Recent glacier changes and their impact on water resources in Chon and Kichi Naryn Catchments, Kyrgyz Republic

M. Duishonakunov, S. Imbery, C. Narama, A. Mohanty and L. King

ABSTRACT

Naryn basin, which has the largest river catchment area in Kyrgyz Republic and many mountain glaciers, is a huge 'water tower' for Kyrgyz Republic and Uzbekistan. Thus, the behavior of its glaciers has a large impact on water resources for the arid flat plain below, providing water for residents, irrigation, and energy in Kyrgyz Republic and Central Asia. We investigated the recent glacier condition in the Naryn basin (Chon Naryn and Kichi Naryn catchments) using topographic maps of 1:25,000 scale and ALOS/AVNIR-2 satellite imagery. For the 45-year period 1965–2010, glacier area decreased by 17.4% in the Akshyirak massif, and by 20.8% in the Borkoldoy, 21.9% in the Jetim, 24.6% in the Jetimbel, 28.9% in the Naryn, 20.8% in the Sook, 20.9% in the Teskey (south-slope glaciers), and 17.8% in the Uchemchek mountain ranges. The dramatic shrinkage was greater for south-facing than for north-facing glaciers, with respective area losses of 23.6 and 19.8%. The glacier shrinkage might affect not only irrigation water withdrawals during summer but also the planning of four cascade power stations to be constructed in the Chon Naryn and Kichi Naryn catchments.

Key words | ALOS satellite data, glacier changes, Naryn basin, runoff, Tian Shan, water resources

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INTRODUCTION

Scientific discussions suggest that, regardless of whether climate change has natural or anthropogenic causes, it will have strong effects on glacier recession, regional hydrological balance, and economic sustainability in arid and semi-arid regions of Central Asia (Alamanov *et al.* 2006; Fujita *et al.* 2011). The probable potential effects of climate change on water resources are of paramount importance because of the high dependency on fluvial water originating from mountains. Monitoring water resources and planning water use and the balance between water use and water resources are more important issues in this region because the majority of the water supplied from Central Asian mountains is used within the irrigation zones of arid flat plains (Report of Eurasian Development Bank 2009; Agrawala *et al.* 2001). Demand will increase in the future due to food- and energy-security concerns in the region, which may lead to water wars among nation states.

Mountain glaciers are one of the major water resources in Central Asia. Runoff in the arid flat plains is determined by annual precipitation and evaporation, which are related to temperature. However, glaciers collect solid precipitation in winter and release water to the arid flat plains during summer (Hagg *et al.* 2007). The expected decrease in glaciers will lead to a reduction in surface runoff during summer because mountain runoff from glacier melting accounts for 30–40% of the contributions to river discharge during summer (Dikich 1999; Dikich & Mikhailova 1976). This could result in water deficits in the Central Asian region. Recent investigations of glacier change in the Tian Shan Mountains using various remotely sensed data have shown a trend of shrinking mountain glaciers in the past decade (Avsuk 1953; Aizen *et al.* 2006, 2007; Bolch 2007; Kuzmichenok 1990; 2008; Narama *et al.* 2009, 2010; Wenbin & Kaiming 2011). However, these studies did not address the

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issue of water resources or the potential impact of glacier shrinkage on water resources. Additionally, the Naryn basin is important not only for water supply but also for water power, providing two-thirds of the electricity needs of Kyrgyz Republic. The hydropower potential of the Naryn basin is 6,956.3 kWh, and it irrigates 400 km^2 of agricultural land (Mamatkanov *et al.* 2006).

Thus, the Naryn basin has a significant influence on socio-economic activity in Central Asian countries through its supply of both water and electricity. In this study, we focus on the impact on water resources of the glacier condition in the Chon and Kichi Naryn catchments, which make a large contribution to the Naryn basin due to their many glaciers.

STUDY AREA

The Naryn basin is the largest river basin in Kyrgyzstan. Its flow runs from east to west across the territory of Kyrgyz Republic, and its length, before merging with the Syr-Darya, is more than 700 km. The major water resources of the Naryn basin are fluvial water from rain and snow and glaciers in the upstream area. There are 654 confirmed glaciers in the Naryn basin (Glacier Inventory of USSR 1973, 1977). We investigated the recent condition of glaciers in the Chon Naryn and Kichi Naryn river catchments in the eastern part of the Naryn basin (Figure 1). These catchments include 69% of the glacier area in the Naryn basin, including 607.9 km^2 (10.8% of the basin) in the Chon Naryn and 344.7 km^2 (8.9% of the basin) in the Kichi Naryn. The catchments include eight mountain ranges, the Akshyirak, Borkoldoy, Naryn, Sook, Jetim, Jetimbel, Teskey, and Uchemchek.

Two meteorological stations are shown in Figure 1, along with the seasonal variation in monthly precipitation for 1930–2010 for selected stations. The climatic condition of the upper part of the Naryn basin is very severe, and each location within it has an average annual air temperature below 0 °C. In the lower part of the upper Naryn basin, annual precipitation is 292 mm at the Naryn meteorological station (2,039 m) and 311 mm at the Tian Shan meteorological station (3,614 m; Figure 1). Annual precipitation is low, and maximum precipitation occurs in summer (May–August) because the topographical complexity of the Tian Shan Mountains combined with the zone of interaction between the westerlies and the Siberian High affect precipitation in the Tian Shan Mountains (e.g. Aizen *et al.* 1995; Aizen & Aizen 1997). The basin has clear cloudless weather with less precipitation during winter, which allows the use of the Arabell, Kumtor, and Chon Naryn catchments as winter pastures. In this paper, local Kyrgyz geographic names are used according to Barataliev (2004) and Barataliev *et al.* (2004).

DATA AND METHODS

Data and processing

To clarify recent glacier changes in the two catchments, glacier boundaries were delineated on 1:25,000 topographic maps based on aerial photography collected in the 1960s and Advanced Land Observing Satellite (ALOS) Advanced Visible and Near Infrared Radiometer type 2 (AVNIR-2) satellite datasets acquired during 2008–2010. The ALOS/AVNIR-2 (70 × 70 km) data that were used consist of four bands, three visible (0.42–0.69 μm) and one near infrared (0.76–0.89 μm), and have a spatial resolution of 10 m (JAXA 2009). We used orthorectified ALOS/AVNIR-2 products by JAXA in this study. To reduce the potential uncertainty in glacier mapping with satellite data, we selected satellite imagery acquired during the glacier ablation period that had minimal cloud cover or nearly cloud-free conditions. The topographic maps were scanned at 700 dpi and were projected by georeference on ArcGIS 9.2.

Glacier outline extraction

The outlines of glaciers were extracted manually by visual interpretation of the 2008–2010 ALOS/AVNIR-2 images (Figure 2). The areas of the extracted glacier polygons were computed using ArcGIS 9.2, with omission of glacier areas smaller than 0.1 km^2. We added the glacier polygon data to attribute data such as mean elevation, minimum elevation, maximum elevation, area, and aspect in each glacier-area class (Tables 1 and 2). The change in the terminus position of some glaciers was observed during fieldwork from 2010 to 2012 using GPS measurements.

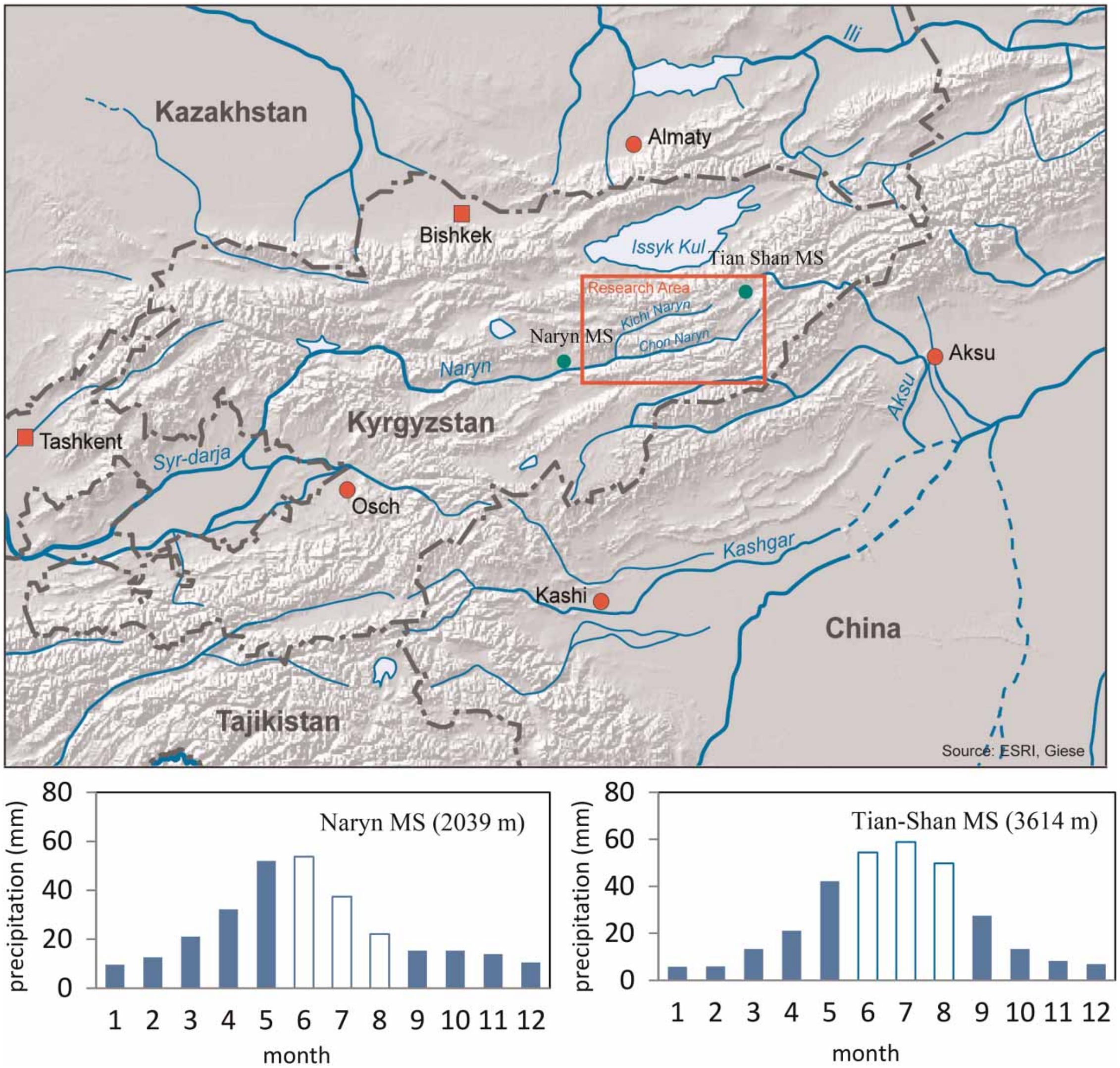

Figure 1 | Location of the Naryn basin. The black rectangle shows the study area. Yellow dots show the locations of the two meteorological stations. Figures at the bottom show the seasonal variation in monthly precipitation for 1930–2010 for selected stations (white bar: JJA). The full color version of this figure is available in the online version of this paper, at http://www.iwaponline.com/ws/toc.htm.

RESULTS

Characteristics of glacier distribution

We investigated 654 glaciers in the two catchments: 15 glaciers in the Akshyirak massif, 126 in the Borkoldoy range, 130 in the Jetim range, 89 in the Jetimbel range, 80 in the Naryn range, 41 in the Sook range, 95 in the Teskey range (south slope glaciers), and 78 in the Uchemchek range (Table 2). Of these, 513 glaciers (435.2 km^2) in the northwest, north, and northeast sectors of the eight mountain ranges account for 74.3% of the total glacial area. The characteristics of the glacier distribution in the study area were analyzed in relation to the statistical relations among topographic parameters of the attribute data (mean elevation, minimum elevation, maximum elevation, area, and aspect in each size class; Tables 1 and 2). A majority of the parameters clearly showed evidence of changes in the regional characteristics of the glacier distribution. Figure 3 shows that the relationship between glacier

Figure 2 | Extraction of glacier outlines in the Borkoldoy range from ALOS/AVNIR satellite images and topographic maps (1:25000). Dark-blue glacier outlines of 2010, and bright-blue outlines of 1965. The full color version of this figure is available in the online version of this paper, at http://www.iwaponline.com/ws/toc.htm.

Table 1 | The basic information of investigated glaciers (1965)

Class (km²)	Number	Total area (km²)	Total area %	Minimum elevation (m)	Maximum elevation (m)	Mean elevation (m)
0.1–0.5	395	98.1	16.8	3,580	4,960	4,187
0.5–1	177	186.6	31.9	3,510	4,960	4,214
1–2	40	70.9	12.1	3,580	5,020	4,232
2–5	30	120.6	20.6	3,720	4,880	4,222
5 >	12	109.2	18.6	3,600	5,170	4,258
Total	654	585.4	100	3,510	5,170	4,223

area and aspect indicates that large glaciers are concentrated on northern aspects. The majority (74.3%) of the total area is located in three sectors, i.e. northwest, north, and northeast. Table 2 shows the distribution of glaciers classified according to area class (0.1–0.5, 0.5–1, 1–2, 2–5, and >5 km^2) for the eight mountain ranges. In three mountain ranges, the distributions of glacier size classes are similar: glaciers with areas of less than 1 km^2 occupy 78% in the Jetimbel range, 86% in the Naryn range, and 84% in the Sook range, and there are no glaciers larger than 5 km^2 in these ranges. In the Akshyirak massif, small glaciers of less than 1 km^2 occupy 11.5%, and larger glaciers of more than 5 km^2 occupy 48%. In the other (Borkoldoy, Jetim, Teskey, and Uchemchek) ranges, the distribution of glacier size classes is different; glaciers with areas of less than 1 km^2 occupy 39–50% and those larger than 5 km^2 occupy 14–28%. The glacier termini elevations in these four mountain ranges are quite different: 5,170 m in the Borkoldoy range, 4,840 m in the Teskey range, 4,825 m in the Jetim range, and 3,510 m in the Uchemchek range. The average glacier termini elevation in the study area is 4,223 m.

Table 2 | Derived glacier parameters (~2010) for eight mountain ranges

	Range	Akshyirak	Borkoldoy	Jetim	Jetimbel	Naryn	Sook	Terskey	Uchemchek
Area (%)	0.1–0.5 (km^2)	2	11	15	24	46	14	18	19
	0.5–1 (km^2)	10	27	30	54	38	72	22	30
	1–2 (km^2)	18	14	6	17	0	14	8	24
	2–5 (km^2)	23	26	29	5	16	0	24	13
	5> (km^2)	47	22	20	0	0	0	28	14
Aspect (%)	N	2	32	48	55	30	58	3	40
	NE	0	20	15	16	33	16	7	12
	E	0	0	2	6	4	6	9	0
	SE	0	5	5	0	0	4	39	0
	S	0	2	1	0	0	0	32	0
	SW	9	2	3	1	0	6	3	0
	W	9	8	2	2	6	4	2	14
	NW	80	31	24	20	18	6	5	34
Total glaciers measured		15	126	130	89	80	41	95	78

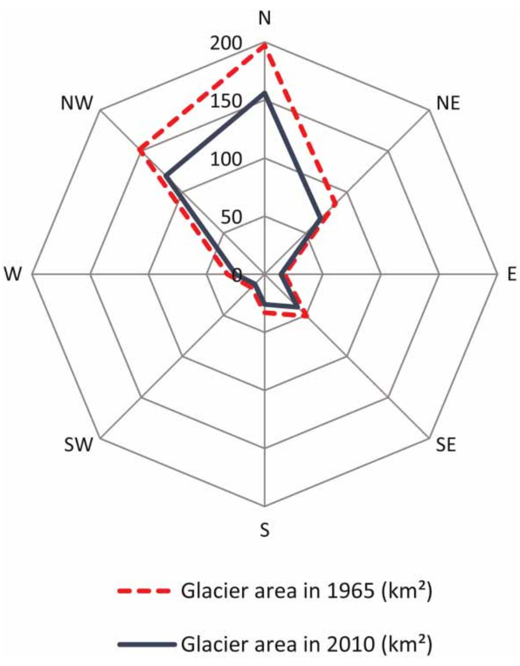

Figure 3 | Distribution and area change of glaciers with different aspects.

Changes in glacier area from ~1965 and ~2010

We investigated glacier shrinkage in the two catchments using 1:25,000 topographic maps (~1965) and ALOS AVNIR-2 satellite data (~2010). The total area of the 654 studied glaciers decreased by 21.3% (from 585.4 to 460.5 km^2) during ~1965 to ~2010 (Table 3). Glacier area decreased by 17.4% in the Akshyirak massif, 20.8% in the Borkoldoy range, 21.9% in the Jetim range, 24.6% in the Jetimbel range, 28.9% in the Naryn range (north slope), 20.8% in the Sook range, 20.9% in the Teskey range (south slope), and 17.8% in the Uchemchek ranges (Figure 4). The greatest shrinkages in area occurred in the Naryn (28.9%), the Jetimbel (24.6%), and Jetim ranges (21.9%).

Table 3 | Summary of glacier area changes in eight mountain ranges

Mountain area	Average area (km^2)	Area (km^2) 1965	2010	Area change (%) (1965–2010)
Akshyirak	2.66	39.9	32.96	–17.4
Borkoldoy	1.13	142.0	112.50	–20.8
Jetim	0.96	125.1	97.75	–21.9
Jetimbel	0.66	58.7	44.25	–24.6
Naryn	0.42	33.3	23.65	–28.9
Sook	0.76	31.4	24.86	–20.8
Terskey	0.96	91.0	71.96	–20.9
Uchemchek	0.82	64.0	52.61	–17.8
Total	0.90	585.4	460.54	–21.3

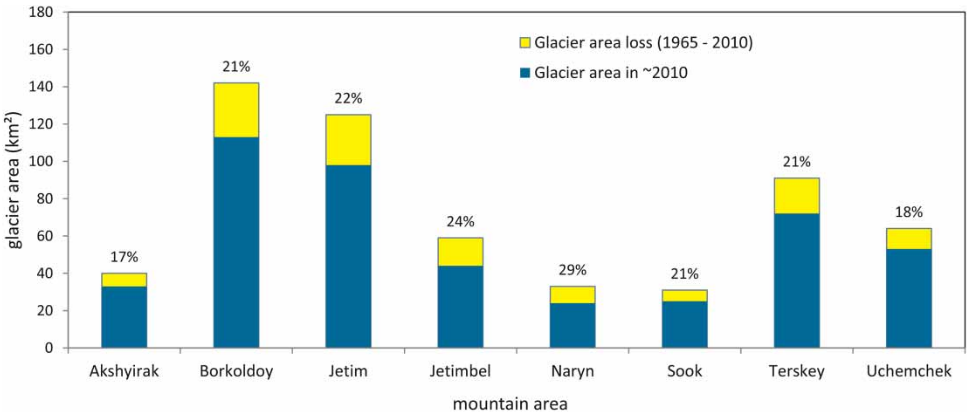

Figure 4 | Changes in total glacier area in eight mountain regions for ~1965 and ~2010.

Additionally, the percentages of glacier loss in the different size classes were investigated. Small glacier areas are sensitive to microclimate changes and local glaciological factors (Jóhannesson *et al.* 1989; Kuhn 1995; Nesje & Dahl 2000). The relative abundances of glaciers in the different size classes strongly affected the total glacier-area loss percentage. Regions dominated by small glaciers may be more sensitive to change because of the shorter response time to climate variability of small glaciers (Bahr *et al.* 1998). In the study area, 89% of glaciers are less than 1 km^2. A comparison of glacier size class distributions and glacier shrinkage amounts revealed that the Naryn range, which has many small glaciers (<1 km^2), experienced large glacier shrinkage (28.9%), whereas, the Akshyirak massif, which has many large glaciers (>5 km^2), had less shrinkage (17.4%; Tables 2 and 3). There were also dramatic differences between glaciers located on northern and southern slopes in these changes (Figure 3). On northern slopes, 513 glaciers decreased by 19.7%, but on southern slopes, 78 glaciers were reduced by 24.1%.

DISCUSSION

Recent glacier shrinkage related to local climate changes

Glacier sizes distributed are variable in the study area. The Naryn range, which is characterized by many small-scale (less than 1 km^2) glaciers, is one of the most significant glacier retreat areas in the study region (Table 3). The Akshyirak massif and the Uchemchek range have not shown much glacier shrinkage because a majority of each area is dominated by large glaciers on north-facing slopes (more than 86%). Large glaciers have longer response times than do considerably smaller ones in other ranges (Hagg *et al.* 2012); glacier size might make the regional differences of glacier shrinkage in eight mountains under the same climate environment. However, overall, glaciers represent a more sustained reaction to recent climate change in the Chon and Kichi catchments. In addition, the results of a previous study by Narama *et al.* (2006) and Kutuzov & Shahgedanova (2009) of the Teskey range and Hagg *et al.* (2012) in Chon Naryn were similar to this study, and these retreats have a significant impact on watershed discharges to lowland arid and semi-arid areas in Central Asia.

We analyzed the recent trends in air temperature and precipitation in relation to recent glacier shrinkage. We investigated trends in temperature in warm (IV–IX), cold (X–III), and summer months (VI–VIII) at the Tian Shan meteorological station (MS; 3,614 m) between 1930 and 2000. The trends at the Tian Shan meteorological station were as follows: (1) the trend in average annual temperature was 0.023 °C/year; (2) the trend in average temperature for the warm months was 0.017 °C/year; (3) the trend in average temperature for the cold months was 0.026 °C/year; and (4) the trend in average summer temperatures was 0.016 °C/year. The overall precipitation recorded at the metrological stations showed a decreasing trend (Figure 5). The precipitation trend at the Tian Shan meteorological station

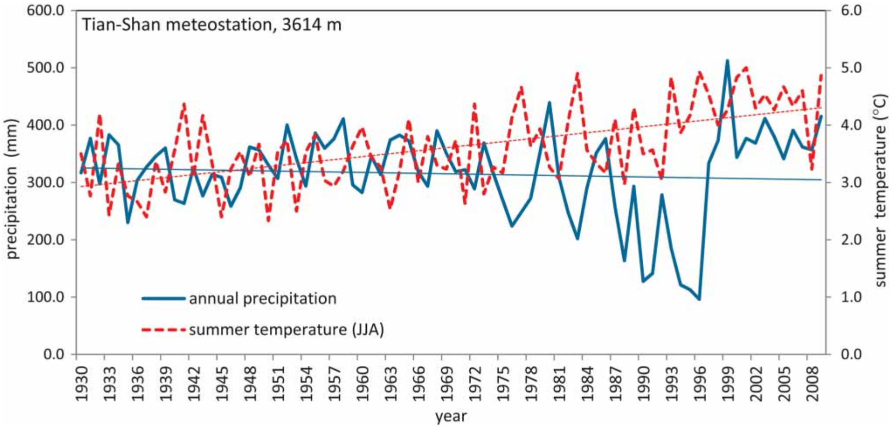

Figure 5 | Annual precipitation amount and mean summer air temperature| (JJA) at the Tian Shan meteorological station.

showed a decreasing trend between 1965 and 2010 and also a decrease of 28 mm of precipitation in the warm-month period over the last 80 years. At the new place of Tian Shan meteorological station (3,659 m) between 2000 and 2012, winter trends were also positive and temperature increases in the warm-month and the summer periods. In contrast, precipitation decreased in this period. The recent glacier shrinkages are due to manifold slight increases in temperature and decreases in precipitation, which leads to (1) decreased snow accumulation of glaciers in spring to early summer season and (2) a decreasing albedo effect for the protection of glacier ice (Dikich & Hagg 2004; Hagg & Braun 2005).

Impact on water resources

It is important to understand the impact of glacier shrinkage on water resources in lowland arid areas. Any change in the glacier regime has a severe impact on Naryn River tributary water entering the Syr-Darya, which is important for Kyrgyzstan and Uzbekistan. Hagg *et al*. (2007) estimated significant changes in seasonal runoff volume related to glacier area loss in the Tian Shan assuming a $2 \times CO_2$ scenario from 2050 to 2075. Decreased glacier area leads to a decrease in summer glacier-melt discharge. The distribution of glaciers among the main tributaries of the Naryn basin is extremely uneven, and the contribution of glacier water to total runoff also varies among the tributaries. In this paper, based on identified regularity of spatial distribution of rainfall, relations of melting ice and snow on the temperature (Dikich 1999) determined the volume of glacial runoff in the Chon and Kichi Naryn rivers. Table 4 contains the values of runoff norm and the share of glacier melt water are analyzed using Dikich's method. The contribution of glacier runoff to the summer discharge is large in both catchments. After the Chon Naryn, the Kichi Naryn catchment is the second major tributary of the Naryn River by amount of glacier coverage. The decreases in glacier area are partly due to decreased precipitation, which not only affects the availability of water for irrigation but also has a cascading effect on the hydropower works in the Toktogul, Kurpsay, Tashkumyr, Shamaldysay, and Uchkurgan parts

Table 4 | Total and glacier runoff of the Chon Naryn and Kichi Naryn catchments

Hydrological station	Average annual discharge, 1930–2010 (m^3/sec)	Runoff volume (mln m^3)	Glacier runoff (mln m^3) From snow melting	From ice melting	Total	Share of glaciers in total runoff (%)	Share of glaciers in summer runoff (%)
Chon Naryn	46.5	1479	196.5	258.5	455.0	30.7	51.3
Kichi Naryn	41.1	1340	201.6	119.7	321.3	23,9	36.5

of the Kambarata-2 project. At present, the upper Naryn hydropower cascade is planned as part of four consecutive steps, the Akbulun, Naryn-1, Naryn-2, and Naryn-3 hydropower stations, with a total capacity of 191 MW and an annual output of 1,055 billion kWh. Construction of the Akbulun hydropower station was started in May 2013.

CONCLUSION

The total area of glaciers of the Chon Naryn and Kichi Naryn catchments of the Naryn basin decreased significantly between ~1965 and ~2010, with a total glacier retreat of 21.3%, due to increasing summer temperatures and decreasing precipitation. This glacier shrinkage varied with regional climate and differed among glaciers of different sizes and according to elevation. The largest amount of glacier shrinkage occurred in the Naryn range (28.9%) because of the dominance of small-scale glaciers on north-facing slopes. Strong glacier retreat can produce large quantities of water in a short time period, which may cause hazards in downstream areas, and continuing glacier shrinkage will result in water and energy deficiencies in the region. The present state of these glaciers needs to be evaluated and monitored scientifically for reasonable development and use of regional water resources and water cycle models, and for regional economic planning.

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