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

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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.

Keywords: ALOS satellite data; glacier changes; Naryn basin; runoff; Tian Shan; water resources

INTRODUCTION

The issue of water availability and the probable potential effects of climate change on water resources are of paramount importance to arid and semi-arid regions of Central Asia. In the last decade the consumption of water increased exponentially at regional and local level, which will further turn water supply security as major challenges to these countries the supply initially will be affects by accelerated shrinkage of glaciers threatened by climate crisis in upcoming days. Majority of the catchment area of the region fall within irrigation (Report of Eurasian Development Bank, 2009) and water demand in this region will increase in connection to food and energy security will further intensify the water war between the states in the region. The solid precipitation are collected in winter in form of glaciers and released as melt water in summer (Hagg et al., 2007), which are potent source of water supply during drought years when no other sources are available. Expected decrease in glaciers will lead to reduction in river runoff in summer resulting in deficit of water in Central Asian region.

Climatically, the Tian-Shan Mountains are characterized by interactions between Westerlies and the Siberian High over complex mountain topography (Aizen et al., 1995). Thawing of glaciers is wholly compensated by atmospheric precipitations. As to "glacial feeding", i.e. considerable contribution of water from melted snow providing increase of water flow is possible only in case of glaciers' degradation (Kuzmichenok, 2008) . The stable decrease of modern glaciations happens because of global warming and ambiguous change of precipitations in high-altitude zone of Tian-Shan. There are few research yet done on comprehensive understanding and evaluation on current state of glaciers in Central Asian region. The present study aim is to fill this knowledge gap in Central Asian region while contributing contribution to recent retreat of glaciers due to climate change and their potential effect on water resources in Naryn basin.

STUDY AREA

As per the Inventory of USSR Glaciers (1973, 1977), 654 glaciers were identified on the eight mountain ranges in the 1960s, the range with the large number of modern alpine glaciers in upstream catchments of Naryn basin, Tian-Shan. The Naryn is the largest and abundant river of Kyrgyzstan – on the territory of the republic it flows from east to west at the length of more than 700 km before interflowing with Syr-Darya. The Naryn has snow-glacial feeding, moreover glaciers in upper reaches are main source of feeding as well as seasonal snow in middle and low stream. Our research area includes upper east part of Naryn basin, i.e. basins of Chon Naryn and Kichi Naryn rivers (Figure 1). The area of glaciation of Chon Naryn amounts to 607.9 km^2 (10.8% of basin) and Kichi Naryn's area is 344.7 km^2 (8.9%). Almost ¾ of area of all glaciers of Naryn basin is located here. Upper Chon Naryn valley, upper reaches of Kichi Naryn and following mountain ranges are located in the investigated area, namely: Akshyirak, Borkoldoy, Naryn, Sook, Jetim, Jetimbel, Terskey and Uchemchek. We have analyzed 654 glaciers on these mountain ranges. Glaciers on south slope of Terskey mountain of investigated area as well as glaciers of west and north-west of Akshyirak mountain have been investigated. The wide spread of mountain range and inter-mountain valley is characteristic for orographic structure of the territory. First of all distinctiveness of the area's nature is defined by considerable altitude of the area. The investigated territory is wholly located at 3000 m above sea level. Separate peaks in Akshyirak and Borkoldoy mountains are 5000 m and higher, however related height of mountain ranges are small over bottoms of inter-mountain valley and usually do not exceed 1000 m. We had following criteria for choosing the Upper Naryn basin as a investigation area: 1). 69% of glacier area of all glaciers in Naryn basin are located in study area. 2). The Naryn is largest river of Kyrgyzstan providing huge water flow and thereby essentially influencing on economic activity of Kyrgyz Republic as well as Uzbekistan, Kazakhstan and Tajikistan.

The climate of Upper Naryn is very harsh and continental. Negative annual temperatures are marked everywhere here, frost-free period is absent, and snow often falls even in July. Here in many places the permafrost is being observed. Annual precipitation volume is not huge. Per year in central part of valley precipitation falls less than 200 mm and 300 mm in upper stream. However, precipitation markedly increases with altitude. Main volume falls in summer. The Tian-Shan and Naryn weather stations are located here within more than 80 years (Figure 1).

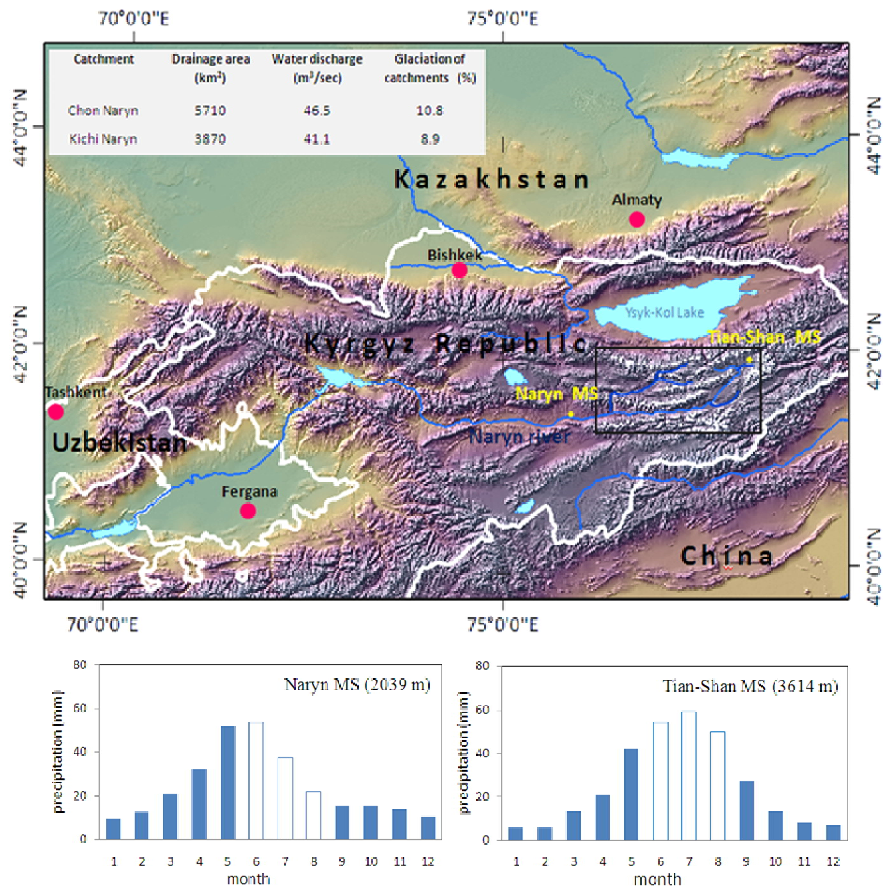

Figure 1. Studied upstream catchments in the Naryn basin. Black rectangle shows the study area. Yellow dots show the locations of the two meteorological stations. Figures at the bottom show the seasonal variation in monthly precipitation for 1930–2010 for selected stations (white bar: JJA).

DATA AND METHODS

Data and processing

The satellite imagery was acquired during ablation period with minimal cloud cover and nearly cloud free conditions were used in the study to reduce potential uncertainty in glacier mapping. The boundary and termini positions were delineated 1:25 000 topographic maps based on aerial photography collected in 1960s and ALOS AVNIR-2 satellite data sets during 2008 – 2010. The topographic maps were scanned at 700 dpi and digitized contour interval and identified spot heights were used to produce a DEM (Digital Elevation Model) for the study area. The remotely sensed images were co-registered and orthorectified using the corrected topographic maps. ALOS/AVNIR-2 (70×70 km) were used consists of four bands from a visible to near-infrared radiometer with a spatial resolution of 10 m (JAXA, 2009). The ALOS data was ortho-projected using topographic map (1:25,000) and Shuttle Radar Topography Mission (SRTM3) with an overall RMSE less than 30 meters by using the PCI Geomatica Orthoengine version 10.1 software. The data was further rectified by using 50 ground control points, evenly distributed across the image.

Glacier outline extraction

The outlines of glaciers were extracted manually using visual interpretation of pan-sharpened ALOS (AVNIR-2) images (2008–2010) at high resolution (10 m, Figure 2). The areas of the extracted glacier polygons were computed using ArcGIS 9.2 with omission of glacier areas smaller

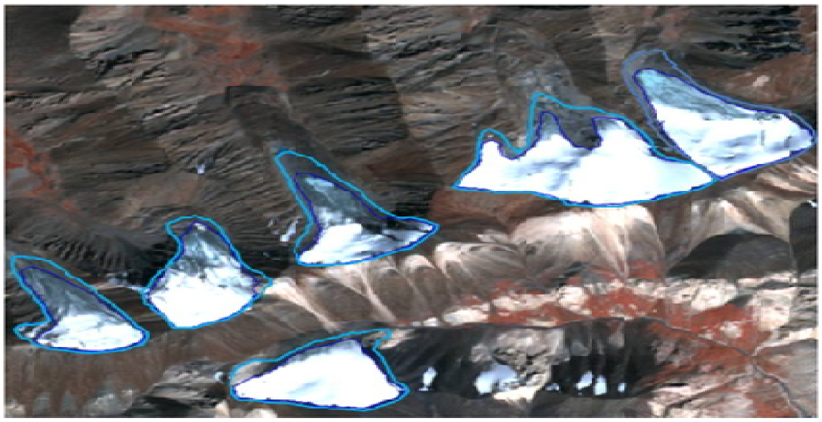

Figure 2. Example of the glacier outlines extraction from ALOS (AVNIR: 10 m) images, and topographic maps (1:25 000) of the Borkoldoy range. Dark blue glacier outlines of 2010, bright blue outlines of 1965.than 0.1 km^2 resulting in a total sample size of 15 glaciers in the Akshyirak massif, 126 in the Borkoldoy, 130 in the Jetim, 89 in the Jetimbel, 80 in the Naryn, 41 in the Sook, 95 in the Terskey (south slope glaciers) and 78 in the Uchemchek mountain ranges (Table 2). Validations of some glaciers were done during field visit from 2010 to 2012 by using GPS ground check points.

RESULTS

Characteristics of glacier distribution

The characteristics of glaciers distribution in the study area was analyzed by finding the statistically relation between topographic parameters (mean, min., max. elevation, area size class, slope, aspect; Table 1) and extracted and delineated glacier polygon data from ~2010. Majority of the parameter have clearly shown the evidence of regional characteristics of glacial distributions. For example, the relation of glaciers' area and aspect demonstrates the tendency of majority of large glaciers to be concentrated in northern aspects (Figure 3). Thus, 513 glaciers with areas of 435.2 km^2 that account for 74.3% of the total area are located in the three sectors, northwest, north, and northeast. We did not researched glaciers of northern aspects of Terskey mountain range and glaciers of southern aspects of Naryn mountain range because Terskey is a northern border of the investigated area and Naryn is the southern one.

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

Class (km^2)	Number	Total area		Minimum elevation (m)	Maximum elevation (m)	Mean elevation (m)
		(km^2)	(%)			
0.1 – 0.5	395	98.1	16.8	3580	4960	4187
0.5 – 1	177	186.6	31.9	3510	4960	4214
1 - 2	40	70.9	12.1	3580	5020	4232
2 - 5	30	120.6	20.6	3720	4880	4222
5 >	12	109.2	18.6	3600	5170	4258
Total	654	585.4	100	3510	5170	4223

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

Study area		Akshyi-rak	Borkol-doy	Jetim	Jetim-bel	Naryn	Sook	Terskey	Uchem-chek
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	39	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
Number of glaciers measured		15	126	130	89	80	41	95	78
Glacier in ~1962 (km^2)		39.9	142.0	125.1	58.7	33.3	31.4	91.0	64.0
Glacier in ~2010 (km^2)		32.9	112.5	97.8	44.3	23.6	24.9	71.9	52.6

The distribution of glaciers classified according to area class (0.1-0.5 km^2, 0.5-1 km^2, 1-2 km^2, 2–5 km^2, >5 km^2) for eight mountain ranges from 1965 to 2010 are shown in table 2. In three mountain ranges, the distribution of each glacier size class is almost similar: glaciers with areas of less than 1 km^2 occupy 78% of the Jetimbel mountain, 86% of the Naryn mountain, and 84% of the Sook mountain and no glaciers are larger than 5 km^2 (Table 2). In the Akshyirak mountain, small glaciers with areas less than 1 km^2 occupy 11.5% and larger glaciers more than 5 km^2 occupy 48% of the total investigated glacier area. In other the Borkoldoy, Jetim, Terskey and Uchemchek mountain ranges, the distribution of glacier size classes nearly similar: glaciers with area of less than 1 km^2 occupy from 39% to 50%, and larger than 5 km^2 glaciers occupy from 14% to 28%. The unusual distributions of glacier-area are found in the Borkoldoy mountain (5170 m), in the Terskey mountain (4840 m) and in the Jetim mountain (4825 m) and lowest glacier located in Uchemchek mountain range (3510 m). The average height of glaciers found in the study region is 4223.

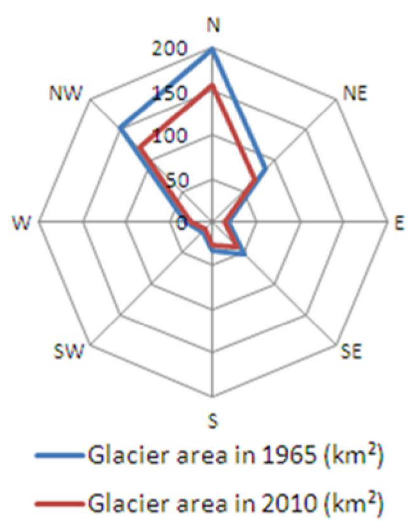

Figure 3. Distribution and area change of glaciers with different aspects

Changes in glacier area from ~1965 and ~2010

The retreat of glaciers extracted from repeat satellite imagery were marked everywhere in upper Naryn basin since ~1965. This fact is derived from the feature of glaciers' form as well as by repeated observation, moreover comparison of remote sensing data of different years. In short span of time period approximately 1965 to 2010 total areas of the 654 studied glaciers had decreased by 21.3% of the value from 585.4 to 460.5 km^2. The glacier area decreased by 17.4% in the Akshyirak mountain, 20.8% in the Borkoldoy, 21.9% in the Jetim, 24.6% in the Jetimbel, 28.9% in the Naryn (North slope glaciers), 20.8% in the Sook, 20.9% in the Terskey (South slope glaciers) and 17.8% in the Uchemchek mountain ranges (Figure 4), and the greatest decrease in areal extent of studied glaciers was in the Naryn mountain (28.9%), followed by the Jetimbel (24.6%) and Jetim mountain range (21.9%).

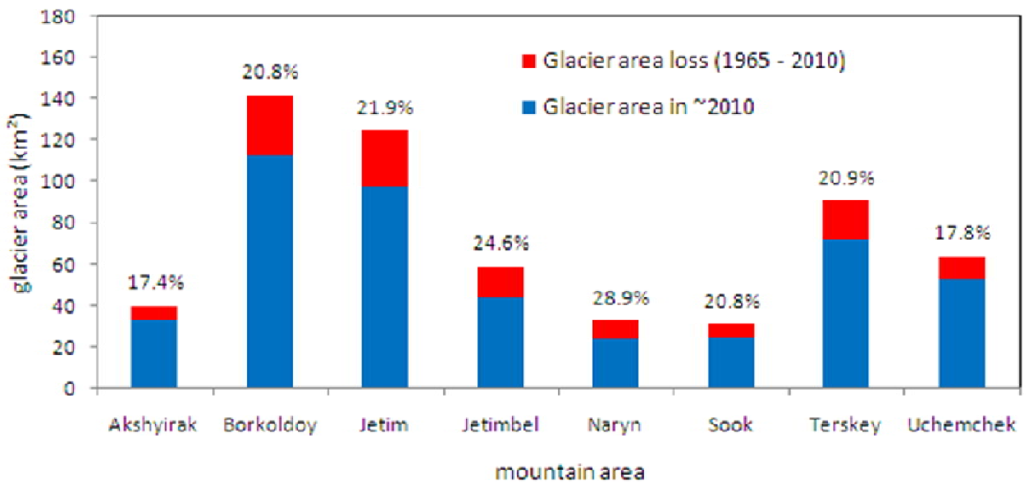

Figure 4. Changes in total glacier area in eight mountain regions for ~1965 and ~2010

Thus, total percentages of glacial loss in study area are to be further investigated in changes in the different size classes. The small glacial areas are sensitive to microclimatic changes and local glaciological factors (Jóhannesson et al., 1989; Kuhn, 1995; Nesje and Dahl, 2000). The relative abundance of glaciers in the different size classes strongly affects on the total percentage glacier area loss. About 89% of glaciers are less than 1 km^2 in area. Regions dominated by small glaciers are generally more sensitive to change because of the shorter response time to climate variability for small glaciers (Bahr D et al., 1998). In fact, comparing glacier size classes and glacier shrinkage, the Naryn mountain range, with its many small glaciers (<1 km^2) experienced large glacier shrinkage (28.9%). In contrast, the Akshyirak mountain has many large glaciers (>5 km^2) and glacier shrinkage was smaller (17.4%).

Table 3. Summary of glacier area change in eight mountain ranges

Mountain area	Average area (km^2)	Area (km^2)		Area change (%) (1965 - 2010)
		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

There are also dramatic differences marked in the changes between glaciers located on the northern and southern slopes. The northern slope having 513 glaciers decreased in total area by 19.7% and while the 78 glaciers found in southern slopes reduced in total area by 24.1% between. The first reason is more direct solar radiation in southern slopes in the study region which is favourable for glaciers' ablation. And second cause is mountain's asymmetry nature (Glacier Inventory of the USSR, 1977). Generally southern slope should have shallow steepness as northern slope but there are long flanks in southern slopes. This local typical configuration of southern slopes will contribute to formation of larger glaciers but such types of glaciers' area are subjected to more ablation leading to large loss of area in the study region.

DISCUSSION

Recent glacier shrinkage related to local climate changes

To understand the changeability and stability of the glacier systems in the study area, it is important to analyze the atmospheric temperature and precipitations regime under the preserved warming trend of climate. The differential trend of temperature during warm (IV-IX months), cold periods (X-III months), year and summer months (VI-VIII) were taken from "Tian-Shan" Meteorological Station were further analyzed. The trends revealed from the above data are as follows: 1) Trend amounted to 0,023°C/year for average annual temperatures; 2) Trend of average temperatures for over the warm period is 0,017°C; 3) over the cold period it is 0,026°C. 4) Trend of average summer temperatures is 0,016°C. There is observed relative high intensity of the air temperature increase of both warm period and summer period (Tian-Shan MS) as compared to cold period. It is probably conditioned by the increase of atmosphere transparency over the mountain region of Central Asia, which leads to the growth solar radiation incoming intensity. The observed increase in atmospheric temperature for both summer and spring season (Tian-Shan MS) as compared to winter season between 1965 to 2010. The probable cause may be the increase of atmosphere transparency over the mountain region of Central Asia (Aizen, 2002), which leads to the growth solar radiation incoming intensity. For over the 80 years there was a general increase in mean annual temperature trending on 1,9 ° C, and the summer season at 1,3°C. During the warm period the temperature increased relatively intensively (1.4°C) as compared to cold period (0.81°C). Amplitude of temperature variability amounted to 3.8°C, and air temperature was mainly above the standard for the last decades. Increasing summer temperature leads to 1) an increased amount energy available for ice and snow melt, 2) decreased snow accumulation (and increased proportion of liquid precipitation), and 3) lower albedo of the glacier surface (Dikich and Hagg, 2004; Hagg and Braun, 2005).

Analysis of precipitations chronological course highlights the variability in total precipitation. Their values rarely equals to long-term average annual amount (norm), precipitations mainly fell less or more than the standard precipitations. The overall precipitation recorded in metrological stations is in decreasing trend (Figure 5).

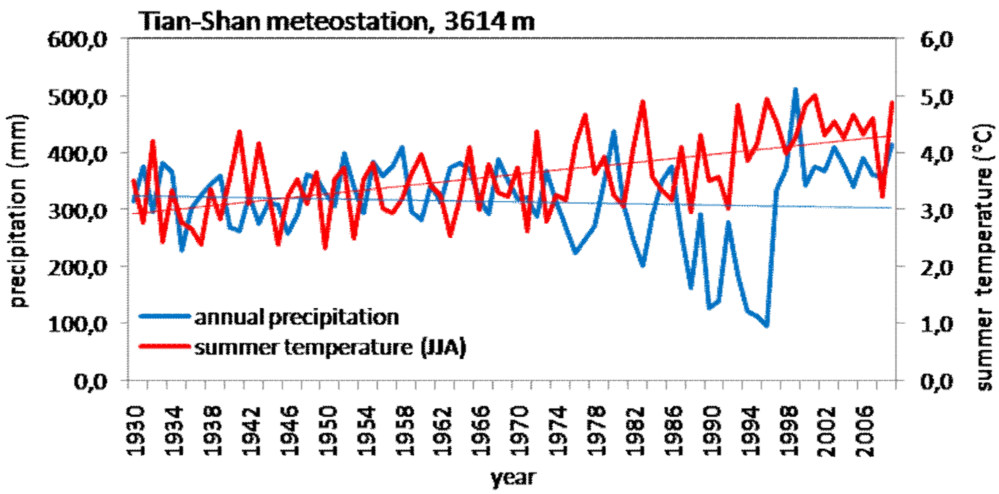

Figure 5. Annual precipitation amount and mean summer air temperature (JJA) at the Tian-Shan meteorological station.

There is a decreasing trend in amount of precipitation due to global warming may be the cause of glacial area loss during short span of time period. Thus, there is decrease of 28 mm of precipitations in warm at the Tian-Shan MS for over last 80 years. Thus, asynchronous condition of temperatures and precipitations is peculiar to the study region with spring-summer humidification maximum, that is warming is accompanied by the reduction of precipitations mainly due to reduction of warm period precipitations. In spite of that in glacial-nival belt the precipitations fell in 2-3 times more than in underlying zones, with continuing unfavorable climatic conditions. Hence, the recent shrinkage of glaciers in study area are due to many increase in atmospheric temperature and decrease of precipitations which plays significant role in expenditure side of glaciers formation may be the cause of reduction of glacier sizes.

Regional differences in glacier area changes

The other parameters like regional difference in glacial retreat give better insight about losses in eight mountain ranges of the Chon Naryn and Kichi Naryn basins. The Naryn range, characterized by many small-scale (less than 1 km^2) and steep glaciers, is one of the most significant glacial retreat area in the study region (Table 3). The other mountain regions like the Akshyirak mountain massif and the Uchemchek have not shown much percentage of glacier shrinkage because majority area dominated by large size glaciers with north facing slopes (more than 86 %). Further investigating the glaciers of the western and northern-western aspect of the Akshyirak massif, it is found that large glaciers have longer response times than the considerably smaller ones in the other ranges (Hagg et al., 2012), may be the cause of more sustained reaction to climate change. The overall areal retreat is approximately similar (between 21-24%) in other five mountain ranges with glaciers in Jetimbel experiencing faster retreat than other ranges. The total glacial loss of 21.3% in the Chon and Kichi Naryn basins in this study is more or less similar to the work done (glacial area change of 23.4% between 1943/1956 and 2007) by W. Hagg et al., (2012). The other studies like Naraма (2006) and Kutuzov (2009) of Terskey range between the years 1971-2002, and 1965-2003 using satellite imagery like Landsat/Corona and Landsat/ASTER has shown similar pattern of result with areal loss percentage, 8% (Narama) and 12% (Kutuzov) respectively. Hence these retreat have significant impact on discharge of watersheds to lowland arid and semi-arid areas of Central Asia.

Impact on Water Resources

The need of hour is to understand the impact of glacial shrinkage on water resources in lowland areas of study region. The Naryn River – tributary of Syr-Darya which is the lifeline of the republics of Kyrgyzstan and Uzbekistan will have severe impact with any change in glacial regime. According to Hagg et al., 2007, there is changes in seasonal runoff volume have been estimated for 50% glacier loss in the Tian-Shan, using models based on meteorological data and assuming the 2×CO_2 scenario for 2050 to 2075. Decreased glacier area leads to decreased summer time glacier-melt discharge. Distributed glaciation on the main tributaries of the Naryn basin of the extremely unevenly, and the contribution of glacial water in some tributaries of the total runoff also varies. There is few research on role of glaciers on the runoff formation and glacio-hydrological direction lack of focus on river basins Chon and Kichi Naryn.

In this paper, based on identified regularity of spatial distribution of rainfall, relations of melting ice and snow on the temperature (Dikih, 1999) determined the volume of glacial runoff on the Chon and Kichi Naryn rivers. The table 4 contains the values of runoff norm and share of glacier melt water under different climatic conditions, are analyzed using Dikih's method. Chon Naryn and Kichi Naryn basins characterized by most developed glaciations. The extensive development of glaciations significantly affects the run-off content of main river. Kichi Naryn basin is in second major tributary of Naryn river after Chon Naryn by size of glaciation and the contribution of glacier water to the total volume of flow is also significant with maximum are glacial feed.

Table 4. Total and glacier runoff of the Chon Naryn and the Kichi Naryn rivers

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

The decrease in area of glaciations are due to decline in precipitation will not only affect the change of water availability for irrigation but also cascading effect of hydro power projects in Toktogul, Kurpsay, Tashkumyr, Shamaldysay, Uchkurgan part of Kambarata-2. At present Upper-Naryn hydropower cascade is planned as part of 4 consecutive steps, with total capacity of 191 MW and annual output of 1,055 billion kWh: Akbulun, Naryn-1, Naryn-2 and Naryn-3 hydropower stations and construction of the Akbulun hydropower station already started in May 2013.

CONCLUSION

Glaciers of the Chon Naryn and Kichi Naryn basins decreased significantly in area between ~1965 and ~2010 with the total glacier retreat of 21.3%, due to increasing summer temperatures. The above glacial shrinkage is due to variation in regional climate and distribution of different size of glaciers according to elevation. The largest glacier shrinkage occurred in the Naryn range (28.9%), because of dominating small-scale glaciers and with north facing slopes. The strong glacial retreat can produce large quantities of water in short time period may cause hazard in down-stream area, and continuing glacier shrinkage will be the cause deficiency of water and energy in the region. The present state of glaciers are to be evaluated and monitored scientifically for reasonable development and utilization of regional water resources, water cycle models and regional economic planning. Hence more detail research are needed to validate the calculation made here with help reliable glacier field data. More simulation and projection are needed to understand trend of climate change and their impact on glacier properties and runoff variability.

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