RAs of 18 sections were less than the 20% accuracy standard, but section TS-B6 exceeded the allowable error, with an RA of 23.09%. Overall, the average RA of all sections was 10.64%, less than the 20% accuracy standard. The discharge estimation results based on UAV data were good, with an average qualification rate of 80%. The NSE is a critical index for evaluating the accuracy of estimations. All selected sections were considered as a whole, and the overall simulation accuracy was evaluated. The value of the NSE was 0.98, and the RMSE was 8.49 m³/s, indicating that the simulation quality was good and that the results were highly reliable.

4.2. River Discharge on Long Time Scales

To reveal the long-term pattern of variations in mountain discharge in the Tianshan region, the discharges of 19 river sections from 1989 to 2019 were estimated using Landsat and Sentinel-2 data. The variation in river discharge (seasonal or interannual variation) mainly depends on the river water supply source. Thus, the study sections were divided into two types: glacial-meltwater-dominated river sections and precipitation-dominated river sections. The glacial-meltwater-dominated river sections include nine sections (TS-B1, TS-B2, TS-B3, TS-W5, TS-3, TS-4, TS-5, TS-6 and TS-7) with large glacier areas in the basins. Since the snow cover area varies very little for the overall area, snow cover has been ignored. The precipitation-dominated river sections include 10 river sections (TS-B4, TS-B5, TS-B6, TS-W1, TS-W2, TS-W3, TS-W4, TS-W6, TS-1 and TS-2), where there are few or no glaciers in the basins. Due to the limitation of remote sensing data, we cannot estimate all the data for each section from March to November each year, in which some of the monthly data were discontinuous. Therefore, we did not accumulate annual data but carried out our analysis on a monthly scale. Linear trend lines were fitted to the monthly discharge data of 19 river sections. Since these sections not only differ in discharge monitoring time, but also in the range of discharge values. Here the overall multiyear trends of discharge at all sections are discussed, followed by details of the actual data form several typical sections.

Figure 6 shows the fitted trends of river discharge changes in 19 sections from 1989 to 2019. Figure 6a shows nine glacial-meltwater-dominated river sections. The multiyear monthly discharge of these sections presents a decreasing trend over the past 31 years. Among them, the decreasing trend of TS-3 was the most significant (Figure 7d), while the decreasing trends of TS-4 and TS-W5 were slight. The decreasing rate of TS-3 was 9.29%, followed by TS-7 (approximately 3.75%), and TS-4 had the smallest decrease of
approximately 0.07%. The average rate of increase in the nine sections was 2.46%. The maximum discharge among glacial-meltwater-dominated river sections appeared in section TS-B2; in October 2000, the discharge was $77.61 \times 10^6$ m$^3$ (Figure 7a). The minimum discharge was zero. These sections, whose monthly discharge shows a decreasing trend, were all located in middle- and high-altitude areas, with the highest elevation reaching 5000 m. Affected by recent climate warming, the glacier area in the basin controlled by these sections has decreased year by year, and small glaciers have even disappeared [24,65], which has led to a decrease in river discharge.

![Figure 6](image1.png)

**Figure 6.** Linear trends of monthly discharge in different river sections; (a) glacial-meltwater-dominated river sections, (b) precipitation-dominated river sections.

![Figure 7](image2.png)

**Figure 7.** The estimated discharge changes of four sections that changed significantly. (a) TS-B2; (b) TS-B6; (c) TS-2; (d) TS-3.

Figure 6b shows 10 river sections dominated by precipitation. The multiyear monthly discharge of these sections presents an increasing trend over the past 31 years. Among them, the increasing trend of TS-1 was the most significant, while the increasing trends of TS-W2, TS-W3, and TS-W4 were not obvious. The increasing rate of TS-1 was 10.43%, followed by TS-2 (approximately 9.88%), and TS-W4 had the smallest increase of approximately 0.003%. The average rate of increase in the 10 sections was 2.27%. The maximum discharge among precipitation-dominated sections appeared in section TS-2; in June 1993, the discharge of TS-2 was $299.61 \times 10^6$ m$^3$ (Figure 7c). The minimum value appeared in section TS-W6; in November 2011, the discharge of TS-W6 was $0.008 \times 10^6$ m$^3$. The increase in discharge in these 10 river sections was mainly due to the change in climatic pattern from warm-dry to warm-wet in the Tianshan region, and the precipitation has increased year by year, thus causing the increase in discharge.

To further explore the changes in river discharge, seasonal changes were analyzed. Figure 8a shows that the glacial-meltwater-dominated river sections have an obvious
seasonal variation as a whole. In March, April, and November, the discharge was small and changed relatively smoothly. In May, it started to increase rapidly, with the maximum discharge occurring in July and August, and it began to decrease in September and October. In areas with mountain glaciers, the spring flood was not obvious, the discharge was more concentrated in summer, in which its proportion was 49%, and the discharge in autumn was greater than that in spring. Among glacial-meltwater-dominated river sections, the maximum discharge appeared in section TS-3 in July, at $80.11 \times 10^6 \text{ m}^3$, and the minimum discharge appeared in section TS-W5 in March, at $1.46 \times 10^6 \text{ m}^3$.

**Figure 8.** The average monthly discharge changes in two types of sections: (a) glacial-meltwater-dominated river sections, (b) precipitation-dominated river sections.

The seasonal discharge of precipitation-dominated river sections presents a double peak trend in summer and spring (Figure 8b). The discharge began to increase in March, there was a minor flood in April and May, and it reached the maximum in July and August, which was 4–5 times the average discharge in winter. Then, the discharge began to decrease from October. The maximum discharge of precipitation-dominated river sections appeared in section TS-2 in June and was $136.79 \times 10^6 \text{ m}^3$, and the minimum discharge occurred in section TS-W4 in September and was $0.23 \times 10^6 \text{ m}^3$.

### 4.3. Influence of Climate Change on River Discharge

#### 4.3.1. Glacier Area Changes

The reduction in snowfall rates in mountainous areas leads to reductions in the sources of glaciers. In addition, rising temperatures also directly accelerate the melting of mountain glaciers. These two aspects lead to the melting rate of solid water bodies in mountainous areas being greater than the accumulation rate, resulting in the reduction in water reserves in mountainous areas and further affecting the water resources in the basins [23]. Figure 9 shows the changes in glacier area in nine river section basins with glacial meltwater as the main water supply source. The glacier area decreased significantly from 1989 to 2019, at a rate of $-4.98 \text{ km}^2 / \text{a} (p < 0.01)$, and the glacier area has the same trend as the discharge in these sections. The total glacier area was approximately 2297.23 km$^2$ in 1989 and retreated to 2163.56 km$^2$ in 2019, a change of 5.82% (Figure 9a). From the perspective of changes in the glacier area of each basin, the glacier area in the basin of section TS-W5 was relatively small, but the glacier retreat was very serious. The glacier area was 1.56 km$^2$ in 1989 but decreased to 0.08 km$^2$ in 2019, a change of 94%. The second-largest decrease in glacier area was in section TS-5, where the glacier area was 6.33 km$^2$ in 1989 and 1.45 km$^2$ in 2019, a change of 77%. The smallest glacier change was at section TS-6. The glacier area in its basin was 17.1 km$^2$ in 1989 and 13.44 km$^2$ in 2019, a change of 21.4% (Figure 9b).
Figure 9. Glacier area changes in the basins of glacial meltwater-dominated river sections during 1989-2018 (as the TS-7 values are relatively large, to better show their changes, they are represented by a line). (a) changes in total glacier area; (b) changes in glacier area at a single basin scale.

4.3.2. Changes in Temperature and Precipitation

For rivers recharged by glacial meltwater, the decrease of glacier area in the basin was mainly due to the increase of regional temperature. In addition, for rivers without a glacial recharge, changes in precipitation within the basin have a direct impact on discharge changes. The temperature and precipitation changes during the study period were analyzed to reveal the correspondence between climatic factors and discharge changes. For the basins of 10 precipitation-fed river sections, since they were in the same geographic unit, they are analyzed as a whole. Figure 10 shows that both the temperature and precipitation exhibited an overall increasing trend during 1989–2018, with a rate of 0.006 °C/year and 1.93 mm/year ($p < 0.01$), respectively. In 2015, the temperature was at the highest multiyear value, with an average temperature in the nine river section basins of 2.11 °C, while the lowest value was recorded in 1996, with an average temperature of 0.44 °C (Figure 10a). The precipitation in 2016 was relatively large, with average precipitation in the 10 river section basins of 1111.36 mm, while the precipitation in 1991 was lower, and the average precipitation was 667.04 mm (Figure 10b).

Figure 10. Temperature (a) and precipitation (b) changes in the basins of studied river sections.

4.4. Discharge Changes in Representative River Sections

Among the 19 river sections we studied, four representative sections were selected for detailed analysis, in which TS-B1 and TS-7 were glacial-meltwater-dominated sections, and TS-B4 and TS-1 were precipitation-dominated sections. Figure 11 shows the river systems of the four representative section basins.
Figure 11. The basins controlled by representative river sections (a) TS-B1; (b) TS-B4; (c) TS-7; (d) TS-1.

Section TS-B1 is located upstream of the Bortala River and controls the above basin of approximately 260 km$^2$ (Figure 11a). The discharge ranged from 0 to 77.61 $\times$ 10$^6$ m$^3$, with an average value of 14.91 $\times$ 10$^6$ m$^3$. In the last 31 years, the discharge showed a decreasing trend, with a change of −3.64% (Figure 12). Due to the large catchment area, the underground water storage and the river-cutting depth were correspondingly large. Therefore, the discharge of this section was much larger than that of other river sections, and the maximum discharge reached 77.61 $\times$ 10$^6$ m$^3$ in October 2000. Its headwaters are 4013 m above sea level and modern glaciers are distributed in the basin, with a glacier area of 11.08 km$^2$, accounting for 4.26% of the total area. From 1989 to 2003, the glacier change was small, and glaciers covered an area of approximately 17.61 km$^2$. However, from 2003 to 2019, the significant increase in temperature in this area led to the retreat of glaciers. As shown in Figure 13, the small glaciers in the western part of the basin completely disappeared in 2019, and the total glacier area shrunk to 11.08 km$^2$.

Section TS-7 is located in Bayingou Ranch, Wusu City. The monthly discharge was between 0.04 $\times$ 10$^6$ m$^3$ and 37.68 $\times$ 10$^6$ m$^3$, with an average discharge of 15.66 $\times$ 10$^6$ m$^3$ and a decreasing rate of 3.75%. The discharge of this section shows an obvious decreasing trend during the study period, especially since, in 2007, the discharge has decreased by 29% compared to the previous period. The topography of the basin controlled by this section is high in the south and low in the north, and its headwaters are 5060 m above sea level. A large number of modern glaciers were distributed in the basin, covering an area of
approximately 177.19 km² and accounting for 16% of the total basin area. In addition to the glacier cover, there was a large area of natural grassland in the northern part of the basin. The glacier area has changed greatly in recent years according to our analysis on discharge variations. In 1989, the glacier area was approximately 232.11 km², accounting for 21% of the total area, but, in 2007, the glacier area shrank to 198.04 km². By 2019, the glacier area has retreated to 177.19 km², accounting for only 16% of the total area (Figure 13h). The shrinkage of mountain glaciers and even the disappearance of small glaciers seemed to be the main reasons for the decrease in discharge in glacial-melt-dominated river sections.

Figure 12. Time series discharge changes in representative glacial-meltwater-dominated river sections.

Figure 13. Glacier area changes in the basins controlled by sections TS-B1 (a–d) and TS-7 (e–h).

TS-B4 and TS-1 were the typical precipitation-dominated river sections. TS-B4 is located in the tributary of the Bortala River, which controls an area of approximately 58 km². Its discharge ranged from $0.27 \times 10^6$ m³ to $28.67 \times 10^6$ m³, with an average discharge of $4.69 \times 10^6$ m³. The multiyear monthly discharge shows an increasing trend in the last 31 years, especially after 2008, with a change of 1.59% (Figure 14). In May
2016, the highest interannual monthly discharge occurred, which was $11.06 \times 10^6$ m$^3$. The basin area controlled by this section is small. There is no glacier cover, and the river’s replenishment mainly depends on atmospheric precipitation. There was a large area of natural grassland in the basin, and the vegetation coverage gradually decreased from 2008 to 2019. Precipitation in the basin of this section had an increasing trend from 1989 to 2018, at a rate of 9.77 mm/a.

Section TS-1 is located in the middle of the Tianshan region and controls an area of approximately 973 km$^2$. The monthly discharge ranged from $6.01 \times 10^6$ m$^3$ to $186.90 \times 10^6$ m$^3$ from 1989 to 2019, and the average discharge was $42.43 \times 10^6$ m$^3$. The monthly discharge had an increasing trend over the study period, and the change was 10.43%. In September 2007, the highest monthly discharge occurred, which was $186.91 \times 10^6$ m$^3$, and the minimum monthly discharge occurred in March 1999, which was $6.01 \times 10^6$ m$^3$. The basin was mostly covered by a large area of meadow grassland and forest, and the vegetation coverage in the basin decreased year by year during the study period. Precipitation was the most important source of river replenishment in the basin. Precipitation increased overall from 1989 to 2018 at a rate of 1.71 mm/a.

5. Discussion

5.1. Challenges of Discharge Estimation Results

Traditional discharge measurements are based on local hydrological stations, which regularly observe the water level and obtain discharge information through the conversion of the water level and discharge curve. Complete monitoring is still subject to technical, financial, and institutional factors. Low-altitude remote sensing (i.e., UAV) has the characteristics of convenience, speed, and high image resolution, which can greatly improve the measurement efficiency of river discharge and rapid inversion under conditions such as ungauged areas, harsh environments, and noncontact emergency monitoring of sudden disasters.

Satellite remote sensing has the advantage of high temporal resolution and can be coupled with UAV data to obtain long-term river discharge. However, for rivers with different widths, the spatial resolution of satellite remote sensing has certain limitations. If the spatial resolution of a satellite sensor is coarser than the scale of spatial heterogeneity of the ground surface, a mixture of disparate substances is inevitably contained in a pixel [66]. To solve this problem, the spectral unmixing method was used to extract the water bodies in studied river sections. It is easier to obtain information about large rivers than smaller rivers. The estimation results were more accurate for river sections, such as TS-2 (43.25 m) and TS-7 (32.25 m), with larger river widths. For river sections with widths that are too small, such as TS-W1 (2.47 m), TS-W3 (2.42 m), and TS-W4 (3.88 m), there may be some errors in the inversion of the river width, but this will not affect the overall trend of discharge changes over the years.
To further improve the estimation accuracy, higher resolution satellite images, such as GF images, can be used to reduce the errors in the inversion and achieve more accurate discharge data. With the rapid advance of remote sensing technology, obtaining more accurate water information is an important research trend in the future.

5.2. Comparative Analysis of Research Results

In recent years, some scholars have conducted related research on the glacial/snow meltwater discharge in the Tianshan Mountains and have achieved meaningful results [23,67,68]. The severe glacier retreat and reduced meltwater discharge we have observed were consistent with findings from other areas of the Tianshan Mountains. Kogutenko et al. [69] estimated the glacier and runoff changes at different time steps in the three sub-basins of the Ile River Basin and found that the discharge has decreased in all three sub-basins, and the contribution of glacier melting to the total river runoff has been declining since the 1980s. This change was attributed to the sharp retreat of the glacier area. Zhang et al. [26] discovered that the runoff of Toxkan River and Kumalak River, which originated from the Tianshan, showed an increasing trend during 1979–2002, but a significant negative trend since 2002. They considered that the decrease of precipitation combined with glacier retreat were the main reason for the decrease of runoff in Toxkan River, while the decrease of summer temperature is the main reason for the decrease of runoff in Kumalak River.

By contrast, there are also some studies that have found that the discharge of some rivers mainly fed by glacial meltwater in the Tianshan Mountains was increasing over the past few decades [23,70]. Most of these previous studies have explored the changes in glacial meltwater runoff in major river basins, and they mainly focus on the annual runoff changes of the large rivers [26,67]. In addition to the melting water of glaciers and snow, the discharge supply sources of these major rivers also include precipitation, groundwater, or mixed recharge of various combinations in plain areas. However, for our research, the sections we studied were all located on the tributaries of the main rivers, and were analyzed at a sub-basin scale. In terms of altitude, most of them were located in high-altitude areas, and mainly dominated by glacier and snow meltwater, with almost no other supply sources. Since the discharge variation depends on various factors, such as watershed characteristics and the source of replenishment, our results are not comparable to other studies in terms of the specific magnitude of discharge changes.

For the Tianshan region, incorporating UAV data with satellite remote sensing to study long-term time series of runoff variations in mountain catchment areas is a new field. There have been some studied of applying UAV data to estimate runoff. Yang et al. [48] used UAV data to the estimation of river discharge in 10 sections located in the Tibetan Plateau and Dzungaria Basin. The overall qualification rate of the estimated discharge was 70%, with the NSE as 0.97. They compared several discharge estimation algorithms to explore the best performance algorithms at different spatial levels and, finally, demonstrated the advantages of UAV techniques. Their proposed approaches offered new solutions for modeling river discharge in ungauged areas. Their research provided a reference for our study in the acquisition method of river sections and runoff estimation, but long-term runoff estimation was not previously carried out. Based on this research, we use UAV data to establish a high-precision digital river section model, combine it with satellite remote sensing data, and monitor the long-term time series of runoff data. The runoff estimations and corresponding analysis are scientifically valuable for the allocation and management of water resources in the ungauged area of the Tianshan Mountains.

6. Conclusions

As the main components of solid reservoirs in mountainous areas, glaciers play an indispensable role in regulating regional water resources. To reveal the pattern of long-term variations in mountain discharge in ungauged areas, this study used remote sensing hydrological station technology and satellite remote sensing images to analyze the
discharge changes and their causes at 19 typical river sections in the Tianshan Mountains during 1989–2019. We conclude:

(1) The NSE, RMSE, and average qualification rate between the measured discharge and estimation results from the UAV data were 0.98, 8.49 m³/s, and 80%, respectively. This means that the discharge estimation method based on UAV and satellite remote sensing, is feasible in monitoring river discharges in the Tianshan region.

(2) According to the water supply source of the river, the study sections were divided into two types: glacial-meltwater-dominated river sections (9 sections) and precipitation-dominated river sections (10 sections). The monthly discharge of glacial-meltwater-dominated river sections showed a decreasing trend during 1989–2019, with an average decrease of 2.46%, and had obvious seasonal variations. The monthly discharge of precipitation-dominated river sections exhibited an increasing trend, with an average increase of 2.27%, and the seasonal discharge presented a double-peak trend in summer and spring.

(3) The shrinking, and even disappearance, of mountain glaciers was the main reason for the decrease in discharge in glacial-meltwater-dominated river sections. The glacier area presented a decreasing trend during the study period, with a decreasing rate of \(-4.98\) (\(p < 0.01\)), and the discharge change in these sections had the same trend. The increase in discharge in precipitation-dominated river sections was mainly attributed to the increase of precipitation at a rate of 1.93 mm/year, which is consistent with the discharge trend.

Overall, this research gives full play to the advantages of UAV and conducts a comprehensive study on the discharge changes of 19 river sections in the Tianshan Mountains. Although previous research for meltwater runoff in the Tianshan Mountains has been reported, comprehensive analysis at the sub-basin scale was rarely conducted. Our study provides new insights into the time series river discharge estimation in the remote or data-scarce regions. The method has extensive applications for rapid and convenient acquisition of river information in ungauged areas in the future, and provides an important reference for water resources monitoring.

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