JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Department of Geography Giessen

Glaciers and permafrost as water resource in Kyrgyzstan

- distribution, recent dynamics and hazards, and the relevance for sustainable development of Central Asian semiarid regions

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Preface and Acknowledgements

The Kyrgyz mountain areas and their glaciers always fascinated me even as a child, as I was growing up in a quite remote mountain village, excursions to the mountains belonged to the daily life of my father and my friends at school. Later on, during my studies in Bishkek university the study of mountain environments and especially water and glaciers were of special interest to me in order to get a better understanding the of beauties and dangers of mountain areas. At Kyrgyz National University in Bishkek, I got the chance to work within several international glaciological research projects. I completed my Post Graduate Diploma on Remote Sensing Geographical Information System in the Department of Water Resources at the Centre for Space Science and Technology Education in Asia and Pacific (CSSTEAP) in India (2007-2008), which helped me during all my research periods that followed. The glaciological work I had done and a good RS and GIS experience certainly formed a base for my successful application in the LUCA project as a PhD student.

The following dissertation study has been funded by the VolkswagenStiftung and was conducted in the frame of the **"**Land use, ecosystem services and human welfare in Central Asia" (LUCA) project.

The main contents of this thesis will be published under the title "Climate Changes in the Naryn Catchments: Consequences for Glaciers, Permafrost and the Economic Development in Kyrgyzstan" in a special volume of the ZEU research center at Giessen university for the LUCA projects results (Duishonakunov et al, 2014). The impact on the water resources is published in a second paper "Recent Glacier Changes and Their Impact on Water Resources in Chon and Kichi Naryn Catchments, Kyrgyz Republic" that appeared in the international journal "Water Science and Technology" (Duishonakunov et al, 2013).

At the University of Giessen, my supervisor Prof. Lorenz King was providing the initial concept of the doctoral thesis. His continuous scientific support and guidance was invaluable during the whole process of my PhD thesis. I really cannot find words to thank him for the kind deeds he has done to me. Definitely I will repeat his style of guiding in my future work at the faculty in the Kyrgyz Republic. I learned a lot how to supervise students also. First and foremost, I would like to thank him for his understanding, helpful support and patience during my seemingly endless doctoral studies. I also wish to extend my gratitude to his family for having allowed me to get to know closely the customs and traditions of German society and having shared with me so many precious moments during my short but unforgettable visit to Germany.

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I would also like to thank other LUCA supervisors and PhD students for asking many interesting questions during several seminars and workshops and providing valuable comments to improve the quality of this thesis. LUCA coordinator Dr. Ira Pawlowski always was available for advice with never ending support and good will in Giessen as well as during my field work and the workshops in Kyrgyzstan. Moreover, Dr. M. Höher and Sabine Viehmann did a great job for the administrative support of my work.

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At the Central Asia Institute for Applied Geosciences in Bishkek (CAIAG) co-director Prof. Bolot Moldobekov generously supported my studies over three years with transport in remote areas, that otherwise could not have been researched. He always showed great interest in the progress of my studies.

In the Institute of Geography at Giessen University the cartographers helped with advice and maps.

This work could not have been done without the continuous support of these persons and institutions. I am deeply grateful for having given this chance as an important step in my life.

Last but not least, expressions of sincere gratitude go to my family. My parents Turganaly Duishonakunov and Shaikul Yrsalieva always supported me, cheering me up whenever I experienced a new thing. My wife Gulzada Askarbekova encouraged me for intense work, hoping me to return soon from Germany with the necessary work accomplished. My deep personal thanks go to my family.

Abbreviations

ALOS Advanced Land Observing Satellite

AVNIR Advanced Visible and Near Infrared Radiometer

CAIAG Central Asian Institute for Applied Geosciences

DEM Digital Elevation Model

ELA Equilibrium-Line Altitude

GCOS Global Climate Observing System

GIS Geographical Information System

GLOF Glacier lake outburst flood

GPS Global Positioning System

GST Ground surface temperature

IPA International Permafrost Association

JAXA Japan Aerospace eXploration Agency

MAAT Mean annual air temperature

MAGST Mean annual ground surface temperature

NSIDC National Snow and Ice Data Center

SHI State Hydrological Institute

SRTM Shuttle Radar Topography Mission

USSR Union of Soviet Socialist Republics

WMO World Meteorological Organization

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ZUSAMMENFASSUNG

Die Republik Kirgistan ist das einzige Land Zentralasiens, das seine Wasserressourcen ganz aus dem eigenen Territorium bezieht. Dieser Wasserreichtum stammt zu einem großen Teil aus den vergletscherten Gebirgen des Landes und ist eine lebenswichtige Grundlage für die Landwirtschaft, aber auch für die Produktion von Hydroenergie. Die Landwirtschaft in den meist sehr trockenen Ebenen am Gebirgsfuß ist auf Bewässerung angewiesen. Die Gebirgsketten Kirgistans erreichen an vielen Stellen über 5000 m hoch. Im Rahmen der Diskussion um die fortschreitende Klimaerwärmung werden die Wasserressourcen des Naryn-Einzugsgebietes in Form der zahlreichen Gletscher und des im Dauerfrostboden enthaltenen Bodeneises detailliert untersucht. Ziel ist es, die Bedeutung dieser Wasserressource aber auch die damit verbundenen Naturgefahren bei der weiteren Entwicklung der zentralasiatischen semiariden Räume vorzustellen.

Die gesamte Gletscherfläche der Gebirgsketten im oberen Naryn-Einzugsgebiet mit insgesamt 654 untersuchten Gletschern nahm zwischen 1965 und 2010 als Folge höherer Sommertemperaturen und geringerer Niederschläge um 21,3 % ab. Die stärkste Abnahme mit 28,9% war in der Naryn Gebirgskette festzustellen, da hier besonders viele kleine, nordexponierte Gletscher vorkommen. Ein weiterer Gletscherrückgang wird hier in naher Zukunft zu einem regionalen Mangel an Wasser und Energie führen. Ein rascher Gletscherrückzug kann aber auch zum Ausbruch von Gletscherseen (GLOFs) führen, was eine Gefahr für die unterliegenden Gebiete darstellt. Ein wissenschaftlich fundiertes Monitoring aller Gletscher ist für eine nachhaltige wasserwirtschaftliche Entwicklungsplanung unverzichtbar.

Das vorhandene Gebirgsklima begünstigt aber auch die Bildung und den Erhalt von Dauerfrostboden (Permafrost), da die mittlere jährliche Lufttemperatur auf einer Höhe von 3614 Meter -7,6 °C beträgt (Zeitraum 1930-2010). Permafrost ist in Höhenlagen um 3300 m weit verbreitet, inselhafte Vorkommen sind aber nordexponiert noch auf 2700 m anzutreffen. Die Mächtigkeit der sommerlichen Auftauschicht kann mit Tiefen von 30 cm bis 300 cm stark schwanken. Große Periglazialformen sind oft mit massiven Bodeneisvorkommen verknüpft, kleine Formen entstehen meist durch saisonalen Frost und auch ausserhalb der Permafrostgebiete.

Eine nachhaltige wirtschaftliche Entwicklung der Hochgebirgsräume Kirgistans benötigt dringend detaillierte Studien sowohl der Gletscher, als auch des Permafrosts. Eine Unterschätzung der glazialen und periglazialen Vorgänge beinhaltet Gefahren und große finanzielle Risiken, sei es beim Abbau von Rohstoffen oder bei der Entwicklung der touristischen Infrastruktur.

Neben dem Wasserreichtum besitzt Kirgistan als weitere Ressource eine beeindruckende Gebirgslandschaft, die ein großes Potential für den Tourismus darstellt. Eine dritte wichtige Ressource des Landes stellen die von Kumtor abgebauten Goldvorkommen dar. Weitere vielversprechende Vorkommen sollen in naher Zukunft abgebaut werden. Für eine wirtschaftliche Entwicklung sowohl im Bergbau als auch im Tourismus ist der Aufbau einer sicheren Infrastruktur entscheidend, dabei können auch Permafrostvorkommen Gefahren beinhalten.

In Zentralasien ist Wassermangel mehr und mehr ein ernsthaftes Problem. Noch kann Kirgistan mit seinen Vorkommen auch die Nachbarstaaten Usbekistan, Kasachstan und Tadschikistan mit Wasser für die Landwirtschaft beliefern. Um zukünftigen Konflikten vorzubeugen, sind weitere Absprachen über Wasserzuteilungen und insbesondere die Rolle der Landwirtschaft als Wasserverbraucher notwendig. Die Ergebnisse dieser Arbeit können einen Beitrag zum Verständnis der Rolle des Wassers für die Nutzer im Lande selbst, aber auch im Rahmen eines transnationalen Wassermanagements bringen.

1 INTRODUCTION, STUDY OBJECTIVES, METHODOLOGY

1.1 Introduction, scope of study

The Kyrgyz Republic is the only Central Asian country, in which its water resources are fully generated on its own territory. Water and power potential of rivers is one of the most important resources of Kyrgyz Republic. At the current stage of the national economic development great attention is paid to study and rational use of water and hydropower resources. A strategy of using transbordering rivers, pricing methods and water tariffs are being developed. Mountainous Kyrgyz Republic is a “water tower” for irrigated arable farming on arid plain territories – Uzbekistan, Kazakhstan and Tajikistan, i.e. water resources are of great significance both for the economy of our republic and neighbouring countries as well.

At this stage of the national development, resource self-sufficiency becomes a prime interest, especially in the fuel and energy industry in connection with the fact that the mechanism of national economy of the former Soviet Union, which was functioning as one integral unit, is no longer possible. Explored and used coal, oil and gas reserves in the republic are insignificant, it is necessary to import a major part of these from neighbouring states by high prices.

The territory under special consideration in this thesis (upstream Naryn catchments) occupies around 9580 km² or 18% of the Naryn River basin area. It includes the Naryn and Issyk-Kul administrative regions of the Kyrgyz Republic. Naryn River is a main flow-forming part of Syr Darya River (Figure 1), flowing into the Aral Sea. Kumtor River is adopted as its headwaters, which flows from the Petrov Lake, into which melt water is discharged from Petrov glacier – one of the greatest glaciers in Tian Shan at an altitude of 3730 meters.

The wellbeing of Central Asia depends on water availability and the irrigation conditions, and includes the territories of Uzbekistan, Tajikistan, Kazakhstan and the Kyrgyz Republic with a total population of more than 20 million people. At the same time Naryn River is the only source for hydro power, which provides two third of the electric energy for the Kyrgyz Republic, and serves also some districts of Uzbekistan and South Kazakhstan.

Naryn River is formed from the confluence of Chon Naryn and Kichi Naryn River. The glacier melt water share is around 45% in the upstream Naryn River, in the middle reaches it is 35% and in the lower reaches up to 20%.

Figure 1 Location of the Syr-Darya (Naryn river basin) and Amu-Darya river basins in Central Asia. Source: ESRI with processing, Giese.

The hydro power potential of Naryn River is 6956.3 MW/h, it provides water to an area of 913,000 ha and irrigates 400,000 ha of land. A water reservoir serves also as a regulator for the flood run-off. The average annual water flow rate in Chon Naryn river outlet makes up 45.7 m^3/s, and the water flow rate in the outlet of Kichi Naryn river is 40.2 m^3/s. Maximum flow rates amount to 68.7 m^3/s and 54.8 m^3/s, and minimum flow rates to 32.1 m^3/s and 27.6 m^3/s, respectively.

Based on the ratio of incoming and outgoing components of the water balance, the territory of the republic is divided into two hydrological zones – stream flow generation and runoff dispersion. A proper mountainous part is characteristic for the first zone, intermountain areas and plains adjoining to mountains, can be attributed to the second zone, where a major part of water courses is used for irrigation purposes and is filtrated to soil and subsoil. Our investigated territory is completely attributed to the zone of stream flow generation.

1.2 Study objectives

Climate changes lead to the degradation of the snow-glacial systems, as well as to the conditions for water availability in the region. This may result in various natural disasters (mudflows, floods by GLOFs, canal silting, flooding of agricultural lands and populated settlements, etc.). With climate warming the vulnerability of life-support systems especially of poor groups of the population is increased. Changes in climate lead to additional costs, required for adaptation to changing environmental conditions. In order to increase a sustainable life for poor groups of population under changing climate conditions, it is required to take adaptive measures, decisions and actions. Objective data are required on monitoring of the natural and social environment.

That is why for the optimization of water, energy and other ratios among Central Asian countries with a population of more than 20 million persons, it is necessary to study the snow-glacier run-off system in detail, to develop methods for runoff forecast during vegetation period and for Toktogul water reservoir and tributaries of Naryn River, where small and medium-size hydropower stations are existing and the construction of new ones is planned for the low-water period as well.

An aim of this thesis is the defining of water resources in the upper reaches of the Naryn River. In order to accomplish this goal, the areal dimensions of glaciers and the glacier areas' reduction was defined as one of the main sources for river nourishment (chapter 5.2). In addition, the distribution and thickness of mountain permafrost was identified (chapters 4.2 and 4.3), and it was prospected for the existence of massive ground ice occurences. The regime and the parameters of river flow were clarified (chapter 5.2), and tendencies of climate change and its influence on the water regime was revealed (chapters 2.3 and 3.5). Topics with applied relevance are as follows:

- Data of hydro-meteorological observations within recent 80 years were summarized and analyzed (chapters 2.3, 3.5 and 5.2).

- Maps of permafrost distribution, graphs of precipitation distribution, temperature, flow rates, diagrams of glaciers' reduction on ranges and many tables were prepared (chapters 4, 3 and 5).
- Comparison of river flows was made during the periods up to 1965, and within 1966-2010, conclusions have been made on the flow dynamics within recent 80 years (chapter 5).

1.3 Methods applied and fieldwork done

1.3.1 Glacier data and methodology

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 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 3 and 4). The change in the terminus position of some glaciers was observed during fieldwork from 2010 to 2012 using GPS measurements.

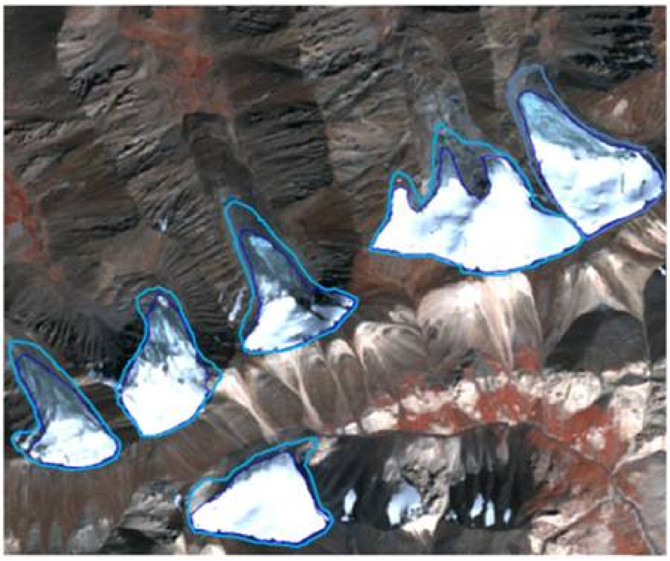


Figure 2 Extraction of glacier outlines in the Borkoldoy range from ALOS/AVNIR satellite images and topographic maps (1:25,000). Dark-blue glacier outlines of 2010, and bright-blue outlines of 1965. Source: ALOS satellite image with processing.

1.3.2 Permafrost research methodology

In addition to the glacier studies, we also investigated the conditions of Permafrost and ground ice. In Kyrgyz Republic, only a few researchers are currently dealing with this topic. However it is studied here, as the melting of massive ground ice and perennial snow patches (as indicators for actual permafrost conditions) may contribute to the regional water balance in a much greater magnitude than assumed today.

For the current study we investigated frozen ground upon upstream Naryn catchments, during August 2010 to August 2013. We measured near-surface ground temperatures in 18 locations at different altitudes and slopes. The objectives of this study are to estimate the distribution of permafrost, and its active layer, and to discuss the permafrost environment in the upstream Naryn catchments. The general features of mountain permafrost such as permafrost distribution and temperatures, active layer thicknesses within the upstream Naryn catchments, Tian Shan Mountains are described. The area of permafrost studies in the Naryn basin is located within the two upstream river basins (Chon Naryn and Kichi Naryn). The mountain permafrost zone in our study area belongs to the Asian mountain permafrost area, the largest in the world.

In the field we used steel rods and a hammer to knock holes up to 1.5 m deep in order to install our thermistor strings, thus measuring continuously ground temperature profiles for the coming study years. Ground temperature measurements were carried out in 18 locations between altitudes 3007 and 4043 meters. These measurements were performed using wireless mini thermistor sensors and loggers (M-Log5W). They have a high memory capacity (2048kB), a very low energy consumption and a waterproof cover (Figure 3). The temperature sensor has a high resolution of 0.01°C and an overall accuracy of ± 0.1°C. This thermistor can work more than 5 years without changing batteries depending on temperature conditions of the logger instrument and the batteries. The temperature recording started in August 2010 at an hourly interval. At all locations the observation period was up to end of August 2013.

Figure 3   M-Log5W wireless mini data logger. Source: http://www.geoprecision.com/

2 STUDY AREA

The basins of the Kichi Naryn and Chon Naryn Rivers are head reaches of the Naryn–Syr-Darya Rivers (Figure 4). Being located in ancient denudation and accumulative surfaces, they are surrounded by mountain ranges of Inner Tian Shan – from the north by the Terskey range, from the east by the Akshyirak mountain range and from the south by the Borkoldoy and Naryn ranges. Within the basin of the Kichi Naryn River there is a west border represented by the southern branch of the Terskey mountain range as well as east parts of sub-laterally stretched Kara-Kaman, Kara-Jorgo, Kapka-Tash and Nura mountains. They are located at an altitude of 3200-3800 meters and are one of the main areas of Tian Shan, where modern permafrost is widely distributed. Basins of the Kichi and Chon Naryn Rivers are also main distribution areas of the modern glaciations of Naryn–Syr-Darya Rivers.

2.1 Relief of the Chon Naryn and Kichi Naryn Catchments

Kyrgyz Republic is a mountainous country, a major part of its area is occupied by one of the highest mountain systems in the world – Tian Shan. More than ¾ of the republic territory have altitudes from 1500 m to 3500 m, and some peaks are higher than 6000-7000 m a.s.l. The relief of the republic is complicated, in general it is a system of dissected ranges, extending latitudinally from the east to the west, with intermountain valleys, located between them.

The Naryn river basin occupies an extensive territory. The territory of the area under consideration is located at a significant average altitude of up to 3610 meter. The highest points rise to an altitude of more than 5,000 meters (Table 1). The crests of the Borkoldoy and Akshyirak ranges achieve such altitudes, the highest point of Akshyirak range extends to a height of 5108 meters. The altitude of Chon and Kichi Naryn river outlets are only 2040 meters. Thus, the difference from the peaks to the basin of the river is almost 3000 meters.

The territory considered for the study is in a triangular form, having Terskey range in the north, Borkoldoy and Naryn ranges in the south, south-east, and Akshyirak massif range in the east. The lower reaches of Naryn River are outside this orographic triangle.

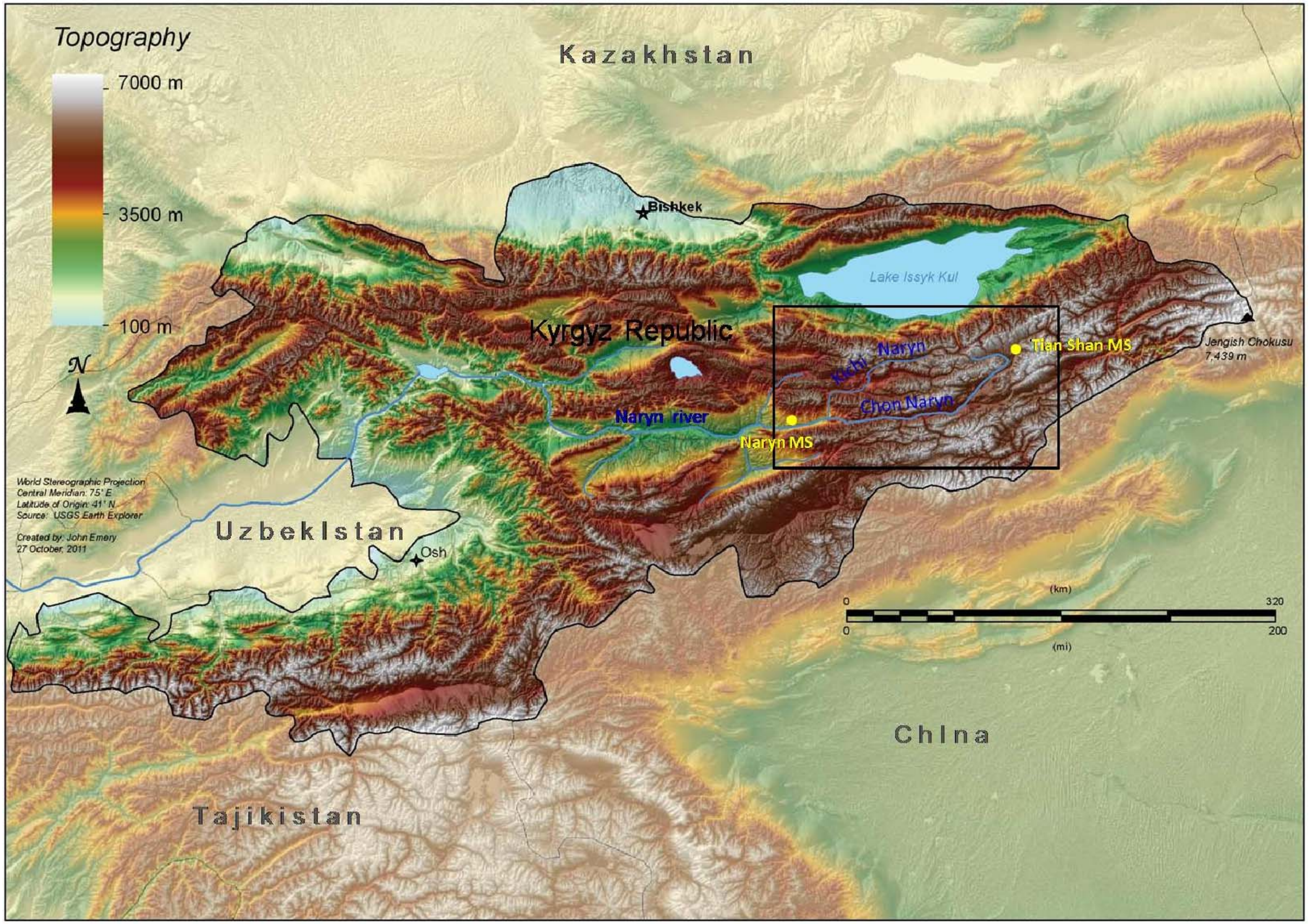


Figure 4 Altitudinal map of Kyrgyz Republic and neighboring countries with the location of Naryn catchment (cp. Figure 8).
The black rectangle shows the study area. Yellow dots show the locations of the two meteorological stations.
Source: USGS Earth Explorer, created by John Emery with additions by author.

Geologically the present relief of Tian Shan was formed mainly between the end of Tertiary and at the beginning of the Quaternary periods. The major uplift and warping of present Tian Shan Mountains also took place during that time period.

According to Shultz (1948), there are recent tectonic activities with mountain folds having large radius of curvature. They are stretched and stressed in latitudinal direction between the Tarim shield and the Siberian platform. The highest plexus of Khan-Tengri Mountains – Pobeda Peak – being an orographic centre of Tian Shan, appeared at the place of the closest approach of these rigid structures. The three largest mountain chains of Tian Shan are separated from here and move in latitudinal direction with a variation of folds extending in west direction. Further, the chain of mountain chains is divided by beaded chains of intermountain areas, which are also having a latitudinal direction.

The middle branch of Tian Shan ranges which belongs to our study area is located between the above mentioned chain of depressions as well as the depressions which are used by Naryn River upstream. The largest of these ranges are Terskey, Akshyirak, Jetimbel and Jetim ranges. They are, in their turn, divided by secondary depressions, which too are stretched in latitudinal direction.

Ranges of the southern branch of Tian Shan are located in the south of Naryn valley. The largest ranges, attributed to Naryn basin, are as follows: Borkoldoy and Naryn Mountains.

The western part of the Tian Shan range is having depressions generally and more specifically present in the Naryn basin. The eastern part of the Inner Tian Shan and Central Tian Shan having high pedestals above the present ranges and the rises are very insignificant. However, the relative elevation of Akshyirak massif above Kum-Tor syrts makes up only 700-800 m (Table 1 and Figure 5). The southern slope of Terskey range has the same elevation. Gradual decreases of the altitude of these ranges are in western direction and also decreases of elevations are observed in the crest zone – in average 2-3 meters per 1 km. Intermountain depressions, dividing ranges, decrease significantly to a larger extent (up to 7 meters per 1 km) and further the relative altitude of ranges in the western direction has increased.

Table 1 Main orographic indicator of mountain ranges, Chon Naryn and Kichi Naryn catchments

Mountain range	Direction of mountain range	length of the range within the Naryn basin (km)	width of the range within the Naryn basin (km)	Maximum height of the range within the Naryn	Average height of the range (m)	Relative height of the range (average, m)		Extent of glaciations
						North slope	South slope	
Terskey	E - W	175	12	4763	4300	-	800	Flat top glaciers; valley glaciers; snowfields
Uchemchek	E- W	47	15	4339	4000	600	1100	snowfields and small glaciers
Akshyirak	N – E S - W	48	18	5108	4400	700	-	Glaciers cover about half of the area; many large valley glaciers
Jetimbel	ENE - WSW	120	15	4620	4300	700	1000	Many snowfields; valley and hanging glaciers, mainly on north slope
Jetim	ENE - WSW	110	25	4931	4200	900	1300	Snowfields and small glaciers
Borkoldoy	ENE - WSW	85	25	5012	4300	900	-	Many valley glaciers; flat top glaciers
Naryn	E - W	110	20	4500	3900	1600	1200	Small snowfields and glaciers, mainly on north slope

Source: own processed.

Degrees of dissected relief increase are observed in the western direction having elevation fluctuations in the crest zone of Akshyirak range, make up 500-700 meters. The eastern part of the Naryn basin is distinguished by the extensive distribution of ancient planation surfaces overlapped by glacial deposits which are almost not affected by erosion of rivers. Furthermore, the planation surface of the study area decreases in western direction.

During the Quaternary period, the high mountainous areas of Tian Shan were covered by potent glaciers. These glaciers were heavily dissected through the crest zones of high ranges, especially in the eastern part of Naryn basin. Such forms of relief prevailed here as cirques, corries and trough valleys, which are often occupied by present glaciers. Erosional land forms such as Akshyirak and Jetimbel Mountains, in the eastern part of Borkoldoy range were of less significance. Erosional relief prevails only in the mountains of the central and western parts of Naryn basin glacial forms are only developed in few ranges and near crests.

During the period of the recent glaciation, glaciers wedged out to planes adjacent to Akshyirak, Borkoldoy and Jetimbel ranges. The ancient moraine relief prevails here with disorderly scattered low hills, between which shallow lakes of different configuration are located. Rivers are swift flowing and sometimes they meander in its course.

River valleys act differently in such intermountain depressions, where there is no glacier. Again these rivers are characterized by well-developed valleys with a large number of terraces, clearly grouped in several stages. Thus, alongside with tectonic movements, creating mountain ranges and intermountain depressions, Quaternary glaciations and river erosion play a significant role in the formation of topography of the territory under consideration for the study. It should be underlined that within Naryn basin, ranges occupy a territory several times larger than the area of intermountain depressions, the territory under consideration for the study has predominantly a mountainous layout.

Intermountain valleys. Several latitudinally stretched intermountain depressions are located within the Upper Naryn catchment. The eastern part of Jetimbel and Terskey range is divided by the high mountainous valley of Arabel river, stretched in latitudinal direction. The local population calls it Arabel syrts. The valley is limited in the west by a watershed of Chon and Kichi Naryn rivers. In the eastern part it is transformed invisibly into the undulating surface of Kum-Tor syrts. This valley is 34 km long and more than 5 km wide. The valley gradually declines in altitude towards the east from 3,800 m to 3,600 m. In the recent past the valley was filled with glaciers, which deepened and extended it gradually. The bottom of this valley is covered by morainic deposits, the thickness of which amounts up to 20-30 m in some places.

The topography of Arabel syrts is hilly. Elevations of some hills reach several tens of meters. Boulders are scattered everywhere. There are many enclosed subsidence areas here with lakes located therein. Regressive erosion did not reach Arabel syrts yet, rivers which often have the form of meanders run swiftly and stagnantly in low banks.

The Kumtor Syrts are located in the east of the Arabel syrts and do not differ greatly from the former altitude, development history and relief nature. A glacier was available here not long ago. The surface of the plain is accompanied by morainic ridges; lakes are available in depressions between them.

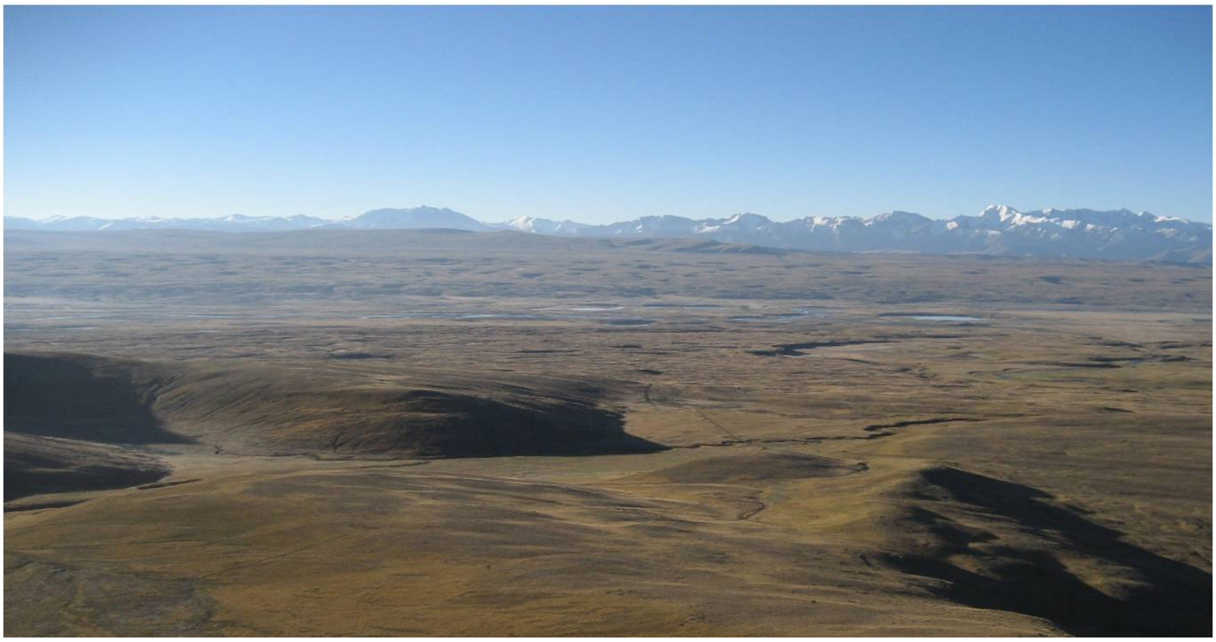


Figure 5 Upper reaches view of the Chon Naryn River. The Borkoldoy range almost throughout has the same altitude (4200 to 4300 meters.).
Source: M. Duishonakunov, 20 August, 2011

An ancient lateral moraine of Petrov’s glacier, stretching at more than 10 km, is especially well expressed in the relief. On the contrary to Arabel valley, regressive erosion started early in Kum-Tor syrts. Cutting of valleys into morainic deposits and formation of river terraces has started here. The reduction of the area, occupied by lakes, takes place simultaneously, now it is often possible to meet dry bottoms of lakes, which have existed here some time ago.

Upper Naryn Depression is a latitudinally stretched tectonic depression, which is used as a riverbed by Chon Naryn River. It is skirted in the north by Jetim and Jetimbel ranges, in the east by Akshyirak Mountains and in the south by Borkoldoy and Natyn mountains. The western slopes of Naryn and Jetim ranges, formed by Paleozoic rocks, approach each other. Below the mouth of Ulan River, Chon Naryn River entrenches in them by a deep heavy-going ravine. The length of depression is around 90 km; the width is 8-12 km. Chon Naryn river flows at a significant length in the form of multiple arms in a wide pebbled bed.

Several river terraces with well expressed relief are recorded in the eastern part of the depression in the upper reaches of Taragai and Kara-Sai rivers (Figure 5). Their relative altitude gradually decreases towards the central part of the depression afterwards they are concealed under the recent alluvial rocks. An area of recent accumulation precipitation is also available in the area of Taragai and Kara-Sai confluence. Gradually elevating terraces appear again downstream. River terraces are distinguished by flat surfaces. They are weakly dissected by rare and not deep water courses and are separated from each other by clear steep benches. Terraces are a characteristic peculiar feature of the relief in the western part of the depression bottom.

Besides the benches of river terraces, the flat relief of the region here is disturbed by low isolated ridges, stretching in parallel to the Valley of Chon Naryn River, and finally moraine lines with 50-60 m in height which is located in the lower reaches of Ulan and East Karakol rivers.

Kulchik ridge, formed by Neogene-Lower Quaternary deposits, is stretched by kilometers in the central and eastern parts of the depression along the northern side of the Chon Naryn valley. It is distinguished by flat weakly dissected slopes and flattened peaks and with a width of 3-5 km at the relative altitude of 100-150 meters above the bottom of the Valley of Chon Naryn River.

In the eastern part of the depression, Kara-Sai valley is cut into a relatively flat surface, which was recently covered with a glacier. High moraine lines of the recent past are preserved here. Ancient lateral moraines are recorded on bedrock slopes of the valley the bottom is formed by multiple disorderly scattered morainic hills, between which enclosed subsidence areas are located and are sometimes occupied by lakes.

A peculiar feature of the Upper Naryn depression relief is the availability of large areas of eolian sands, located downstream on the left bank of Kara-Sai River. Sands are of alluvial origin and are stretched by tens of kilometers on the surface of the second terrace above the flood-plain. The existence of eolian sands at an altitude of around 3,500 meters in a zone of many years' permafrost is very rare. As far as it is known, such sands are not found at these altitudes.

2.2 Geomorphology of the Chon Naryn and Kichi Naryn catchments

The history of geomorphological investigations of this area is closely related to the formation of geographical and geological ideas on the Inner Tian Shan and adjacent areas of Central Asia. The first significant geomorphological data were accumulated from 1930 to 1945 through the implementation of small-scale geological surveys. A monograph by Shults (1948) was a fundamental work, in which all materials, collected during this period, were summarized and analyzed. Cardinal issues were solved in it, which gave rise to further development of both - theoretical and practical geomorphology. In particular, not only the rather old age of pre-orogenic peneplain was provided, but also its subsequent folding deformations were described in this work.

One of the basic provisions, developed in the works of S.S. Shults, is a structural nature of the relief. Though terms such as "morphostructure" did not exist at that time, basic Tian Shan orographic elements were understood exactly in this way. The preparation of geomorphological maps was commenced simultaneously with geological or hydrogeological surveys. However, legends of these maps were so different, that it was rather difficult or just impossible to correlate them. A basic principle in geomorphological mapping before the 1960s was the morphogenetic principle. On maps researchers started to distinguish "complexes of relief types" such as mountain, piedmont, intermountain and foothills depression, etc. (Grigorenko, 1970; Trubin, et al., 1972). It is more correct to call maps with such legends, maps of geomorphological zoning, because they gave, so to speak, integral characteristics for such large areas as mountains, piedmonts, intermountain and foothills depressions, etc. The works indicated here, as well as a large number of articles (Isaev, 1960) were devoted to the description of meso - and micro relief, formed in highlands and lowlands under the influence of one or another leading factor: soilfluction-nival processes, sheet wash, wind corrosion, exaration, etc. This type of investigation allows explaining the variety of current landscapes.

Problems related to geomorphology are encountered in one way or another by all researchers occupied with matters of stratigraphy of Quaternary deposits, glaciation and paleography of the Naryn basin. Thus, different districts of Kyrgyz Republic were embraced by regional geomorphological investigations. The relief, the history of development of the Issyk-Kul, Chui, Suusamyr, Naryn depressions and their mountainous framing were studied based on the historical-genetic approach, their morpho-structural analysis and geomorphological characteristics were given (Chedia, O.k., Trofimov, A.K., Sydykov, J.). We shall consider the basic types of relief below.

Accumulative type of relief. Brief characteristics of glacial, fluvio-glacial, alluvial, proluvial deposits in the basins of Chon Naryn and Kichi Naryn rivers will be given below.

Fluvio-glacial deposits are developed hypsometrically under morainic sediments. They are represented in the relief by the alluvial piedmont plain with undulating surfaces. Sometimes terraces are developed in them. Such terraces are mainly socle terraces and more rarely accumulative. Fluvio-glacial deposits are represented by boulder-pebble masses, overlapped from the surface by loess-like loams. The average thickness of fluvio-glacial deposits is 8-20 meters, but sometimes they amount to 60-80 meters.

The alluvial type of Quaternary deposits is spread mainly in valleys of large rivers and their tributaries, forming river terraces of all complexes. They are well separated in the relief by smooth, wide surfaces, amounting to 3-6 km in width, which at present in most cases is ploughed up. River terraces are often socle terraces. Either Tertiary sandy-argillaceous or Paleozoic rocks are exposed in the socle. Alluvial deposits of Quaternary cover sheets also have a binominal structure: a pebble bed below with different pebbles from separate boulders, sandy-gravel filler and on the top loess-like loams with the soil layer. The thickness ranges from 3-6 to 60-80 meters. The thickness of the river-bed alluvium makes up several tens meters in case of U-shaped valleys.

Proluvial deposits are recorded in river valleys as well as in the piedmont zone, forming inter fluvial spaces, of which the surfaces correspond to certain terrace levels. The facial composition of proluvial soil is the same as in alluvial sediments, but it is distinguished by poor rounding of pebbles, non-sorting and large contents of sandy-argillaceous particles. Their thickness ranges from 6 to several tens meters.

Glacial deposits are represented by moraines of half-cover and valley glaciation. They are recorded mainly in the mountainous part, more rarely in the piedmont zone and depending on the location, accordingly, have a half-cover (or piedmont) and a valley nature of spread. Moraines in the relief, as a rule, are usually represented by terminal morainic complexes. The surface of terminal morainic lines is not smooth, but hummocky with some hollows. On the surface all moraines, except current ones, are grassed. Density of the vegetation cover reflects to some extent the age of the moraine. The lithological composition of the moraines depends on the age - boulder clay loams and in some places - boulder rocks with sandy-gruss filler are characteristic features.

Deluvial-eluvial deposits are developed very extensively, but they do not represent a unified continuous cover. They are scattered and have a variable thickness. Gentle slopes of mountains and river terraces accommodate eluvial-deluvial deposits. Their lithological composition is very variegated and depends on the composition of the bedrock on which they have developed. Their thickness amounts to 10-20 m.

Quaternary deposits are inseparable from underlying Pliocene deposits, especially in the central parts of the area under consideration, where conglomerates are gradually replaced by more fine-grained sandy-argillaceous rocks.

Lower Quaternary deposits comprise the upper part of the Tian Shan orogenetic complex (Q^1_1) (Shults, 1948). Overlying younger sediments are separated from this complex by a sharp angular unconformity and comprise four separate stratigraphic complexes: Arpatektir (Q^2_1), Bolgart (Q_{II}), Kalmakashuu (Q_{III}), and Naryn (Q_{IV}).

Denudation (destructive) type of relief. Most structural forms, created in areas of most recent uplift, have developed continuously. It is known (Shults, 1968) that development of the recent Tian Shan mountains was preceded by formation of the “initial” peneplain, of which its timing is uncertain (Chedia, 1972), but researchers without exception qualify it as pre-orogenic.

Usually fragments of pre-orogenic peneplain have absolutely smooth surfaces and look as if “cut with a razor” in cases when they are cladded by Cenozoic sediments with depressions. In case of prolonged recent erosion-denudation, their surface becomes undulating and sometimes the topography acquires a hummocky nature.

Owing to the large amplitude of dislocations and intensive dissection of uplifting ranges by erosion processes, the old denudation surface (developed on Paleozoic basement under conditions of platform formation) or pre-orogenic flattened surface was destroyed. In places where it was preserved, it is possible to observe its anticlinal and synclinal deformation and significant dislocation in raptures, as a result of which it appeared on widely different hypsometric levels with extreme values ranging from 5-6 km in depressions up to 6-7 km in the mountains.

During the significant mountain uplift and destruction and dislocation of the pre-orogenic peneplain, tectonic stratification of the relief started to be formed. Under the impact of deep erosion, accelerated by most recent dislocations, steep-slope topography formation commenced. Under conditions of tectonic dislocations compensation by denudation at the end of the stage, terrace-like surfaces were formed in river valleys and in the mountains foreland – piedmonts, which form a general step-like nature of the relief. Each of these steps is regarded by us as a sub-stage of relief. A relief stage can consist of several sub-stages: it occurred during a certain tectonic phase and is correlated with a relevant series of molasses, forming depressions. One or several steps, developed during the process of the tectogenesis phase, are combined in the relief stage.

Studying of the stages of relief in mountainous framing has allowed us to identify basic stages in the relief development of uplift and denudation zones and in conjugated zones of down warping and accumulation. At formation of pre-orogenic relief descending relief-forming processes prevailed, uplifts were compensated by denudation, the depth of vertical dissection was insignificant.

The upper level of the relief is represented by one or two steps, which cut in the old denudation surface and encompassing general wide gentle, slightly hilly, ravine-like forms along basic old subsequent valleys, which connect with most recent synclines or fault troughs, as a rule, not coinciding with a pattern of current hydro-network or inclined towards the periphery of the range by piedmonts.

Two generations of valleys (two steps) have developed in areas, included into uplift starting from Oligocene rocks. Hypsometrically these occur one above the other, below the old denudation surface. The first generation of valleys is traced at the absolute altitude of around 4000 meters and the lower generation at an altitude of 3000 -3500 meters. The erosion cut in of the upper stage of the relief into old denudation surface makes up 300 to 600 m. The upper stage is synchronized with the first tectonic stage of Oligocene-Miocene period and is correlated with the lower red part of molasses in the depressions.

The middle stage of the relief matched with the stage which has just been described. It is also represented by two erosion-denudation steps of narrower and deeply cut in, mainly, subsequent tectonic valleys or inclined from the range to the periphery of piedmont depressions. This stage is synchronized with the second stage of the most recent tectogenesis (Pliocene-Early Pleistocene) and is correlated with the most rudaceous pale-yellow-grey sediments of the Bashnur suite of the Arpatektir complex. The erosion in the middle stage of the relief ranges from 200 to 500 m, increasing in some cases up to 600 m or decreasing down to 150 m.

The lower stage of the relief is formed in the third stage of orogenesis. – significant increase of tectonic movements, when grey boulder-pebbled rock mass of Balgart (Q_{II}), Karagaman (Q_{III}), and Naryn (Q_{IV}) complexes is accumulated. At that period narrow V-shaped terraced valleys of recent river networks are developed in mountains, with prevailing spread of six regional terraces (Q_{II-IV}). The development of this stage continues until today.

It should be underlined in the conclusion that a three-stage structure of the relief is evident in mountainous areas, the older the stage, the higher is its uplift. There are two stages of the relief - middle and lower – in piedmont areas, which have the same ratios as in mountains. Only the lower stage is represented in the Naryn depression: Pliocene-Lower Quaternary deposits correspond to the middle stage and Upper Oligocene and Miocene deposits to the upper stage.

Geomorphological data are a fundamental tool for restoration of the general development of relief, the nature of the most recent structural forms, as well as the regime of latest movements and their rate during the whole most recent period and by separate epochs. Refer to more detailed geocryology forms and processes given in chapter 4.1.

2.3 Climatological conditions of the Chon Naryn and Kichi Naryn catchments

Data of array stations situated below 3600 meters is used for drawing up climatic characteristics. Only one station Tian Shan (3610 m) is situated directly on the border of the glacial zone, 5-6 km from glaciers Davydov and Petrov.

Solar radiation. The annual sunshine duration in upper Naryn catchment exceeds 2500 hours, i.e. it comes up to about 60% of possible quantity of hours of sun light (taking into consideration the topography). Depending on the glacier size in the mountains of Central Asia the temperature differences between glacial and extra glacial surfaces can make up from 0.6-0.7 °C up to 2.1-2.5 °C (Bakirov, 1988, Vilesov, et al. 1983, Voloshina, 1988). Thus, the so-called "temperature rise" depends to a significant extent not only on glacier dimensions, but also on the level of warming of the surface free from ice, on development of the mountain-valley circulation, on the structure of the mountain valley, etc. The higher the air temperature above the surface outside the glacier is, the larger is the temperature difference between the glacier and the earth surface free from ice (Voloshina, 1988). If we take into account that the area of Tian Shan glaciers by present time is reduced in average up to 15-30% in comparison to the 60s and 70s of the last century, than it is not improbable that the air temperature on the glacial surface also has a tendency towards the increase. Solar radiation is one of the leading factors, forming a glacier regime and permafrost. It is a leading factor in the ablation regime for Tian Shan.

Non-uniform emission of the total incoming radiation is manifested on each concrete glacier individually, which is explained by differences in elevations of glacier tongue and different slopes, occurring on variably oriented sides of valleys.

In diurnal variation maximum incoming solar radiation falls on the period from 11:00 to 12:00 both on glaciers of southern and northern orientation, irrespective of the surface slope. For glaciers with western orientation the heat maximum is recorded at the slope of 30°, and it is confined to the time period of 14:00-15:00 hrs. At the slope of 10-20° most favourable conditions for incoming maximum direct radiation are recorded in the period from 12:00 to 13:00 (Dikih, and Dikih, 1988).

Direct radiation (S) is one of the basic inflows of solar radiation and the intensity of the surface ice melting is in direct dependence on its receipt. In the high mountainous zone due to the active development of the cyclonic activity within the warm period and air-mass convective clouds, maximum values can be recorded within separate years in any months from April to August (Dikih, and Dikih, 1988). A characteristic indicator of the solar radiation is its intensity. In high mountainous zones the intensity of direct radiation within clear days is higher than in valleys, because with increase of the absolute altitude above the sea level the transparency of the atmosphere increases as well.

Maximum intensity of direct radiation is observed at the clear sky, when the sun level at midday is significant and the transparency of the atmosphere is high. In the high mountainous zone it amounts to 1010 w/m^2, MS Tian Shan (Applied science handbook on climate of the USSR, 1989). In connection with development of the cyclonic activity within the spring-summer period and air-mass convective clouds, the inflow of radiation heat depends to a large extent on the scattered radiation. In high mountainous zones its value is significantly higher than on territories, located below (Climate of Kyrgyz SSR, 1965).

A significant portion of scattered radiation in general makes positive influence on the glaciation development, because on high mountainous syrts Tian Shan zones the average annual contribution of scattered radiation to the total one makes up 43%, varying within the year from 36% up to 51% (Dikih, and Dikih, 1988).

Total solar radiation is of great significance for glaciation. The annual variation of total radiation values is a consistent result and is in compliance with variations in the day length and the height of the sun. In the high mountainous zone maximum values fall on May due to many clouds – up to 800 MJ/m^2 (Durgerova, et al., 1995), which is connected with favorable conditions in the atmosphere, contributing to incoming of both direct and scattered radiation. High intensity of the total radiation is recorded on glacier systems of Inner Tian Shan.

Annual variations of the albedo value are consistent and are defined by variations in the nature of the underlying surface. Frequent snowfalls are a reason for albedo fluctuations within the summer period. As a rule, after snowfalls albedo of the glacier surface increases up to 60-80%, and in some cases – up to 90% and more. Sharp and frequent albedo fluctuations, as well as the relatively large significant radiation losses deviating from the stipulated average value, contribute to reduction of melting and retention of glaciers.

Radiation balance of the glacial-nival zone. The annual distribution of radiation balance values is consistent with variations in the total radiation and albedo values. In the high mountainous zone the radiation balance starting from March is positive and by June-July it is increased up to 360 MJ/m^2, decreasing by November up to 24 MJ/m^2 (Applied science handbook on climate of the USSR, 1989). Maximum values are recorded from May to August – 82% of the annual radiation balance heat value.

The negative radiation balance on glaciers is recorded from October to May. The radiation balance on different glaciers is rather peculiar. Orientation of valleys plays a great role in values of the radiation balance accumulation. Under conditions of a heavily dissected relief the role of orientation is manifested not only in unequal intensity of incoming radiation, but also in duration of solar ray's impact.

Glacier slopes are connected with their morphological types. Complex valley glaciers of Enilchek, Semenov and other glacier types are characterized by slopes of 2-4°. Valley glaciers with 4-6 km in length have a slope equal to 5°, and small valley glaciers have a slope equal to 8°. Hanging glaciers have maximal slopes – up to 30° and more. In summer reduction of the total radiation value, depending on the steepness, amounts to 9-12% on surfaces with slopes of 10° and 22% - with slopes of 30° (Bakov, et al. 1991).

Most favorable for the incoming total radiation are slopes of southern orientation with slope angles from 10 to 30° (Dikih, 1982, Dikih, et al. 1991). In summer such slopes receive the total radiation by 10% more in comparison with horizontal surfaces. Glaciers of northern orientation with the same slopes, on the contrary, receive less solar radiation.

In diurnal variations, maximum incoming radiation falls on the period from 11:00 to 12:00 both on glaciers of southern and on glaciers of northern orientation, irrespective of the surface slope. Glaciers of eastern orientation receive heat maximum at the slope of 10-20° from 9:00 to 10:00, with increase of the slope up to 30° heat maximum is shifted to a period from 8:00 to 9:00. For glaciers of western orientation heat maximum is recorded at the slope of 30°, and it is confined to a period of 14:00-15:00. At the slope of 10-20° most favorable conditions for the incoming maximum of direct radiation is recorded from 12:00 to 13:00 (Dikih, and Dikih, 1988).

Different exposure of glaciers at non-uniform slopes, both on transverse and longitudinal profiles of the glacier surface will lead to a different extent of glacier retention. Glaciers of northern orientation with slopes from 10° to 30° are in a more favorable position.

Natural surface contamination is of great significance for the glacier regime. If eolian chernozem is detected practically on the whole glacier surface and contaminating snow changes its albedo, intensifies its melting and accelerates fortification processes, moraines are spread not on the whole glacier surface, but on such places, where its thickness is significant, they often protect ice against melting.

As a rule, the decrease of the ice surface albedo contributes to the increase of absorbed radiation, accordingly, the volume of melting, because glacier melting under Tian Shan conditions takes place mainly due to solar radiation. Non-uniform contamination of the glacier surface by Aeolian black soil stipulates different albedo of the glacier surface (Figure 6).

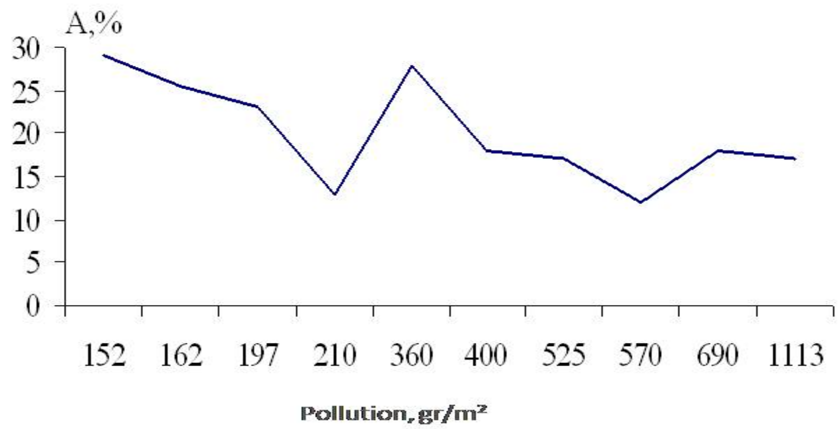


Figure 6 Variation of glacial surface albedo depending on contamination degree. Source: Dikih, A.N., 1988

Similar values are identified at artificial impact on melting acceleration. In the result of blackening of the surface of some Tian Shan glaciers by black dust (up to 400g/m^2), albedo of the glacier was reduced from 29-27 up to 16-17% (Dikih, 1975, Dikih, and Blagoobrazov, 1965). At artificial blackening the effect of melting acceleration appeared to be short-term: 3-4 days and it is insignificant, whereas natural contamination functions permanently.

Observations on Zvezdochka glacier (a left tributary of South Enilchek glacier) showed that areas, cleared of eolian fine earth, melted and became within eight days by 13 cm less than contaminated ice, i.e. diurnal melting of pure ice was by 1.2 cm less (Serebriannyi, and Orlov, 1990). Similar results were obtained on Kara-Batkak glacier, where pure ice melted within eight days less by 9 to 15 cm than contaminated ice (Dikih, and Mihailova, 1976).

The ice, covered by morainic material with a thickness more than 50-60 cm, was almost not subjected to melting (Dikih, and Mihailova, 1976). According to other sources, for example (Kamalov, 1967) at the thickness of morainic cover equal to 100 cm, the intensity of melting makes up 8% of non-contaminated glacier surface melting, and complete termination of melting under the impact of warmth from the surface occurs under the thickness equal to 1.5 to 2 m.

The increased contamination of the glacier surface leads not only to changes in melting intensity at one hypsometric level, but their non-uniform concentration on the glacier surface is a reason for disturbing regular decrease of the melting volume in line with the altitude. For example, the value of ablation on Kara-Batkak glacier in average at the altitude of 3300 meters made up 42 cm, at the altitude of 3500 meters – 35 cm and at the altitude from 3600 to 3800 meters – 36 cm (Dikih, and Mihailova, 1976). The reason for the relatively less value of ablation at the altitude of 3500 meters is insignificant contamination of the glacier surface in this part of the glacier. Melting decrease under morainic cover can lead to inversion of melting within the limits of the tongue and can be a factor for glaciers' self-retention.

Glacier contamination with Aeolic fine earth and small fractions of moraines with a thickness up to 2 cm makes the biggest influence on the ablation regime. If we take into account that a characteristic sediment cover of Tian Shan glaciers is equal to 200 and up to 500 g/m^2 (Dikih, 1975), then one of the reasons for the intensive reduction by ablation of the Tian Shan glaciation is its natural cover with sediments (Figure 7).

Figure 7 Sediment cover of the Petrov glacier, Akshyirak mountain massif.
Source: S. Erohin, August, 2006

Air temperature of the study area. Multiformity of thermal conditions is mainly connected with hypsometry and topographical forms of different parts of the catchment-basin. On climbing mountains, the average annual temperature decreases from +3.1 °C at an altitude of 2040 meters (Naryn meteostation) to to -7.5 °C at 3610 meters (Tian Shan meteostation) respectively (Table 2). This gives a gradient for 0.675 °C per 100 meters. To a greater extent topographical periglacialforms are determined by the daily and seasonal temperature amplitude.

Table 2   Long-term monthly and yearly mean values of climate elements

Month	Air temperature (^{0}C)			Precipitation (mm)	Relative humidity of air (%)	Wind	
	Avg.	Avg. min	Avg. max			Average speed, m/sec	Main direction
Naryn meteorological station, 2039 m (1913-2010)							
January	- 16.4	-25.7	-10.3	9.6	77	1.2	E
February	-12.7	-19.1	-2.2	12.6	76	1.4	E
March	-3.3	-10.8	2.8	21.1	70	1.7	E
April	7.0	2.4	13.0	32.2	53	2.1	E
May	11.7	9.0	16.4	52.0	53	2.2	E
June	14.7	12.1	18.3	53.7	54	2.2	E
July	17.2	14.5	20.4	37.4	49	2.3	E
August	17.3	14.1	21.8	22.1	46	2.2	E
September	12.8	8.9	15.9	15.3	44	2.1	E
October	5.8	2.1	9.2	15.3	50	1.7	E
November	-3.6	-10.5	0.9	13.9	64	1.4	E
December	-13.8	-27.9	-6.3	10.5	74	1.1	E
Year	3.1	-2.6	8.3	298.8	59	1.8	E
Tian Shan meteorological station, 3610 m (1930-2010)							
January	-21.5	-26.8	-17.1	5.7	71	1.4	N
February	-19.8	-23.3	-15.5	6.0	70	1.1	N
March	-13.8	-16.8	-8.9	13.4	68	1.9	N
April	-6.4	-11.5	-2.6	22.5	69	2.2	N
May	-0.7	-4.1	4.6	43.4	70	2.5	N
June	2.3	0.4	4.5	54.9	70	2.2	N
July	4.7	2.0	7.1	57.8	68	2.1	N
August	4.4	1.6	7.2	49.6	67	2.2	N
September	0.3	-3.8	3.2	28.0	67	2.2	SW
October	-6.1	-10.8	-3.4	14.6	65	2.3	SW
November	-13.9	-18.5	-9.9	8.7	67	1.8	SW
December	-19.0	-24.3	-15.5	6.8	71	1.4	N
Year	-7.5	-11.3	-3.8	311.4	68	1.9	N

Source: own calculated with data from Meteorological Center in Bishkek

In equal conditions the temperature increases in trenches and small snowy places. The warm period comes out of step in the end of March (27/III) in Middle Naryn mountain trench and two months later (28/V) in Kum-Tor syrts. The highest surface temperature is observed in July-August. The maximum temperature reaches 24 °C on borders of the glacial zone in Naryn Main Stream. It is possible to estimate the grade monthly mean temperature of Karakol and Tian Shan by way of using vertical gradient and at this time "eternal freeze" is observed above point 4100 m. Transfer of daily average air temperature through 0 °C to aside of negative meanings in the glaciation zone happens in the midway through September (13/IX) glaciers become snow covered in the beginning of November (6/XI). Accordingly, the continuity of the warm period, at the level of grade monthly mean temperature in Tian Shan, makes up 107 days. The air temperature is negative during the cold period of the year (October-May) with lowest temperature is observed in January (Tian Shan meteostation, - 45 °C).

Atmospheric humidity: Relative air humidity of the study area (Table 2) is characterized by high amount of stability (59-68%) and further increases with terrain elevation. It reaches uppermost limit (70%-77%) in winter time and notably it is observed in trenches. The driest air is found in August-October (44%-67%).

Precipitation. Per annum the Chon Naryn and Kichi Naryn catchments receive 298 to 311 mm of precipitation (Table 2). All differences of precipitation spread are connected with orographic particularity of precipitation places in small sizes of area and the vein system of glaciation. At this rate the relative dryness of bottom of trenches are distinguished as well as Arabel- Kumtor syrts (till 310 mm). The glacial zone is more damp (330-390 mm) in some place and extent of precipitation increases till 410 mm and even 480 mm. Precipitation is most abundant in summer months (May-August) and rainfall is heavy in the warm period at an altitude of 3000 - 4200 meters which is on an average two third of annual extent of rainfall. In cold periods the quantity of rainfall decreases and becomes negligible during the months December to February.

The fluctuation of annual rainfall is sometimes high. Maximum precipitation amount was 512.1 mm in 2000 and minimum 96.1 mm in 1997 during the last 80 years. The sum of the separate months of the warm period can exceed the conventional value twice or can be 2 to 5 months less. With increasing altitude in the mountains the fluctuation of precipitation for separate periods increases. There are some peculiarities of the moisture regime in the nival-glacial zone of the territory that we can judge, according to data of accumulative precipitation collected from gauges installed on and near glaciers at heights of 3700 - 4200 m in mountain margins of Arabel-Kumtor and Karasai syrts.

Investigations conducted by the Naryn-Khantengri expedition in periods of 2nd International Polar Year (1932-1933) in the largest glacier Petrov in the Akshyirak massif showed that rainfall increases with an increase of altitude. Collected factual material nowadays confirms such dependence. Substantiation of such dependence is given by data received on the glacier Davydov. One precipitation gauge is installed in front of a moraine glacier at an altitude of 3720 meters and another in the sphere of the catchment basin at an altitude of 4170 meters. We determined the annual amount as 470-480 mm according to the last precipitation gauge within the period of parallel observations (1937-1944) as rainfall norm at ice stream accounts for 390 mm; a smaller amount of rain falls below the glacier on syrts (306 mm). On approximately equal hypsographical levels slopes are better humified due to the moisture carrying air mass coming from West and Northern-West. Smaller amount of rain falls in masked valley deeply plunged in Akshyirak massif. For instance in the wide valley of glacier Davydov, opened to northern-west, rain falls 390 mm per annum while at the same altitude (3740 m) of Karasai where the headstream is covered with outskirts rain falls 330 mm.

The glaciation of Chon Naryn River exerts an influence of local air mass working way through chain of mountains of Terskey Mountains from the water area of ice-free Issyk-Kul Lake besides the influence of western moisture transfer. In this context apparently it should be expected more leveled annual course of rainfalls for passage sections.

Snow cover. The type of rainfall is regulated with the temperature conditions of the high altitudinal zone; therefore the share of solid precipitations is quite considerable in glacial areas and reaches 60%. At altitude of 4000 m precipitation occurs throughout the year but apparently in the form of snow.

In the warm period of the year rain falls heavily. Prevailing rain precipitations (98%) in the lower reach of Chon Naryn River conduce to increase the river flow while summer snow falls on glaciers (46%) where the decelerated ablation is hindering the river flow. Snow fall in a nival-glacial vein system results in temporary snow cover round the year which remains unchanged in syrts altogether within 25 days (almost quarter of the warm period). Whereby, the height of snow cover rarely exceeds 10 cm. Stable snow cover in glacial zone falls on the surface of glaciers in the beginning of November –one month earlier. By the end of October, for instance the height of snow exceeds 30 cm in the ice stream Davydov, which quite corresponds to rain falling for October- November (26 mm). The circularity and inaccessibility of the territory determine the small amount of snowfall in winter. In valleys and syrts the height of snow cover varies from 5 to 40 cm reaching 50-60 cm and in separate periods of winter.

Information on snow accumulation in glacial zone is inconsiderable in number and scrimpy. It is not likely that at a height of 4000 meters the snow height on ice streams exceeds 60 cm. In separate years (1941, 1958) the maximal height of snow exceeded one meter.

Deposit of moisture in snow mass is due to dry influence of a cold and meagre winter of highlands. It does not exceed 140 mm before the beginning of snow melting on Davydov glacier.

In the event of the wind redistribution of snow storage, the zones of glaciation are registered between the catchment-basins of separate glaciers. Bondarev, L.G. (1976, 1986) in particular connects this phenomenon with formation of monolithic snow field in disadvantageous conditions of orientation on abrupt slope in the system of Karasai glaciers, where snow is transferred from glacier reservoirs of western margins of the Akshyirak massif.

A small amount of precipitation falling in Naryn basin in winter defines small height and characterizes the thickness of snow cover. The amount of precipitation, falling in winter months, decreases in the direction from the west to the east. Owing to small thickness of snow cover, cattle’s grazing is possible in winter in some intermountain depressions. Winter nomad camps are organized in the upper reaches of the Big and Small Naryn River.

Stable snow cover on Arabel and Kum-Tor syrts appears at the beginning of October, and in the western part of Naryn basin it appears only in the second half of November. Snow cover in Naryn town is maintained 125 days in a year in average and sledding is possible within three months. The largest height of snow cover is observed at the end of March (30-40 cm on smooth areas). Further, snow is melted in depressions in the first half of April and snow cover is maintained only on syrts, sometimes up to the end of May. The amount of snow falling in mountains is larger than the amount of snow in mountainous depressions.

Wind. Predominant western transfer of air mass in combination with mountain and valley breeze result in wind asymmetry especially in clearly middle mountainous and lateral oriented valleys.

The annual course of wind regime is governed by general process of atmospheric circulation. Maximal quantity of stable air at glacial zone is observed in winter (42-49% from total number of observation's hours) in a time of existence of non-mobile altitudinal anticyclone; the least (26-31%) is intended to coincide to development of spring cyclone. In winter in the absence of temperature inversion the stream flow of frigid air originates essentially from east to west across the territory and flows according to general depression. Gravity winds repeat the hydrographic network of the catchment-basin as it happens for instance on monthly mean temperature of Karakol, where direction of northeast and east streams correspond to the placement of river-valleys Taragai- Karasai. At this time descending northern and north-eastern winds prevail over on smooth surface of Arabel−Kumtor syrts reaching in January its maximum (correspondingly 38% and 24%).

Seasonal activity of local winds heightens by summer. In the periglacial zone with increase of temperature distinctions of underlying surface (snow, ice on the one part and surface of syrts on the other part) the quantity of gravity wind increases on glaciers located in south and east part of Tian Shan.

Wind speed in mountains to a large extent depends upon degree of roughness, which creates additional dynamic air distortion. In whole the monthly mean wind speed is insignificant on the territory and does not exceed 4 m/s (Table 2). In zone of glaciation wind is apparently to be strong in connection with increasing influence of airflow of free atmosphere.

The unique result of eolation in the area is a dust haze, which induces a sharp optical haze that can reduce radiative balance of glaciers in separate period of ablating season. This phenomenon continues for few days.

3 CLIMATE AND GLACIER CHANGES: IMPACT ON THE WATER RESOURCES OF THE NARYN CATCHMENT (KYRGYZ REPUBLIC)

The main results of this chapter has already been published as:
M. Duishonakunov, S. Imbery, C. Narama, A. Mohanty, L. King, 2013: Recent Glacier Changes and Their Impact on Water Resources in Chon and Kichi Naryn Catchments, Kyrgyz Republic. IWA Publishing 2013, Water Science and Technology: Water Supply.

3.1 Glaciological Introduction

3.1.1 Problem statement

The Naryn basin, which has the largest river catchment area in Kyrgyz Republic and many mountain glaciers, is a huge “water tower” for the Kyrgyz Republic and Uzbekistan. Thus, the glacier conditions in the Naryn catchment have a large impact on the available water resources for the arid flat plain below, providing water for residents, irrigation and energy in the Kyrgyz Republic and Central Asia. We investigated the recent glacier conditions 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, the 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 Terskey (south-slope glaciers), and 17.8% in the Uchemchek mountain ranges. The shrinkage was more dramatic for the south-facing than for the north-facing glaciers, with respective area losses of 23.6% and 19.8%. The glacier shrinkage might affect not only irrigation water availability during summer but also the planning of four cascade power stations to be constructed in the Chon Naryn and Kichi Naryn catchments.

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; Hoelzle et al., 2012; Duishonakunov, M. and Osmonov, A., 2005). 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 most important issues in this region because the majority of the water supplied from Central Asian mountains is used within the irrigation zones of the arid flat plains (Report of Eurasian Development Bank, 2009; Agrawala et al., 2001). This demand will increase in the future due to food and energy-security concerns in the region, and this might even lead to water wars among nation states.

3.1.2 Existing research

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 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 (Dikih, 1999; Dikih and 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, 2008, 1990; Narama et al., 2009, 2010; Wenbin and Kaiming, 2011). However, these studies did not address the 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 the 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 our 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 its many glaciers.

3.2 Glaciological study area

The Naryn basin is the largest river basin of the Kyrgyz Republic. 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 kilometers. The major water resources of the Naryn basin are fluvial water from rain and snow and glacier melt in the upstream area. There are 654 identified 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 8). 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, Terskey, and Uchemchek.

Figure 8 Catchments of the Chon Naryn and Kichi Naryn (watershed in red) and location of the meteorological stations. Sourse: Google Earth image with additional informations.

The climatic conditions in the upper Naryn basin are very severe, and all locations within it show an average annual air temperature below freezing point. In the lower part of the upper Naryn basin, annual precipitations are 292 mm at the Naryn meteorological station (2039 m) and 311 mm at the Tian Shan meteorological station (3614 m; Figure 8).

Annual precipitation is low, and the maximum precipitation occurs during summer (May to August) because of the topographical complexity of the Tian Shan Mountains and the complex interactions between the Westerlies and the Siberian High that affect the precipitation in the Tian Shan Mountains (e.g., Aizen et al., 1995, 1997). The basin has clear cloudless weather with little precipitation during winter, and this allows the use of the Arabel 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).

3.3 Glaciological Results

3.3.1 Investigated glacier characteristics

In the two catchments all together 654 glaciers were investigated: 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 Terskey range (south slope glaciers), and 78 in the Uchemchek range (Table 4). 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 3 and 4).

Table 3 The basic information of investigated glaciers (1965)

Size class (km^2)	Number of glaciers	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

Source: own

Table 4 Derived glacier parameters (~2010) for 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

Source: own

A majority of the parameters clearly showed evidence of changes in the regional characteristics of the glacier distribution. Figure 9 show that the relationship between glacier area and aspect indicates that large glaciers are concentrated on northern aspects. A majority (74.3%) of the total area is located in the sectors northwest, north, and northeast. Table 2 shows 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, 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% (of the area). In the other ranges (Borkoldoy, Jetim, Terskey, Uchemchek), 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: 5170 m in the Borkoldoy range, 4840 m in the Terskey range, 4825 m in the Jetim range, and 3510 m in the Uchemchek range. The average glacier termini elevation in the study area is 4223 m.

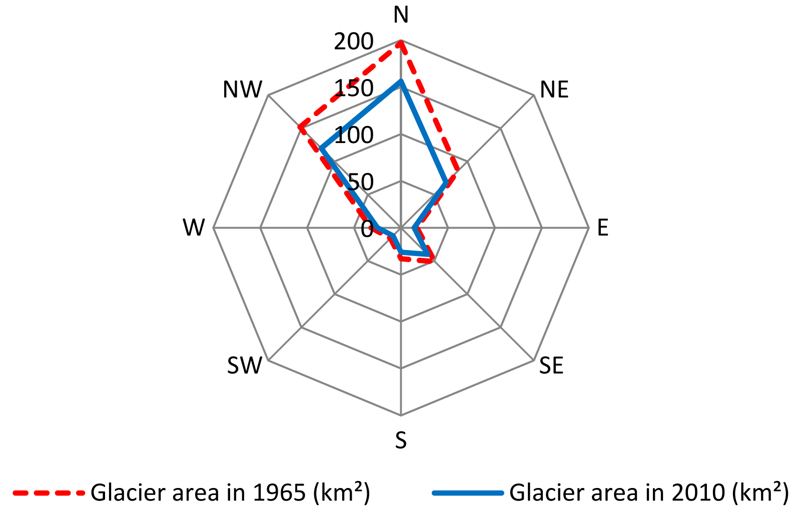


Figure 9 Distribution and area change of glaciers with different aspects. Source: own

3.3.2 Glacier distribution characteristics by river basin

Chon Naryn river basin. Glaciers of the Chon Naryn catchment are distributed essentially in the Akshyirak, Borkoldoy, Terskey, Jetim, Janyjer, Naryn, Sook, and Jetimbel Ranges. The distribution of glaciers is different, mainly concerning their numbers and areas. 715 glaciers (618.6 km^2) occupy an area of 10% in the catchment. The number of glaciers increased recently, because some large glaciers are divided in several small glaciers (0.1 km^2). The average glacier area decreased from 2.3 to 1.1 km^2 between 1965 and 2010. An average glacier area in the eastern part is larger than one in the Western part of the Naryn basin. Moreover this tendency is more considerable on the northern slopes of Naryn Too, Borkoldoy and Akshyirak massif (from 0.27 to 4.2 km^2) than in southern slopes of the Jetim, the Jetimbel, and the Terskey Ranges (from 0.44 to 1.4 km^2).

The glaciers of the Chon Naryn catchment are classified according to their morphology such as cirque, valley, and hanging glacier types. Valley type glaciers (29.1%) are distributed in the river basins of Arabelsuu, Karakol and Chakyrkorum. Although the numbers of valley type glaciers are small, they occupy large areas (227.2 km^2 or 37.0% from all glaciers). Cirque glaciers cover a total area of 1.5 km^2. The 12 complex valley glaciers represent 2.1% of the total glacier occurrence, the area of these glaciers is more similar to the valley glacier type, which exist on the valley bottom. These glaciers are located in the river basins of Karakol, Chakyrkorum, Karasai, Kumtor, and Arabelsuu. Some glaciers are extended over a large area: Petrov glacier (69.8 km^2), northern Karasai (49.2 km^2), southern Karasai (16.2 km^2), No. 190 (13.4 km^2) in the river basin Jagalmay. These glaciers are specified as the complex valley glacier type. There are 25 glaciers with flat-tops and an average area of 1.0 km^2. Figure 10 shows an example for this glacier type, mainly located in the Arabelsuu river basin. Hanging type glaciers, classified as the small alpine type, occupy 0.13 km^2 (which is 12.8% of all glaciers). These three glacier types are distributed non-uniformly in the Naryn sub-basins. Compared to the right bank the glacier volume is twice that of the river basins of the Naryn left bank.

Figure 10 Flat-top type glacier on the south slope of Terskey mountain range. Source: own

According to the distribution analysis, the Arabelsy river basin has 70 glaciers with a total area of 98.3 km^2 or 16.1% of all glacier areas. These glaciers are located at the northern slopes of the Jetimbel and the Sook Ranges. Glaciers on the left bank are distributed in the Terskey Range. On the southern slopes of the Terskey Range, large valley glaciers are developed such as Popov (9.9 km^2) and Chontor (8.1 km^2) glaciers. The ice-cap type Grigoriev glacier (8.3 km^2) is located in the Chon Naryn river basin. Altogether large quantities of melt-water are discharged during summer by 13 ice cap glaciers. Glaciers in

the Arabelsuu river basin occupy 13.1%. Only 35 glaciers (6.2%) exist in the basin of the Kumtor river, but the glacier area (133.3 km^2; 36%) is the largest among the Chon Naryn sub river basins. On the other hand, the number of glaciers is small in the other Naryn River sub-basins and does not exceed 3-6% of the total area. These glaciers are distributed on the northern, the north-western and the north-eastern slopes. Only a few large glaciers exist in the Chon Naryn catchment, 11 glaciers are 5 km long. 84.0% of the glaciers are less than 2 km long and 317 glaciers are even below 1km. Small glaciers occupies 61.6% of the glacier area with areas of less than 0.5 km^2. The majority of small glaciers (63) is located in the Karakol River basin. The largest glaciers are located in the Kumtor and the Karasai river basin (Petrov and Northern and Southern Karasai glaciers).
The glacier termini were especially investigated. The average altitude of glacier termini is 4223 meters (Table 3). Low glacier tongues are situated at the range of 3750 to 4070 meters a.s.l., and the front of the valley glacier No.12 in the Basin of Tuejailoo River is even just at an altitude of 3460 meters. The glacier fronts of the cirque glacier No. 181 at Jagalmay River and of the hanging glacier No. 500 at Karachunkur River are at an altitude of 4640 meters.

The average equilibrium line altitude (ELA) is located at 4200 m, the highest ELA is 4320 meters in the Karakol basin. The ELA in Kumtor and Taragai is close to the average ELA value of the whole basin.

Snow avalanches play an important role when the mass balance is researched more in detail. Several cases of snow avalanches from slopes to the glaciers of the Akshyirak massif are described in reports from Bondarev L.G. (1986), Maksimov, E., and Osmonov, A. (1995) at Tuiuk-Chakyrkorum river basin. Analogue patterns can be observed in the neighboring basins of the rivers Chakyrkorum and Jagalmay. Avalanches have been observed from the surfaces of the glaciers No. 270-273, 280, 285 as well as from glacier No. 258, a small hanging glacier with the size of less than 0.1 km^2. Moreover, snow avalanches are noticed at altitudes of 3000 m and higher in many districts of the territory and in the narrow river valleys of the Jetim and the Naryn mountains. Aerial photos have revealed the presence of avalanche feeding of glaciers in the basins of the rivers Arabelsuu (glaciers No. 389, 392) and Karakol (glacier No. 165). Predominantly glaciers receive avalanche feed from slopes with northern and north–eastern expositions. In the

Arabelsuu basin some glaciers receive accumulation of drift snow from windward northern slopes due to storms.

Kichi Naryn river basin. Most glaciers can be found in the eastern part of the Kichi Naryn river basin. 13 morphological types of glaciers are identified from complex-valley to flat and conical-summit type glaciers. There is a great variety of glaciers with different morphological types. For example, 152 valley glaciers occupy an area of 214.3 km^2 (60.8%) in this basin. Nine ice-cap glaciers cover 2.4 km^2. There are 13 glaciers of the kettle-hole type that occupy 13.6% of the total glacier area. Two slope-corrie glaciers (0.5 km^2) make up only 0.1% of the total glacier area. Corrie glaciers prevail with 102 glaciers (area: 22.6%). Glaciers occupy 270.7 km^2 (77%) on the northern slopes in the Kichi Naryn catchment. The smallest glacier area is on the south-eastern slopes with 0.2 km^2 (2.9%), the glacier area on the southern slopes covers 47.5 km^2 (13.5%). Glaciers on the western and eastern slopes are approximately equally frequent (15.3 and 16.9 km^2, respectively). The characteristic glacier in the Kichi Naryn river basin is of relatively small size. 86% of glaciers have a length within 2 km. The longest glacier is only 6.8 km long. 66.3% of the glaciers have a mean size within 0.5 km^2. Only two glaciers are larger than 10 km^2 each: glacier No. 58 (10.5 km^2) and glacier No. 395 (10.2 km^2). The average glacier surface area is 0.7 km^2.

Most current glaciers are developed in the Jyluusuu river basin, 98 glaciers have a total area of 65.8 km^2. The glaciers can be found on the southern slopes of the Terskey range and on the northern slopes of the Uchemchek range. The Jyluusuu River basin is typical for the investigated area. 63 glaciers (out of 98) have a length of less than 1 kilometer, only one glacier reaches a length of 6 km. There are 63 corrie glaciers that cover 25.2 km^2. There are 16 valley and kettle-hole type glaciers covering an area of 37.6 km^2, at which the five kettle-hole glaciers take up 15.7 km^2. The average glacier area in the basin of Jyluusuu River is 0.7 km^2. In the basin of Archaly river, 51 glaciers cover 8.8 km^2 (2.5%), the average glacier area is 1.1 km^2. The 32 small valley and corrie type glaciers are located on the northern slopes of the Jetim range. Three glaciers are classified as conical-summit type. The Archaly River basin is limited by the Jetimbel range, glaciers are located on the northern slopes. The average size of glaciers in the Jetim range does not exceed 1 km^2.

The largest glacier area is in the Kyzylbel and the Chon-Karagaman catchments. The Kyzylbel river basin has 32 glaciers (11.9%) that cover 43.1 km^2. The Chon-Karagaman river basin has 37 glaciers (12.2%) with a total area of 42.1 km^2. The average altitude of the glacier termini in these basins is 3900 meters. Glacier sizes in both basins are from 1 to 6 km^2. The largest glacier (No. 58: 10.5 km^2) is in the basin of Chon-Karagaman river. The aspects of glacier distribution are different in the two basins. Glaciers are located on the eastern and western slopes of the range. Glaciers of the valley and the corrie type occupy 87.5%. The Chon-Karagaman River is distinguished by a great variety of morphological types of glaciers. Glaciers of 13 types are confirmed in this area. The complex valley glacier (2.8 km^2) is located here on the south-western slope. Corrie glaciers occupy 59.4% of the total number in this basin.

60 glaciers are located in the upper part of Burkan River (41.7 km^2), on the northern slopes of Jetimbel range, on the southern slopes of Terskey range, and on the slopes of the intermediate watershed – the Uchemchek mountains. 41 glaciers (37.3 km^2) are located on the northern slopes, 27 glaciers (45%) on the southern slopes. 36 glaciers (60%) have a size of less than 0.5 km^2. The largest glacier does not exceed an area of 6 km^2. The average glacier front is at an altitude of 3850 m. The basin of the Kichi-Karagaman river is one of three river basins (the two other basins are the Jyluu-Suu and Chon-Karagaman basins), with 26 glaciers (26.8 km^2). In the basin of Kichi-Karagaman basin, 22 glaciers have a length within 2 km, 18 glaciers or 69.2% cover up to 1 km^2 each and only two glaciers extend up to 6 km^2. An average area in the Kichi-Karagaman basin is 1 km^2. Valley and corrie glaciers experience different climatic conditions. There are nine valley glaciers (3.9 km^2) and three kettle-hole glaciers (12 $km^{2,}$ 44.7%). Glacier No. 87 (5.7 km^2) is located on a south-eastern slope. An average elevation of glacier terminus in this basin is 3940 m.

The glacier area in the Kalcha river catchment has a size of 21.1 km^2. 23 glaciers (66.3%) cover an area of 0.5 km^2 or less. The largest glacier in this catchment is within 3 km^2. In the Kalcha River catchment the largest glacier area exists on southern slopes. Glaciers are located mainly on northern slopes. Glaciers are of the corrie-hanging type (75.7%). Seven different morphological types of glaciers are represented in the basin of Kalcha river. They are kettle-hole, the valley and the ice-cap types. The glacier area in Sary-

Kungoy River is 10.7 km^2. Among eight glaciers, six glaciers are valley glaciers; the others are of the corrie and the hanging type, respectively. Eight glaciers (1.8% of the total number of glaciers) occupy 3% of the total area of glaciers. An average glacier has a surface of 1.3 km^2 and the mean lower altitude of glaciers is 3790 m.

The basin of the left tributaries of Burkhan River has a larger number of glaciers (10.6 km^2). These glaciers are located on the northern slopes of the Jetimbel range, there are14 glaciers on the northern slope, three glaciers on the north-eastern and the north-western slopes. The glaciers are about 1.0 km in length and cover about 0.5 km^2. The total glacier area is 10.6 km^2. The average glacier altitude is 3640 m. The glacier area within the 10 km^2, includes the catchments of the rivers Kokturpak, the right tributaries of the Kichi Naryn downstream the mouth of Sary-Kungey river, the Jylanach river, the right tributaries of the Burkhan river between the river mouths of the Jyluusuu and Kalcha, the left tributaries of the Kichi Naryn–the Sultansary, Nagorgonsu, Karatal and the right tributaries of the Balgart river between the river mouths of the Karagaman and Jyluusuu. The total 86 glaciers (33.9 km^2) are located in these river basins. The glaciers developed corries, circuses and grass-covered old marginal moraines. The main glacier type is corrie, and an average glacier area is within 0.1- 0.6 km^2.

Glaciers are investigated about morphological types (there are 10 different types of glaciers in nine basins – from valley to conical-summit glaciers), there is a predominance of small (up to 0.5 km^2) dimensions and their prevailing location on slopes with a general northern orientation. The glacier elevation zone is lower, compared to the territory. Balgart River is 4040 m, not exceeding in average 4240 m, in the basin of Karatal River (northern slope of Akchatash range).

3.4 Glacier area changes from 1965 to 2010

We investigated glacier retreat 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 km^2 to 460.5 km^2) during the period 1965 to 2010 (Table 5). The 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 Terskey range (south slope), and 17.8% in the Uchemchek ranges (Figure 11). The greatest shrinkages in an area occurred in the Naryn (28.9%), the Jetimbel (24.6%), and Jetim ranges (21.9%); (Duishonakunov, M. et al., 2013).

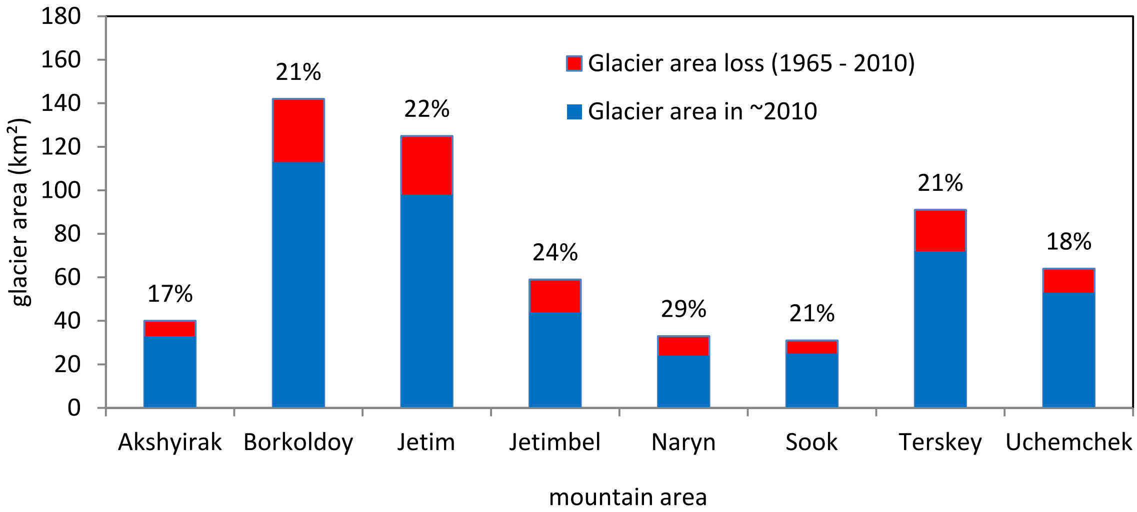


Figure 11 Changes in total glacier area in eight mountain regions for ~1965 and ~2010

Source: own

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 (Johannesson et al., 1989; Kuhn, 1995; Nesje and 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

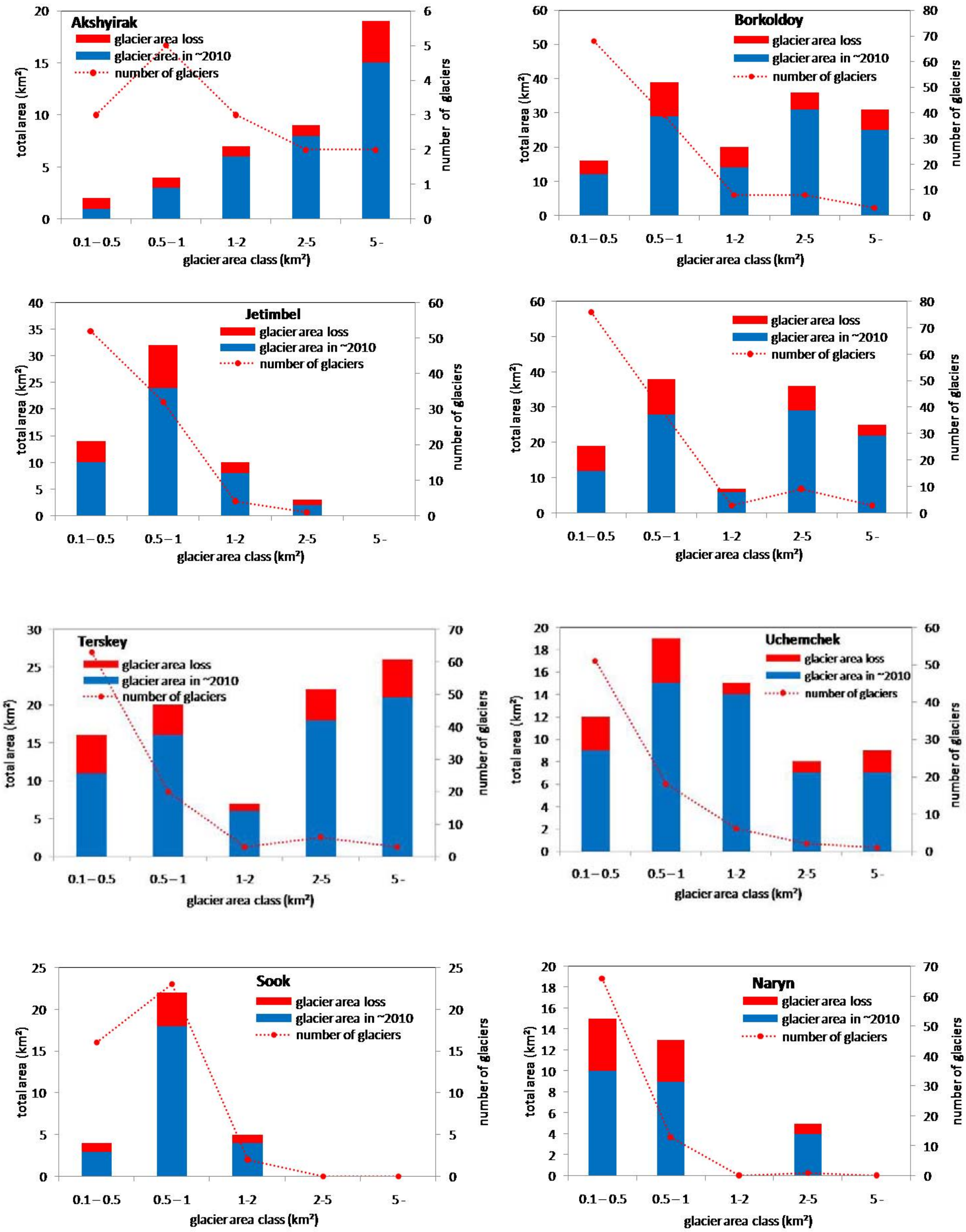


Figure 12 Changes in total glacier area by glacier size classes in eight mountain regions for ~1965 and ~2010. Source: own.

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 km2), has shown less shrinkage (17.4%; Table 5). Figures 12 show the specific glacier changes related to the glacier size class. There were also dramatic differences between glaciers located on northern and southern slopes in these changes (Figure 9). On northern slopes, 513 glaciers decreased by 19.7%, but on southern slopes, 78 glaciers were reduced by 24.1%.

Table 5 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

Source: Processed from ALOS satellite images

3.5 Interpretation of data

3.5.1 Glacial changes and its relation to local climate change

The distribution of glacier size is very dissimilar 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 4). 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 Narama et al., (2006, 2010) and Kutuzov and Shahgedanova (2009) of the Terskey range, Hagg et al., 2012 in Chon Naryn and David et al., 2013 in Naryn basin was 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; 3614 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 was recorded at the meteorological stations and showed a decreasing trend (Figure 13). The precipitation trend 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 (3659 m) between 2000 and 2012, the winter trend was also positive and the temperature increases in the warm-month and the summer periods. In contrast, precipitation decreased in this period.

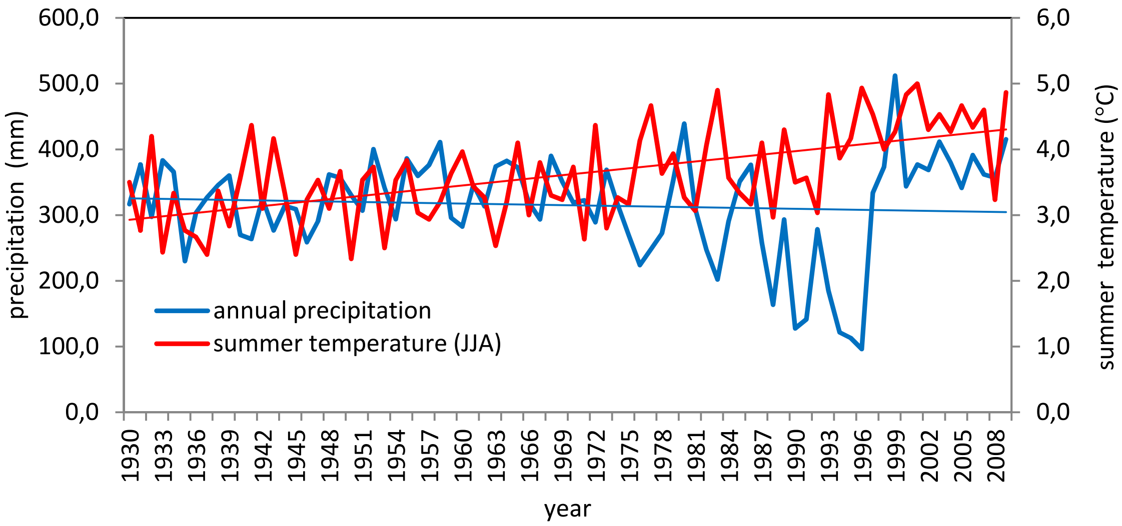


Figure 13 Annual precipitation amount and mean summer air temperature (JJA) at the Tian Shan meteorological station. Source: compiled from Meteocenter data.

The recent glacier shrinkages are due to manifold reasons. There are slight increases in temperature and decreases in precipitation, which leads to (a) snow accumulation decrease on glaciers in the spring to early summer season, and (b) a decreasing albedo effect for the protection of glacier ice (Dikih and Hagg, 2004; Hagg and Braun, 2005).

3.5.2 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 areas in the study region (Table 4). The other mountain regions like the Akshyirak mountain massif and the Uchemchek have not shown much percentage of glacier shrinkage because the majority area is 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), that 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 Narama et. al, (2006), Narama et. al, (2009) and Kutuzov, et. al, (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 retreats have significant impact on discharge of watersheds to lowland arid and semi-arid areas of Central Asia.

4 PERMAFROST IN THE CHON NARYN AND KICHI NARYN CATCHMENTS

4.1 Introduction to permafrost and periglacial processes of the Upstream Naryn catchments.

Permafrost is defined as ground that remains at or below 0 °C for at least two consecutive years. Mountain permafrost regions are traditionally divided into several zones based on estimated geographic continuity in the landscape. A typical classification recognizes continuous permafrost (underlying 90-100% of the landscape); discontinuous permafrost (50-90%); and sporadic permafrost (0-50%) (www.ipa.arcticportal.org). In the Tian Shan Mountains at altitudes of more than 3300 meters there is permanently frozen ground spread almost everywhere.

The permafrost – is the product of climate and heat-flux from the earth. Its origin and preserving is promoted by the low average annual and winter temperatures and the insignificant snow cover, which favor the cooling off in winter. Permafrost has been identified as one of the cryospheric indicators of global climate change within the monitoring framework of the WMO Global Climate Observing System (GCOS) (Harris et al., 2001 a,b; Cihlar et al., 1997). Ground ice can only persist from year to year, or century to century in the cold part of the world where there is permafrost for otherwise it would melt (Mackay, 1972). In the permafrost area, the active layer thaws in summer and freezes in winter. Accordingly, any underground ice must lie in permafrost below the depth of summer thaw. Underground ice can only persist in permafrost not all permafrost has underground ice, because permafrost is defined solely upon a temperatures basis (0 °C or below) and not upon the presence or absence of ice (water). King et al. (1992) notes: "Whereas practically all water is frozen in permafrost material at temperatures of about -15 °C, a considerable amount of water remains unfrozen at temperatures between 0 °C and -5 °C, especially in materials with high clay content". However, this may be important in the interpretation of geophysical properties. Permafrost may exist in soils or other surficial materials (from peat or clay to boulders) or even in bedrock (King, 1986). Mountain permafrost known from high altitude regions, such as the Rocky Mountains in North America (Janke, 2005), the Alps in Europe (Harris et al., 2003; King 1990, 2000; King et al., 1993, 2003; Haeberli et al., 1992), the mountains in Scandinavia (King, 1986; King et al., 1988), the Himalaya in Asia (Jin, H. et al, 2000). Also recent studies have reported warming of permafrost temperatures in many places of the world (e.g. King, et al., 2014, Marchenko et al., 2007; Gruber et al, 2004; Ostercamp, 2003; Imbery et al., 2013; Romanovsky et al., 2002; Zeng et al., 1993; Beniston, et al., 1996).

Under climate change, the temperature increase and the distribution of permafrost in the mountain areas get more and more in the focus of the scientific community especially because of its impact on the water balance, but also concerning slope instabilities.

Periglacial processes and phenomena. The study of periglacial environments is very important for the Kyrgyz Republic with high mountain areas. By definition, the term “periglacial” means “The conditions, processes and landforms associated with cold, non-glacial environments”. The NSIDC Glossary (1998) notes: “The term was originally used to describe the climatic and geomorphic conditions of areas peripheral to Pleistocene ice sheets and glaciers. Modern usage refers, however, to a wider range of cold climatic conditions regardless of their proximity to a glacier, either in space or time. Many, but not all, periglacial environments possess permafrost; all are dominated by frost action processes”. Therefore the periglacial environment does include ground ice, but not include glacier areas. This is important to understand, because ground ice in permafrost, in contrast to glacier ice, does not contribute to the annual runoff, hence the water level in the rivers (French, 2007). However, the ground is frozen, which means that the water stays frozen within these grounds. But, in the future the ground ice which is stored in the permafrost can be a significant water source. That is why it´s important to study the differences between the glacial and the periglacial environment. The corresponding sciences are **glaciology and geocryology**, respectively.

Periglacial processes include frost jacking, frost sorting, frost wedging, cryoturbation, and the development of cryotextures, cryostructures and cryogenic fabrics in soils and its phenomena include landforms like seasonal and perennial frost mounds, as well as the cryotextures, and cryogenic fabrics found in soils. Special landforms exist in areas with frost, although only some indicate proofs of permafrost presence. Surface features formed under cold, non-glacial conditions are known as periglacial landforms (Washburn, 1980; French, 1996). Many researchers were fascinated by the wealth of periglacial forms, and many well illustrated textbooks on periglacial processes and "geocryology" exist (e.g. Washburn, 1973; 1979).

The permafrost in the Naryn basin can partly be considered as the relict phenomenon inherited from an epoch with even more severe climate. But there are also signs of its formation at the present time as well. This is witnessed by the presence of recent floodplain sedimentations on the Arabel heights icebound by frost. The alpine permafrost zone in the Chon Naryn and Kichi Naryn catchments belongs to the Asian high-mountain permafrost region. First data of frozen ground in the high mountain areas (syrts) of the Upstream Naryn basin were reported by a well-known Kazakhstan soil scientist Bezsonov (1914). He pointed out, in his preliminary report on works on syrts of Ak-Sai, Taragai and Arabel-Suu, carried out in summer 1913 that soils at altitudes of around 4,000 meters "… are sometimes bogged with the frost by 60-80 cm".

Earlier geocryological findings: "Syrt" is the regional name for high mountain areas in Kyrgyz Republic. They form large unified permafrost massifs and include several mountain ranges of the Upper Naryn catchments such as: Terskey, Naryn, Borkoldoy, Akshyirak, Jetimbel, Jetim, Sook, Uchemchek and series of less significant ridges. The intermountain depressions Arabel, Kumtor, Upper-Naryn, and Akshyirak are included into the composition of the Syrt massif.

The construction of Tian Shan Meteorological Observatory near Petrov glacier on the Kumtor river bank, at the end of the 1920s, was a notable impulse in cryogenic investigations. The Construction of the massive building required a careful studying of the ground. It was defined by drilling that its unfrozen layer was traced only up to the depth of 120 cm, and the thickness of frozen ground below exceeded 15 m (Kalesnik, 1933). In 1932 during the period of the activity of Naryn-Khan-Tengri Expedition, Kalesnik (1935) collected rather interesting data on permafrost and on some cryogenic phenomena. Thus, during the installation of the temporary hydrological station on the bank of Kumtor river workers of the expedition discovered an ice lens at the depth of 80 cm in the frozen ground. Kalesnik also pointed out impartially that the modern climate of

Kumtor syrts is favorable for the existence of permafrost. He observed striated solifluxion formations with alternating rocky and silt strips at the foot of the western slopes of Akshyirak. He thought that all these forms were indirect features of permafrost.

In 1931 – 1932 a geologist S.S. Lark worked on the syrts of the Inner Tian Shan. Here ported of the development of permafrost in the valley of Arabel-Su and described, in brief, sinkholes on banks of Taragai, which, according to his supposition, appeared due to melting of buried ice (Lark, 1932-1933). Especially interesting data on permafrost, cryogenic forms and temperature conditions of the active layer were collected by the Ecological Expedition of Leningrad University headed by Kashkarov. It worked in the vicinity of the Tian Shan Meteorological Station in 1934 (Kashkarov et al., 1937).

The construction of the high mountain meteorological observatory and investigations, connected with conduction of the 2nd International Polar Year in 1932, allowed to collect the first certain data on permafrost of Arabel and Kumtor syrts of Upper Naryn basin. Moreover, it was found out that current climatic conditions were favorable for its development. The attention was also paid to other phenomena, which at present are known as cryogenic ones. Some additional data on permafrost in Tian Shan were collected in the 1940s during geologic, soil and botanical investigations.

Glazovskaya (1953a) conducted a large complex of soil and landscape investigations in the Inner Tian Shan within two summer seasons in 1947 and 1948. She investigated syrts of Arabel-Su, Kumtor, Sary-Chat, Taragai, Kara-Sai, and Sary-Djaz. During the study of soil sections permafrost was discovered in several places at altitudes from 3600 m to 4100 meters, although the description of soil profiles did not require deep prospecting pit. Permafrost was reached only in such places, where it was at a depth around 1 m., i.e., on bogged areas or at very high altitudes. That is why M.A. Glazovskaya was initially of the wrong opinion that frozen ground disappears even in the area of Tian Shan Meteorological Station on slopes of the southern exposure. She, apparently, changed her opinion to some extent. Thus, in another work Glazovskaya (1953b) writes that ground ice on syrts of Arabel-Su and Kumtor above the altitude of 3500 meters is distributed throughout. The works were conducted over 8 years in the same places and showed that permafrost occurs on slopes of the southern exposure at the depth of 150-200 cm. The author M.A. Glazovskaya made a significant contribution to the study of cryogenic formations. She described and sorted out fields of denudation surfaces of Terskey range and Kok-Shaal-Too. The credit is due to Glazovskaya for separation of high mountain takyr-like desert soils and identification of the ground ice impact on soil formations. Glazovskaya put forward a good proposal to call a system of "mud paths" on slopes, separated by grass-covered strips "a striated complex". She correlated its formation with solifluction and the latter with ground ice.

Glazovskaya explained deep land subsidence on moraines of Kara-Sai and Taragai by leaching of gypsum lenses in Tertiary rock masses. Serious objections can be put forward against such statement. As it is now ascertained, permafrost is developed there everywhere, and in the presence of permafrost it is unlikely that karst processes can develop actively. Subsidence is available only in such places, where morainic deposits are developed. In places where tertiary deposits outcrop to the surface subsidence can not be observed. Fresh subsidence is spread in Tuyuk-Chakyr-Korum valley, where gypsum-bearing deposits are not available. In general, materials of Glazovskaya, published in several works (1952, 1953a, 1953b), are significant contributions to the study of permafrost and cryogenic forms.

The beginning of the 1950s is marked by deployment of hydro-geological investigations on syrts of the Naryn basin. They were connected with demands of the developing livestock husbandry in Kyrgyz Republic. A vital necessity arose connected with reliable water supply to pastures. The Geological Authority of Kyrgyz Republic started a planned hydro-geological survey of syrts in the Naryn high valleys. Simultaneously prospecting of underground water reserves was carried out, and mineral sources were studied. Discovery and development of different deposits, increased with each year. And all these works required construction of bridges, roads, a passage of power transmission lines, etc. Naturally, active economic development of syrts resulted in the intensive collection of new data on permafrost.

A scientific expedition, headed by A.A. Kasymkhodzhaev, worked in 1951 and 1958 on Ak-Sai syrts. It was found out that ground ice was wide spread throughout, it occurs in rocky soil at a depth of 3 to 4 m. The most important result was the definition of the permafrost thickness, the first value for the Tian Shan, and discovery of sub-permafrost head water. The thickness of permafrost at an altitude of 3350 meters appeared to be 107 m (Kasymkhodzhaev, 1952 and 1958).

A series of interesting data on ground ice was reported by workers of the Geologic Authority of Kyrgyz Republic and different exploration organizations of Bishkek city. Data of G.P. Bogomazov, I.P. Vorobiev, V.Z. Daminov, V.N. Dolzhenko, A.I. and G.I. Paschenko, N.N. Popkov, V.M. Popov, L.I. Turbin, E.A. Mitrofanov, E.S. Motorin, E.A. Stepanov, V.M. Skorokhodov (Annual report of the Geologic Authority of Kyrgyz Republic, 1955) appeared to be especially valuable. These materials confirmed the initial suggestions on the extensive distribution of permafrost in the Inner Tian Shan above an altitude of 3000 meters.

In 1956, according to the proposal of R.D. Zabirov, special works were commenced on the study of permafrost in the Upstream Naryn basin, which were carried out and are being carried out by the author of this work on the basis of the Tian Shan High Mountain Physical-Geographical Station of the Academy of Sciences of Kyrgyz Republic.

Thus, it was found out by 1956 that frozen ground was recorded in some places in the Naryn basin and their thickness amounts to several tens of meters. Such cryogenic phenomena as solifluction (Figure 15), soil heaving, thermokarst and formation of polygonal systems were correlated with permafrost and buried ice. The impact of permafrost was recorded on flora, fauna and soil-forming processes. The opinion was expressed that current climatic conditions of Kumtor syrts were favourable for the existence of permafrost. At the same time some researchers, for example, V.P. Goloskokov, were inclined to the idea of permafrost degradation at lower altitudes. That's all that was known about permafrost of Tian Shan by 1956.

A series of published and hand-written works has become known since 1956, in which we find new data on permafrost and some cryogenic phenomena of the Naryn basin. A valuable contribution to the study of permafrost phenomena was made by L.G. Bondarev. In 1960 he pointed out the role of permafrost in formation processes of the shore of high mountainous lakes on Arabel and Kumtor syrts. He showed that permafrost made an evident impact on bogged shores of some lakes, and flooding of large polygons leads to the formation of a peculiar shoreline (Bondarev, 1960a). Jointly with the author L.G. Bondarev was occupied with the study of the impact of deep seasonal freezing on up-freezing phenomena. He (Bondarev, 1960b) also summarized data of permafrost on significant parts of the Inner Tian Shan.

The observations of Blagoobrazov, V.A. also deserve attention. He, for the first time in the history of Tian Shan, studies published materials on icings at Akshyirak massif (1960). In this work he reported on the existence of not only seasonal, but also on perennial icings, he pointed out 1957-1958 years as especially favorable years for their development, defined maximum thickness of icings and described the structure of some of them. In another work Blagoobrazov (1964) tried to find out dynamics of permafrost layers, depending on the air temperature and snow cover. For this purpose he used indications of ground thermometers at Tian Shan Meteorological Station. According to the author's opinion, not all of these indications in the period from 1930 to 1952 can be used with confidence, especially concerning the years from 1935 to 1936. However, the work of V.A. Blagoobrazov is of valuable scientific interest.

Based on his observations and investigations Chupahin (1964) summarized some results of permafrost and cryogenic phenomena study in Tian Shan. Mamytov, A.M in his monograph (1963a) pointed out that products of weathering and soil formation were accumulated in surface layers of soil, developed on permafrost. He also reported on ground ice in spruce forests of Sary-Djaz river basin. In another article, written jointly with V.A. Makarenko, he rather more explained the impact of permafrost phenomena on the formation of high-mountain soils of the Naryn basin (Mamytov, 1963b).

And at last, it is necessary to point out extremely valuable temperature observations in ground ice by the Tian Shan and Chatyr-Kul Meteorological stations. At the Tian Shan Station these measurements are made at the depth of 160, 240 and 320 cm. Although temperature observations of permafrost on Tian Shan were commenced since 1934, until 1953 they are not sufficiently reliable. This is testified in particular by temperatures at the depth of 160 cm, going in 1935, 1936, 1937 beyond the norm, which probably is connected with the disturbance of the thermal regime of the ground by the arrangement of the boreholes, in which thermometers were installed. From 1939 up to 1945 temperature observations in the prospecting boreholes were carried out at the depth of 220 cm and 320 cm. From 1952 data on temperatures at the depth of 240 cm were obtained and only starting from 1953 special observations of temperatures in ground ice were carried out at the depth of 160, 240 and 320 cm.

Thus, the history of permafrost and cryogenic phenomena study in Tian Shan starts perse from the beginning of the 1930s. Construction of Tian Shan Meteorological Observatory and the II International Polar Year were the impulse to its development. All permafrost observations until 1956 were conducted by different specialists (zoologists, glaciologists, soil scientists, botanists, geologists, hydrogeologists) concurrently. Special investigations of permafrost and cryogenic forms and phenomena on Tian Shan High Mountain areas were carried out from 1956 on the basis of the Tian Shan High-Mountain Physical-Geographical Station located in upstream Naryn basin (same location as Tian Shan meteorological station). These researches only describe local permafrost occurrences, but they give no general picture concerning the laws of the distribution. However, permafrost studies in our research area are completely missing.

Permafrost in the Tian Shan mountains is of practical and scientific interest, and the regional estimation of its distribution is described in numerous studies (e.g. Marchenko, 2003, Marchenko et al., 2005, 2007; Gorbunov, 1967, 1978, 1993, Gorbunov et al., 1989, 2004; Ermolin et al., 1982, 1988, 1989; Shwarzman, 1985; Gravis et al., 2003 etc.). With observations of the permafrost temperatures in the upper Naryn catchments were studied in 1986 by Kazakhstan Alpine Permafrost Laboratory. Their several boreholes with depth 2, 5, 10, 15, 20, 25 and 30 m were located in the territory of the "Kumtor" goldmine (Annex A-01).

4.2 Studies for distribution and temperature of ground ice

For the current study we investigated frozen ground in the upstream Naryn catchments, between August 2010 and August 2013. We measured the near-surface ground temperature at 18 locations at different altitudes and slopes. The objectives of this study are to estimate the distribution of permafrost, and its active layer, and to discuss the permafrost environment in the upstream Naryn catchments. The general features of mountain permafrost such as permafrost distribution and temperatures, active layer thicknesses within the upstream Naryn catchments, Tian Shan Mountains are described. The area of permafrost studies in the Naryn basin is located within the two upstream river basins (Chon Naryn and Kichi Naryn). The mountain permafrost zone in our study area belongs to the Asian mountain permafrost area, the largest in the world.

In the field we used steel rods and a hammer (Annex A-02) to dig holes up to 1.5 m deep for our thermistor strings. Ground temperature measurements were carried out in 18 locations in our study area between altitudes 3007 and 4043 meters. These ground temperature measurements performed using wireless mini thermistor sensors (M-Log5W) and data sampling continues. They have a high memory capacity (2048 kB), low energy consumption and waterproof cover (Figure 3). The temperature sensor has a high resolution of 0.01 °C and an overall accuracy of ± 0.1 °C. This thermistor can work more than 5 years without changing batteries depending on temperature conditions of the ground. The temperature recording started in August 2010 at an hourly interval at all locations the observation period was up to end of August 2013.

In the investigated area permafrost is developed above 3300 m a.s.l. (Figure 14). The definition of the lower limit of the permafrost zone in mountains is not an easy task. The point is that physical-geographical conditions here are extremely variable: exposure and steepness of slopes is changed over short distances, bedrocks are replaced by soft sedimentary masses, vegetative ground cover and ground moisture contents are very variable. Winter air temperature in versions and extremely variable depth of snow cover are usual for mountainous areas. All these factors have influence on the permafrost development. Moreover, it is necessary to distinguish between the lower limits of sporadic, discontinuous and continuous permafrost.

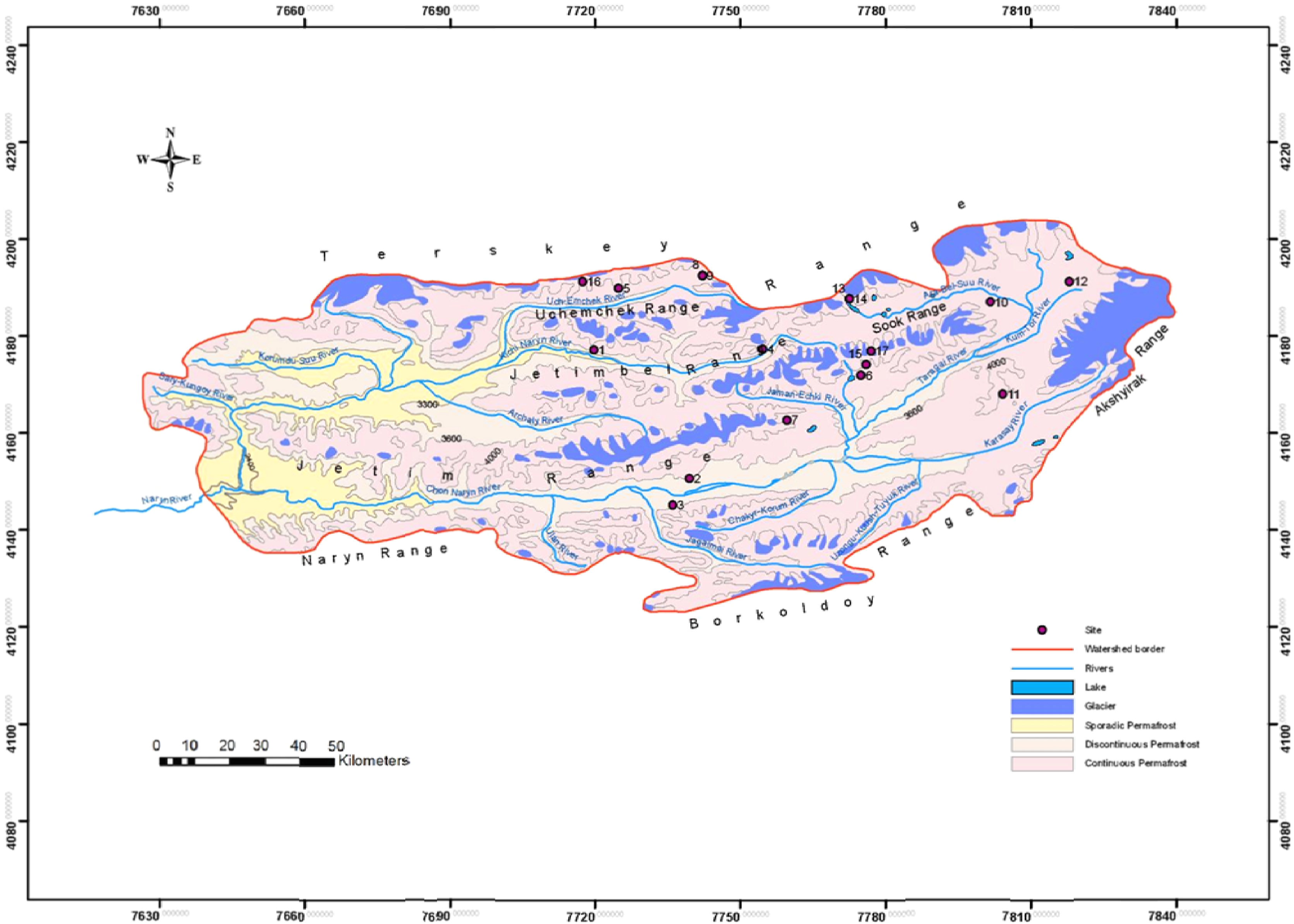


Figure 14 Glacier and Permafrost distribution map of the river basins Chon Naryn and Kichi Naryn in the Inner Tian Shan. Glaciers occur well above 4000 m a.s.l. with an ELA of often more than 4200 meters. Red dots show the location of ground temperature sensors. Source: own

The lower altitudinal limit of the sporadic permafrost in Naryn basin is as low as 2700 meters. We have data at our disposal (Table 6) on location of permafrost on northern slopes at altitudes between 3334 and 3756 meters (Akshyirak, Uchemchek and Sook mountain ranges), on southern slopes at altitudes between 3007 and 3875 meters (Terskey, Sook, Uchemchek, Jetim mountain ranges), on western slopes at altitudes of 3650 to 4043 meters (Akshyirak and Sook mountain ranges) and on eastern slopes at altitudes of 3781 to 3865 meters (Terskey and Sook mountain ranges). The sporadic permafrost area is increasing by the altitude; there are more and more such areas and the area of discontinuous permafrost starts somewhere near the hypsometric line of 3300 meters (Duishonakunov et al., 2014). Here the area with permafrost is larger than the non-permafrost area. Permafrost is wide-spread throughout, at altitudes above 3200-3400 meters we propose to regard the contour line of 3300 meters as the lower limit of discontinuous permafrost in the Upstream Naryn basin.

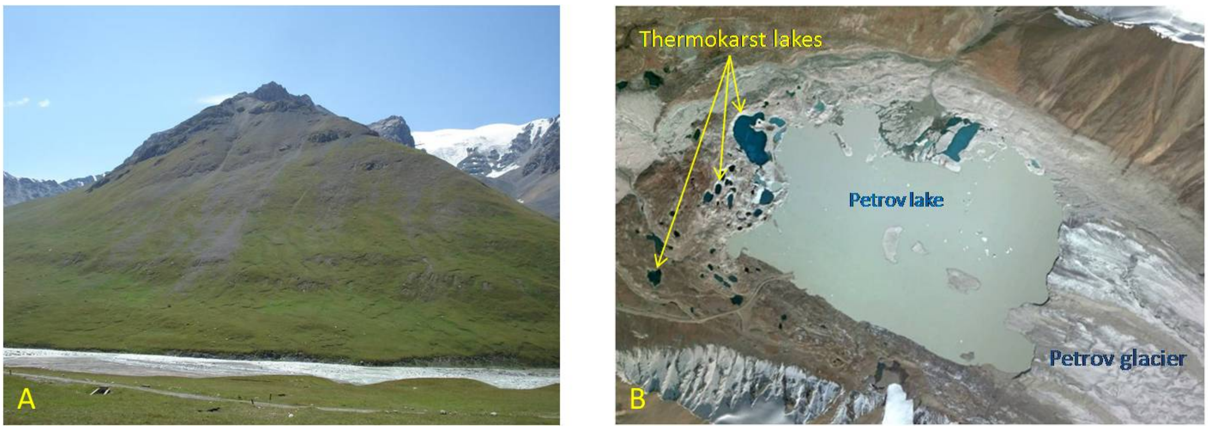


Figure 15 Solifluction lobes in the north slope of Jetimbel Mountain, and thermocarstic lakes on the Petrov lake moraine dam, north-west slope of Akshyirak Mountain. Source: (A) M. Duishonakunov, 25 July, 2010; (B) Google earth imagery; date: 10/4/2002.

Different forms of relief and phenomena that in many cases may be connected with the occurrences of permafrost (frost mounds, solifluction formations, thermokarst etc.) also indicate to a probable high-altitude position of such boundary near the isohypse of 3300 meters (Figure 15).

Table 6 Metadata of all installed temperature loggers in the Chon and Kichi Naryn catchments. Vegetation cover: VC1 = dense grass cover, VC2 = sparse grass cover, VC3 = total absence of grass cover.

Logger ID	Altitude (m a.s.l.)	Slope (^{0})	Aspect	Vegetation cover	Mean annual ground surface and ground temperature, ^{0}C; depth from surface (01.09.2010—31.08.2013)					
					0 cm	10 cm	31 cm	52 cm	82 cm	132 cm
A10202	3007	15	S	VC1		4.38	4.30	4.40	4.26	4.45
A10207	3070	8	S	VC2		3.01	2.96	3.02	3.10	3.00
A10249	3334	25	N	VC2		-1.04	-1.32	-1.34	-1.36	-1.72
A10201	3370	23	SW	VC1		2.52	2.54	2.31	2.15	2.50
A10205	3410	7	S	VC1		2.26	1.98	2.13	2.08	2.26
A10221	3495	7	SW	VC2		0.08	-0.22	-0.24	-0.21	-0.31
A10208	3513	11	S	VC2		-0.32	-0.30	-0.54	-0.56	-0.60
A10206	3645	12	N	VC1		0.29	0.43	0.33	0.15	0.06
A50200	3645	12	N	VC1	-1.44					
A10247	3650	4	W	VC2		-1.10	-1.28	-1.48	-1.63	-1.85
A1023C	3727	8	W	VC1		-1.86	-1.87	-2.31	-2.02	-1.98
A1022C	3756	9	N	VC2		-1.34	-1.06	-1.38	-1.22	-1.24
A10238	3781	18	SE	VC1		-0.11	-0.12	-0.11	0.06	0.23
A50220	3781	18	SE	VC1	-0.36					
A10222	3865	14	SE	VC3		-1.67	-1.62	-1.80	-1.88	-1.90
A50205	3875	5	S	VC3	-2.80					
A50209	4043	6	W	VC3	-4.27					

Source: Own

Thus, permafrost in the Naryn basin is wide-spread mainly above an altitude of 3300 meters. Above 3600 m the continuous permafrost zone starts. Isolated permafrost islands and their “tongues” at the foot of steep slopes with northern exposure (protalus remparts) exist as low as 2700 m, and maybe even below.

High mountain permafrost and periglacial landforms may contain large quantities of fresh water in the form of ice. Especially glacier moraines and rock glaciers (Annex A-03) have high ice content. Rock glaciers are ice-rich periglacial landforms, ice can occupy up to 80% of the volume (Annex A-04). A more suitable descriptive definition of a rock glacier (Washburn, 1979) is “a tongue-like or lobate body, usually of angular boulders, that resembles a small glacier, generally occurs in high mountainous terrain and usually has ridges, furrows, and sometimes lobes on its surface, and has a steep front at the angle of repose.” Most of the active and inactive rock glaciers are located in the south-west slopes of the Akshyirak mountain massif, in the west part of the Jetimbel and in the Borkoldoy mountain ranges.

Our data in the Kumtor catchment during 2001-2011 show that the ten years average annual ground temperatures were between -0.2 °C (at the depth of 5 cm) and -1.3 °C (at the depth of 300 cm) warmer than the mean annual air temperature (-5.73 °C; MAAT). Annual average temperatures during the last ten years at the depth of 100, 150 and 300 cm never were above 0 °C (Figure 16). Other measurements in 18 locations during August 2010 and August 2013 show that the average annual ground temperatures (Figure 17) at the depth of 10 cm ranged between +4.4 °C (south slope of Uchemchek mountain, 3007 m) and -4.3 °C (north slope of Sook mountain, 4043 m).

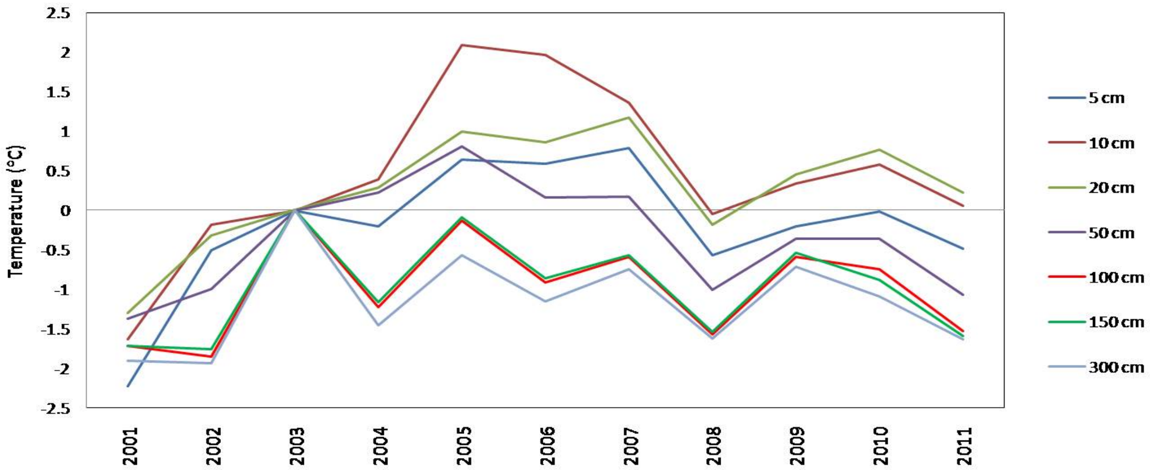


Figure 16 Average annual ground temperature variability at the depth of 5 cm, 10 cm, 20 cm, 50 cm, 100 cm, 150 cm and 300 cm, Tian Shan meteorological station, 3659 m a.s.l., 2001-2011). Source: processed from the Tian Than Meteo data.

The data in figure 16 show that average ground temperatures at similar depths are significantly below at Tian Shan Station. Large-amplitude temperature variations are observed at Tian Shan Station and other 17 locations.

The mean annual temperature at the permafrost table is the main thermal characteristic of permafrost. This parameter is very important for estimating the distribution and thicknesses of permafrost. Ground temperature measurements (2001-2011) in the Kumtor catchment (3659 m a.s.l.) showed that the mean annual permafrost table temperatures vary from -1.1 °C to -1.9 °C and the active layer thicknesses reached 2.0 to 3.0 m. The mean annual ground temperature (MAGT) usually decreases by about 0.5 °C to 0.6 °C per each 100 m of altitude (Gorbunov, 1986). The differences in MAGT between north and south slopes at the same altitude vary from 1.0 °C to 5.0 °C depending on factors as vegetation, snow cover etc. Our data on geothermal observations during 2001-2011 indicates that permafrost has been warming in the Kumtor catchment area (Tian Shan meteostation area, 3659 m a.s.l.) during the last 10 years. The increase in these permafrost temperatures varies at the depth of 5 cm from -2.23 °C (2001) to -0.49 °C (2011) and at the depth of 300 cm from -1.94 °C to -1.09 °C. Marchenko (2007) also notes that Permafrost is warming in the Inner Tian Shan. Permafrost temperatures increased by 0.1 °C over the period 1986 -1993, both in the valley and on the mountain slopes. The geothermal gradient in the Tian Shan changes from 0.01 °C/m at the mountain ranges up to 0.02 °C – 0.03 °C /m at the valleys (Schwarzman, 1985).

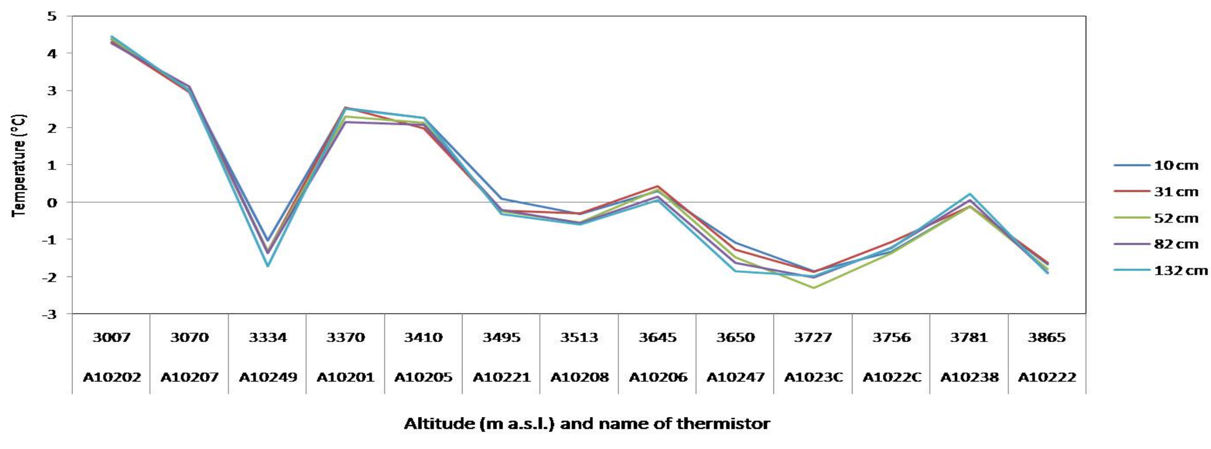


Figure 17 Mean annual ground temperature variability at the depth of 10 cm, 31 cm, 52 cm, 82 cm and 132 cm, at different altitudes between 3007 and 3865 meters (2010-2013). Source: own.

4.3 Thickness of Permafrost

Changes in permafrost thickness in different places in connection with increase of altitudes seem to be of great practical interest. Unfortunately, data on its thickness in the Inner Tian Shan are very limited. Besides, some of them are obtained by poll that is why they are not always sufficiently reliable. However, we try to summarize the knowledge.

Collected data by Gorbunov (1967) shows that the permafrost thickness at altitudes of 2800 to 3000 meters makes up several meters, but hardly exceeds 20—25 meters. For example, permafrost thickness in the area of the Kara-Keche brown coalfield on the northern slope was equal to 6-7 m. Permafrost thickness increases at altitudes of 3100 to 3200 meters. At the same Kara-Keche coal field it amounts to 29 m on the northern slope at an altitude of 3180 meters. Apparently, the thickness of permafrost on northern slopes at altitudes of 3100-3200 meters does not exceed 50-60 meters (Gorbunov, 1967).

At altitudes of 3300—3400 m the permafrost thickness is known for several points of the Inner Tian Shan. According to data of Kasymkhodzhoev, A.P. (1952), the thickness of permafrost at the bottom of Ak-Sai depression at the confluence of Terek and Ak-Sai rivers achieves 107 m.

In another area of the Inner Tian Shan, on slopes of Baidulu range the permafrost thickness at the same altitudes was significantly less. On the steep windward slope of the north-western exposure the permafrost thickness in fractured rocks appeared to be equal to 60 meters. On the downwind more snow-covered slope on the eastern exposure in the same area it decreased at the altitude of around 3400 meters to 10—15 meters (Atakanov, 1963).

Massive ground ice with dimensions typically from a few meters to tens of meters also occurs in permafrost. For example, we have found outcrops of massive ground ice in the Akshyirak area at altitudes of 3753 meters (Figure 18), confirming the extraordinary high ground ice content in the region.

Figure 18 Massive ground ice exposed in the north-west slope of Akshyirak mountain massif (3753 m a.s.l.). Source: August, 2012 by S. Imbery (on the photo M. Duishonakunov).

Thus, the maximum thickness of permafrost at an altitude of around 3000 meters can amount to 20-25 m, at 3100-3200 m to 50—60 m; at the altitude of 3300— 3400 m to 100-110 m, at 3500-3600 m to 150 to 160 m, and on the altitude of 4000 m to more than 200 m. At altitudes above 5000 meters it is likely that the permafrost zone thickness makes up several hundred meters (Gorbunov, 1967).

There are gradient values of permafrost thickness increasing alongside with the increase of altitudes. Several factors influence its thickness. Some factors contribute to the earth surface cooling, others, on the contrary, prevent it. This is complicated also by the fact that one and the same factor within different seasons of the year change its direction. Thus, a snow cover in winter prevents soil freezing, and in summer, delays its warming up. A steep slope of the southern exposure in summer receives less heat at the expense of direct solar radiation, than a horizontal site.

4.4 Active layer processes.

The active layer processes in the high-mountain zones of the Inner Tian Shan is distinguished by rather variable material composition. It depends on the lithological-geomorphological features of the area, which are also related to their altitude above sea-level.

The altitude and the general climatic conditions connected with it, define a winter frost depth. With increase of the altitude its thickness decreases under other similar conditions, and probable variety in the structure of the active horizon is decreased with it vertically, in other words, it becomes more homogenous.

The composition and structure of deposits within the active layer sharply increases below the nival zone, at altitudes of 3000 – 4000 m. Slope detritus, current and ancient moraines, proluvial, fluvioglacial, lacustrine formations, eluvium, peatlands and other current deposits, widely different by composition, are extensively spread here. The depth of seasonal thawing in mountain depends on general climatic conditions, peculiarities of lithology, relief, moistening of ground, and the nature of vegetation.

The thawing process is most demonstrative for a temperature regime of the seasonally thawing layer. In this respect the 2001-2011 observations at Tian Shan Meteorological Station (3659 m a.s.l.) and data from our 17 mini temperature loggers (Figure 13) are of the greatest interest (Annex A-05). They testify the fact that thawing of the active layer at the depth of 50 cm takes place usually in beginning of May at the depth of 150 cm in mid-June. Its maximum thawing is at the end of July or at the beginning of August. In general, over the period 2001-2011, it reached 300 cm depth (Figure 19).

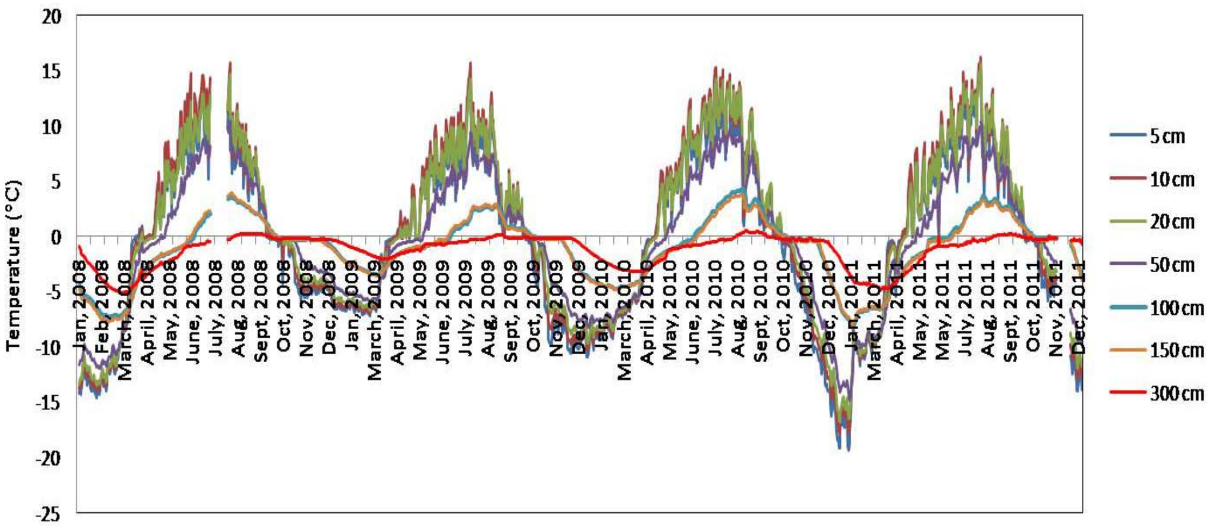


Figure 19 Ground temperature variability in the Tian Shan meteorological station, with depth 5, 10, 20, 50, 150, 300 cm (01.01.2008 - 31.12.2011). Source: processed from Tian Shan meteorological data.

At the end of summer 2010, the layer of winter frost starts to freeze simultaneously from the top and on the bottom at an altitude 3659 meters in the Arabelsuu catchment. At the end of October 2010 this process is completely finished (Figure 20). The zero curtain persisted until about 5 November 2010, the date of freeze-up of the active layer. At this time, the lower part of the active layer and upper part of the permafrost began to cool (Figure 20). Ground surface temperature during spring, 2011, remained near 0 °C from March 24 to April 21, when the active layer began to thaw. At this period the snow starts to melt. Zero curtain means the persistence of a nearly constant temperature, very close to the freezing point, during annual freezing (and occasionally during thawing) of the active layer (NSIDC Glossary, 1999); zero curtain as a zone, region, or layer in the soil (Washburn, 1973); as a freezing boundary (French, 1976); and as a length of time (Harris et al., 1988).

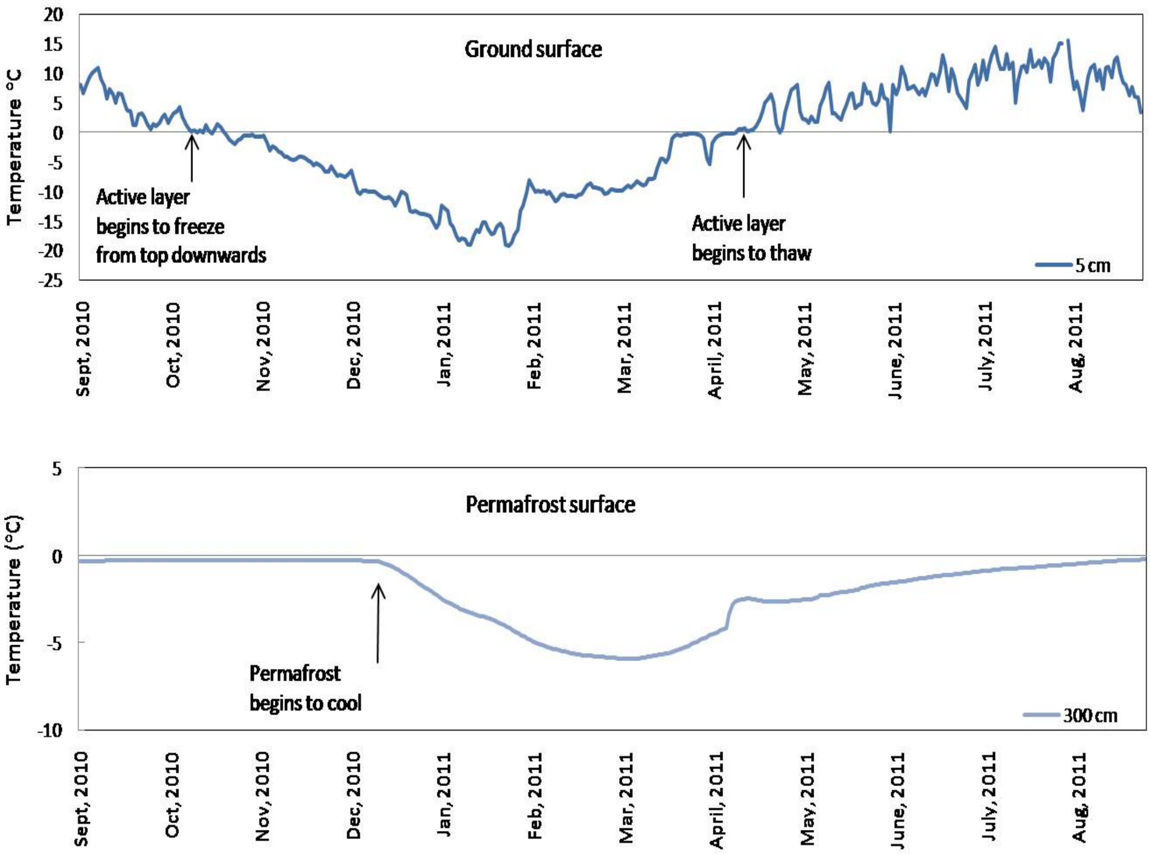


Figure 20 Time series of temperatures at the ground (5 cm) and permafrost surfaces (300 cm) for the annual cycle; Kumtor catchment, Tian Shan meteorological station (3659 m). Source: processed from Tian Shan meteorological data.

The duration of the freezing period is increased with the depth of the active layer. The number of days which daily are crossing 0 °C in Tian Shan meteostation (3659 m) at the depth of 5 cm make up 197 days, at the depth of 50 cm 219 days, at 150 cm 271 days, and at 300 cm – 365 days (average for 2001-2011; Table 7).

Table 7 Number of days with daily crossing 0°C at a depth of 5, 10, 20, 50, 100, 150 and 300 cm in the Tian Shan meteorological station (3659 m a.s.l.) from 2001 to 2011.

Depth	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
5 cm	228	201	-	208	192	202	173	206	206	199	197
10 cm	230	203	-	222	171	176	177	207	211	195	198
20 cm	233	203	-	205	196	201	178	206	189	193	198
50 cm	246	223	-	215	206	219	189	221	235	218	219
100 cm	295	275	-	279	272	274	239	269	283	270	277
150 cm	301	276	-	270	262	272	227	264	281	276	281
300 cm	365	365	-	365	365	365	339	365	365	365	365

Source: Calculated from from Tian Shan meteorological data.

Observations of the active layer depth and temperature variations (Annex A-05) at different depths within a year on a major part of territories of the investigated area were commenced only in 2010. In non-permafrost sites, the winter frost does not reach the permafrost conditions, or it is not intense enough to create new permafrost (sites No A10202, A10207, and A10201). This is the case at altitudes below 2600 meter, and at sites on slopes exposed to the south.

5 SURFACE WATER OF THE UPSTREAM NARYN CATCHMENTS

5.1 Hydrographic network of the study area.

Naryn River is the largest river in Kyrgyz Republic and abounding in water – it runs on the territory of the republic from the east to the west at a length of more than 700 km (Figure 1). On its way it takes 130 tributaries with a length of more than 10 km and around 500 less significant rivers and streams. The Naryn River catchment (58200 km^2) is one of the main water arteries in Kyrgyz Republic, it occupies 25% of the Kyrgyz territory (Mamatkonov, 2006). Our investigated area of Naryn River upper reaches (basins of Chon Naryn and Kichi Naryn rivers) includes 9580 km^2 or 18% of Naryn River basin area. The average annual discharge is 45.7 m^3/s in (1) Chon Naryn River and 40.2 m^3/s in (2) Kichi Naryn River. The maximum discharge is (1) 68.7 m^3/s and (2) 54.8 m^3/s, and minimum discharges are 32.1 m^3/s and 27.6 m^3/s accordingly. The Kyrgyz territory is divided into several hydrological zones, a mountainous part, intermountain areas and plains, and a major part of water courses. We investigated the mountain part, which is the supply of water for the downstream part.

At the edge of Petrov glacier (north-western slope of Akshyirak range), Kum-Tor River is flowing from a lake located at an altitude of 3730 meters. This glacial lake is usually regarded as the headwater of **Chon Naryn River**. In its upper reach Kum-Tor river flows on a smooth flattened surface of Kum-Tor syrts and takes several tributaries, the largest of which is Arabel, its right tributary. It is distinguished by tranquil flow and multiple meanders.

A river, created from confluence of Kum-Tor and Arabel rivers, is called Taragai. It has up to 25-30 m in width and flows in a trough ravine, dividing Jetimbel and Akshyirak ranges. Coming from the mountains, Taragai River flows in western direction on a flat surface, covered by a mantle of ancient morainic deposits. Here the river is distinguished by tranquil flow; it is often split into river arms. The bed width amounts to 40-50 m. Bayou lakes are sometimes met near Taragai River. The nature of the river is changed notably at the cross section of Kulchik ridge.

Kara-Sai, is the most significant tributary of Taragai River, it flows into Taragai within the limits of the Upper Naryn depression. Kara-Sai River in its upper reach uses a trough valley, located in the western part of Akshyirak range. Here it flows in the form of a braided river. Coming from the mountains, Kara-Sai River is mainly the uniform stream and only at the very mouth it is split into several arms. In the lower reach the river sometimes is soaked into sand and does not have overland flow.

After the confluence of Taragai and Kara-Sai, the river is called Chon Naryn and flows towards the west through a wide terraced valley. In the central part of the Upper Naryn depression there are low bogged banks, the river in this part is split into a lot of arms. In the western part of such depression, Chon Naryn River has a single bed, with 20-40 m in width. Here it merges with two large left tributaries – Eastern Karakol and Ulan, flowing from the northern slopes of Borkoldoy range.

After flowing of Ulan River, Chon Naryn River enters a heavy-going ravine. It is interesting to point out that the water of the small tributaries of Big Naryn River is exclusively transparent. Paleozoic crystalline rocks, on which they flow, are practically not eroded so there is no significant sediment transportation. Naryn River itself during its total length has very turbid water.

To the west of confluence of the right tributary Airan-Su to Chon Naryn River, the valley is gradually widened, river terraces appearand the longitudinal profile of the river becomes more flat. Chon Naryn River enters the area of Tertiary red earth's development, forming the bottom of the Naryn depression. In the eastern part of Naryn depression Chon Naryn River joins its right tributary – Kichi Naryn River. After the confluence the river is called Naryn and flows in the latitudinal direction, retaining to the left side of Naryn depression. That is why left tributaries of Naryn River, flowing from northern slopes of Naryn range, are usually shorter and have a lower water level, compared to the tributaries starting from the southern slopes of Nura range. Naryn River has a wide valley in this section with a high number of terraces. Only in the part of merging with a small left tributary (Teke-Sekrik), the valley is narrowed. There one can find Carbonic limestones in the left bank and Tertiary red earths in the right bank approaching each other closely. The width of the bed is reduced here up to 19 m, the flow rate is increased sharply.

The head water of the **Kichu Naryn River** flows westwards in a tectonic depression between the Jetimbel and Terskey ranges. In the upper reach, the river is distinguished by low water and small flow rates, its local name here is Burkhan. The width of Burkhan valley does not exceed 1-1.5 km, the width of the bed is 10-15 m, and its depth is around 1 m. The river is widened downstream up to 15-20 m and in some places it flows in the form of a braided river. After the confluence of Burkhan River with its right tributary Djylu-Su, the river is called Balgart. The latter has a well-defined valley, its width in some places amounts to 5 km. Downstream Balgart joins it's longest left tributary Archaly, which has a low water level. After that it merges with Djylanach, which has a smooth flat nature. These rivers are fed from the melting of snow fields and glaciers on the northern slope of Jetim range. Balgart in this section also merges with the significant right tributary Kara-Kaman, which has a relatively tranquil flow. After confluence of Balgart and Djylanach, the river is called Kichi Naryn and forms a powerful quick-flowing stream with 25 m in average in width. It has a narrow valley, limited by gradually approaching Jetim and Kapka-Tash ranges.

Downstream in the area of inflow of the right tributary Kashka-Su, Kichi Naryn River changes its direction sharply and flows in the southern direction.At the length of 25 km it runs in a deep heavy-going ravine, dividing Jetim and Nura ranges. Here the Kichi Naryn river is characterized by a multiply broken longitudinal profile, a quick flow rate (up to 4 m/s), and a lot of falls. Coming from the ravine, Kichi Naryn River forms a wide valley with several terraces where it soon joins Chon Naryn River.

5.2 Hydrological regime of surface water flow

The studies of hydrography and hydrology started in the 1920-s, after the establishment of the State Hydrological Institute in 1919 (SHI) and Hydro meteorological Service of Kyrgyz Republic in 1926. The main objective of these organizations is to establish an observational network of the hydrological regime and to develop national economy related with hydro-meteorological information. The network of hydro meteorological observations (meteorological stations and facilities, hydrometric stations) implied a zonalityof natural landscapes. Hydrological studies in mountainous areas of Kyrgyz Republicwere carried out in the Soviet period with a UNESCO program (International Hydrologic Decade), SHI program (water balance investigations) and Central Asian Scientific Research Hydro-Meteorological Institute programs (glaciological and snow-measuring investigations; CASRHMI, Tashkent). Glacier mass balance, temperature, precipitation, snow depth, evaporationand humidity was observed in some river basins, the water balance of the river basins was estimated, based on observation data. These hydrological studies were developed in Kyrgyz Republic mountainous hydrology (Abylgaziev B., 1975, Alamanov S., 1977, Atlas of the Kyrgyz SSR, 1987, Bolshakov M., 1956, 1974, Ilyasov A., 1969, Mamatkanov D., 1977, Mikhailova V., 1967, Petryashova E., 1966, Pozmogov V., 1972, Braun L.N. and Hagg, W., 2009, Annina S., etc. 2012).

5.2.1 Annual discharge

The upper reaches of Naryn River are fully located in the mountainous area, the part with the highest altitude (above 3000 m) serves as the natural accumulator of moisture in the form of perennial snow patches, glaciers and seasonal snow cover. Investigations of many authors are devoted to matters of studying hydrological regime and mountainous rivers stream flow generation (Bolshakov M., 1974, Ilyasov A., 1969, Surface Water Resources of the USSR, 1967, 1974, 1978, 1987, etc.). Three different runoff types are identified in the annual cycle of stream flows in Chon Naryn and Kichi Naryn rivers:

1. Snow runoff: A stream flow is generated by melt water of seasonal snow at mountains. Snow flood in the upper parts of Naryn river starts in the middle of April under air temperature increasing.

2. Glacier-snow runoff: A stream flow is generated mainly by melt-water of high mountainous snow patches and glaciers. This period is in July-August of summer, when a zero-isothermal line is raised above the altitude of 3500-4000 meters.

3. Underground water: The stream flow consists of underground water without surface water related to termination of melting processes. It is carried out owing to

underground water. Minimum discharge is observed in this period (Surface Water Resources of the USSR, 1987).

The discharge in the Chon Naryn and Kichi Naryn river basins where a large glacier area exists is supplied of melt –water from glacier and snow. Glacier melt-water occupies

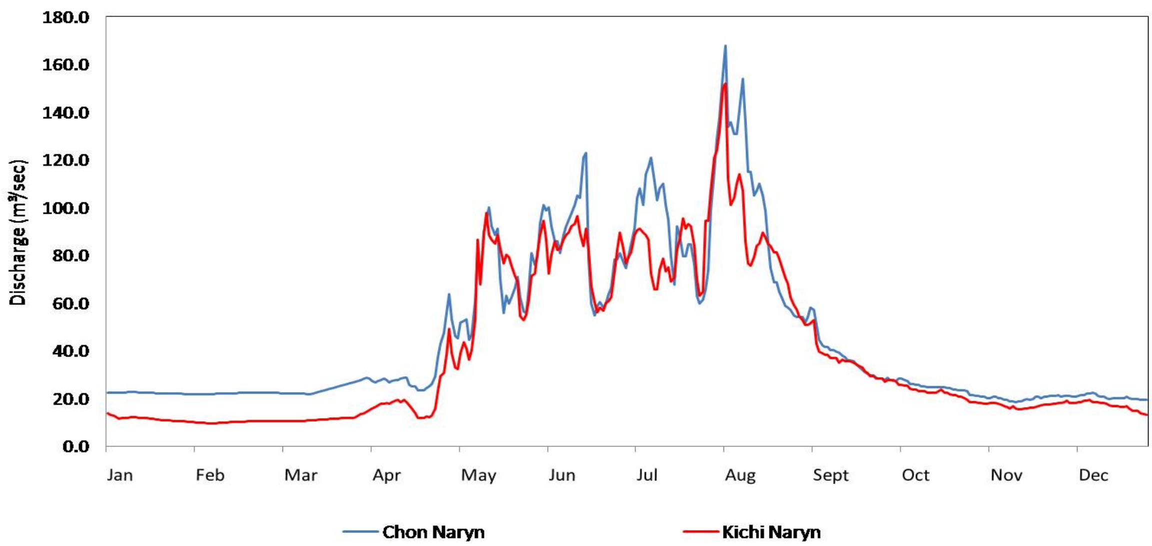


Figure 21 Runoff hydrographs of the Chon Naryn and Kichi Naryn rivers, 2010. Source: processed from Meteocenter data in Bishkek.

30.7% in Chon Naryn River, 23.9% in Kichi Naryn River (Duishonakunov, et al., 2013). The increasing discharge in these rivers is observed between May-June and ends in September-October (Figure 21). Maximum discharge is observed in July-August. Precipitation is less significant in the discharge. Underground water plays an important role in the water supply of the river after melting season. These seasonal hydrograph are attributed to Tian Shan type (Atlas of the Kirgiz SSR, 1987).

5.2.2 Seasonal runoff

Information of the seasonal discharge is necessary for water management and water consumption calculations. Many hydrologists in the USSR have worked on this matter (Andiryanova, 1960; Kuzin, 1960; Lvovich, 1981). In mountainous areas, seasonal discharge is clarified in Naryn River (Surface Water Resources of the USSR, 1967, 1974, 1978, 1987; Bolshakov, 1974). Seasonal discharge is defined by processes of accumulation and melting of snow and ice in the mountains, as well as by incidental processes of infiltration into the soil and moisture wastage for evaporation. The impact of climatic factors for the seasonal discharge is large. In the Chon Naryn and Kichi Naryn rivers, the seasonal boundary is defined as a snow flood in April-June, snow-glacial flood in July-September, and low-water period in October-March (Figure 22, Figure 23). Seasonal discharge depends on climate conditions and glacier distribution at the higher altitudes.

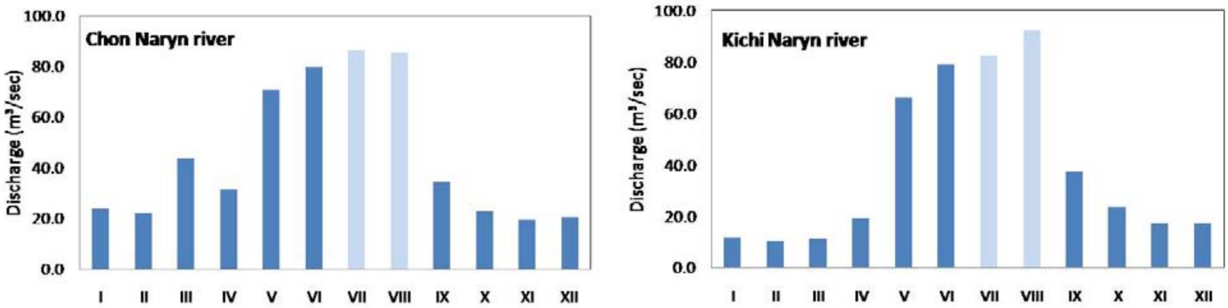


Figure 22 Annual flow distributions in the Chon Naryn and Kichi Naryn rivers, 2001-2011. Source: processed from Meteocenter data in Bishkek.

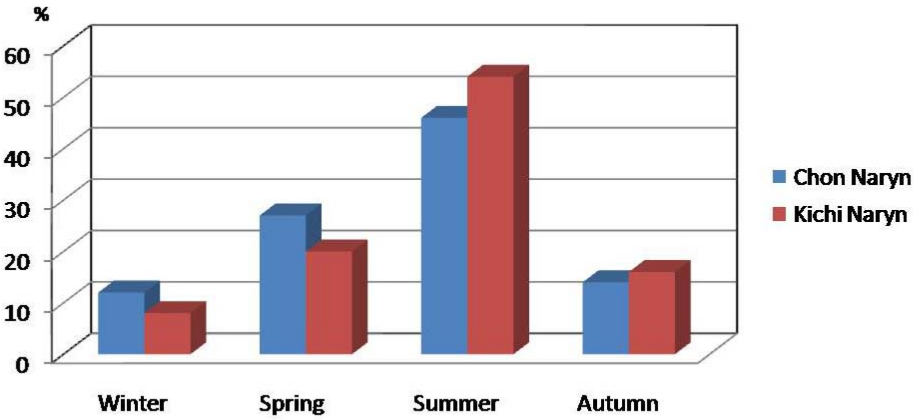


Figure 23 Distribution of seasonal flow in Chon Naryn and Kichi Naryn rivers (%). Source: processed from Meteocenter data in Bishkek.

5.2.3 Maximum discharge in spring to summer

The maximum discharge during summer achieves 50% to 95% of the annual discharge. According to classification of Zaikov (1946), all rivers in Kyrgyz Republic are classified in two groups. (1) Rivers with maximum discharge within the warm period of the year, to which Chon Naryn and Kichi Naryn rivers are attributed. In homogeneous processes of snow and glaciers melting in the catchment area is a peculiar feature for them. They maintain the increased water content within the whole warm period. (2) The discharge in spring is characteristic for the seasonal snow melting. Maximum discharge during summer was used at data integration on two hydrologic gauging stations. Information on maximum discharge in Chon Naryn and Kichi Naryn rivers are indicated in Table 8.

Table 8 Maximum fixed date and maximum average annual water discharge (m^3/sec).

River – observation station	The average height of the catchment (m)	Maximum fixed date		Maximum average annual	
		Discharge (m^3/sec)	Month, year	Discharge (m^3/sec)	Year
Chon Naryn - estuary	3700	428	06.1966	68.7	2002
Kichi Naryn - estuary	3500	407	06.1959	54.8	1942

Source: compilation from Meteocenter data in Bishkek.

Based on the analysis of hydrographs, maximum discharges were defined in Chon Naryn and Kichi Naryn rivers. The first peak is generated from snow melting in spring, second peaks are snow patches, glacier melting and liquid precipitation (Figure 21).

5.2.4 Low discharge in winter

For Naryn river basin, the cold season is a low-water period (October-March), where the underground water is accumulated in the river water. A low discharge appears in winter. In comparison with rivers during low discharge season, rivers in high mountains are stable (Figure 21 and 24). Low discharge in the Chon Naryn and Kichi Naryn rivers starts in October-November. In Chon Naryn and Kichi Naryn rivers, the fluctuations depend on the accumulation from underground water in each year (Figure 24).

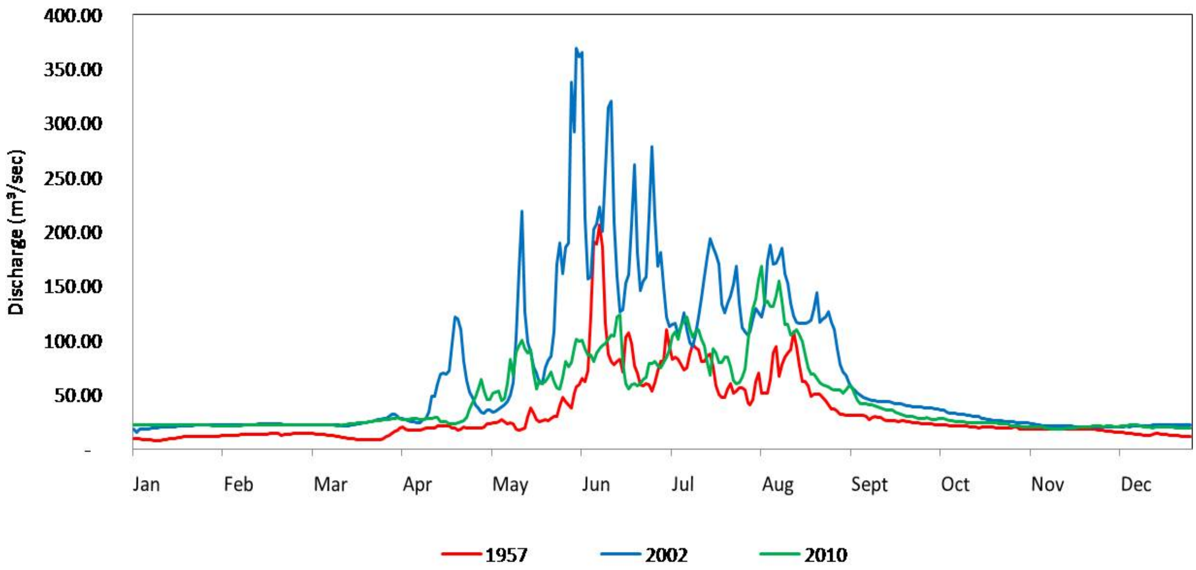


Figure 24 Hydrographs of the Chon Naryn river for maximum (2002), minimum (1957) and present flows (2010). Source: processed from Meteocenter data in Bishkek.

The analysis of river hydrographs shows that a quick drop from maximum to minimum is a characteristic in glacier and snow catchment areas. Maximum discharge occurs in glacier and snow melting season, in large glacier areas (above 3500 m). A decline of discharge starts in October, obtaining its minimum in February. Figure 25 shows discharge in winter in Chon Naryn and Kichi Naryn rivers. Snow flood starts in the second half of April due to snow melting.

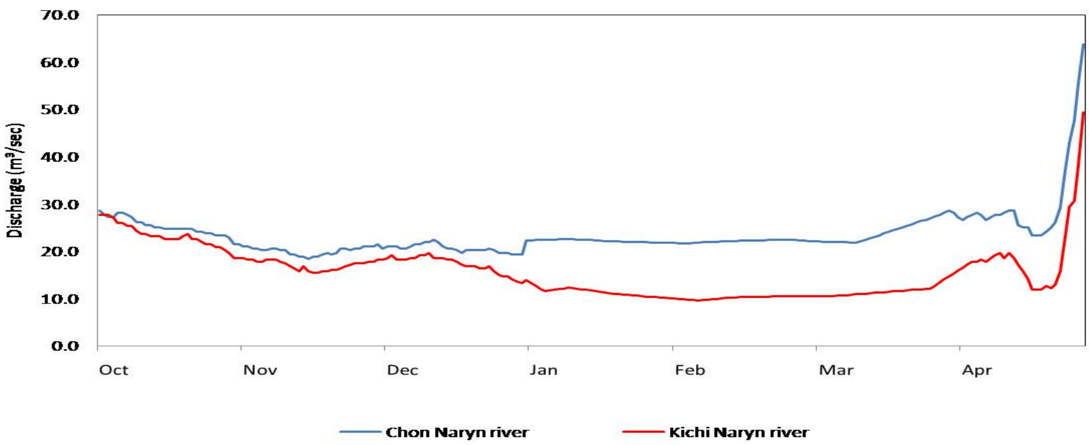


Figure 25 Average monthly discharge of water for low-water period, Chon Naryn and Kichi Naryn Rivers (2008). This year same with perennial average flow. Source: processed from Meteocenter data in Bishkek.

Minimum discharge is observed in the end of the low discharge period, when underground water reserves reach a point of the greatest depletion. This aspect is detailed in the book “Surface Water Resources of the USSR, 1987”. The methods for calculation of parameters in low discharge seasons are indicated for rivers in Kyrgyz Republic. Minimum discharge is observed in Chon Naryn and Kichi Naryn rivers in March-April. The quantity of precipitation is one of the main factors defining the value of underground water. The value of the minimum flow is not so much depending on the quantity of liquid precipitation, basically it is more regulated by evaporation from the surface. Thus, Naryn river basins minimum discharge is changed within the range of 0.96-3.25 l/s km^2. The basin of this river is located inside the mountain system. It receives annual precipitation (200-400 mm), 60% of the annual precipitation in summer.

5.2.5 Glacier runoff

The increase of summer discharge in Chon Naryn and Kichi Naryn rivers is due to glacier melting processes. The role of glaciers as a water resource is exclusively great in area with unsufficient quantity of precipitation. Runoff of melt-water from glaciers starts from the second half of June or at the beginning of July, and continues up to the end of September. This period is also the season of agriculture irrigation. Figure 23 shows the seasonal discharge in Chon Naryn and Kichi Naryn rivers. Glacier runoff makes a high contribution for water discharge in summer. In the Naryn river basin, glacier runoff supply alternates from 1.8% in the Kokomeren River to 32% in the Chon Naryn River (Mamatkanov, et al, 2006). In short, every glacier area in each basin is very different. The input of glacier water is especially significant under increased summer temperatures and little precipitation.

In previous studies, we investigated glacier runoff in Terskey mountain range (Aylampa glacier). Figure 26 shows glacier runoff in 2006-2009 in the Chon-Kyzylsuu catchment of the east Terskey mountain range. Glacier runoff was calculated using stake

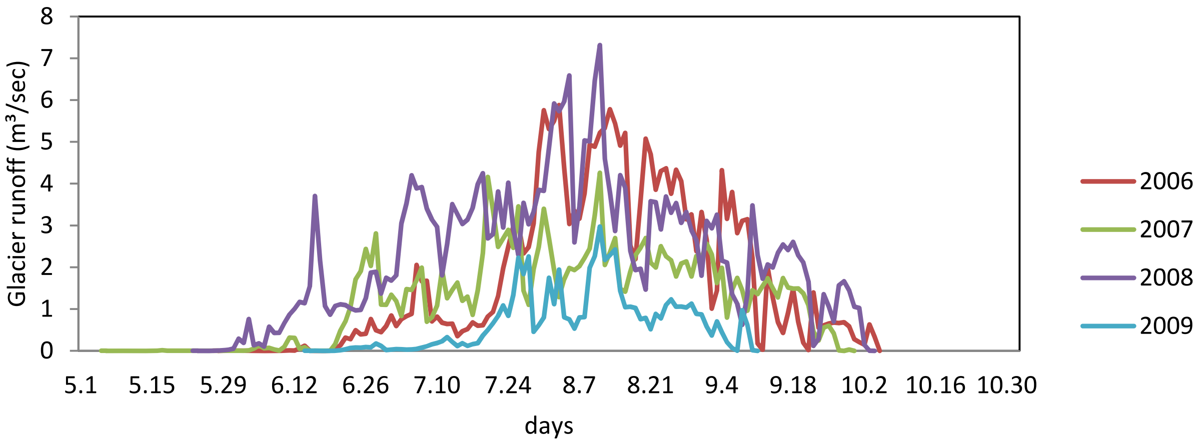


Figure 26 The estimated glacier runoff changes in the Chon Kyzylsuu catchment during 2005-2009, Terskey mountain range. Source: processed from own data.

measurements on the Aylampa glacier (Figure 27) and a heat balance model (Fujita and Ageta, 2000) with automatic meteostation data.

In this region, snowmelt occurs in April to June and glaciers actively melting from beginning of June to end of September (Figure 26). Glacier runoff in 2008 was much greater than that during the same time period in 2005, 2006, 2007, and 2009. And several glacier lakes became bigger and West Zyndan Glacier Lake (Terskey Mountain range) was outburst flood in summer 2008.

Figure 27 (A; 2010) Stake measurements and (B) the weather station in the Aylampa Glacier which was installed in 2006 within the previous project , Terskey Mountain range. Source: own.

In recent years, the contribution of glacier runoff augments from 30% to 51%. The average air temperature exceeds a standard value by 0.7-1.4 °C and the precipitation decreases by 25-40% below the standard value. The input of glacier water increases in the annual volume up to 40-60% and in summer up to 60-90%, because shortage of precipitation causes intensive melting of glaciers. The analysis of air temperature and precipitation in the high mountain shows a decrease of precipitation and increasing summer temperaturesby 0.7 °C from standard. The intensity of ice melting has caused large glacial melting. The change in glacier runoff related to glacier change is a reduction trend. A decisive role is played by the ratio of the accumulation area to the total glacier area. For example, glacier shrinkage increases in large glacier areas by rising of the Equilibrium Line Altitude (ELA). It is defined by distribution of glacier areas in elevations, where the ELA is located. Thus, glacier melting in the basin of the Naryn River at altitudes of 3100-3700 meters will result in loss of 82.1 km^2 of glacier areas. If a rising of the ELA occurs by 100 m (up to the elevation of 3800 m), the melting area will make up already 212 km^2 and will increase by 132 km^2 (Dikih, 1999). At such changes glacier runoff in general will increase in the Naryn River basin. As the result, significant reduction of glacier areas leads to decreasing of glacier runoff.

Naryn River is the most water-bearing component of Syr-Darya trans-border river. It flows through two adjoining states – Kyrgyz Republic and Uzbekistan. The glaciers of Naryn river, especially in the upper parts, are studied well, glacier changes are assessed qualitatively (Hagg et al., 2012; Duishonakunov et al., 2013) and dynamics of glaciers are investigated (Dikih, 1999). Table 9 shows glacier area from 1.0 to 10.8% in each catchment.

Table 9 Characteristics of glaciers of the Naryn catchments

River basin	Catchment area (km^2)	Glacier area (km^2)	Coefficient of glaciers	Height of the snow line (m)	Average glacier area (km^2)	Moraine cover (%)	Module of flow ($L/sec^* km^2$)
Chon Naryn	**5710**	**607.9**	**10.8**	**4245**	**0.88**	**2.3**	**8.3**
Kichi Naryn	**3870**	**344.6**	**8.9**	**4105**	**0.71**	**1.8**	**11.3**
Kokomeren	10400	104.7	1.0	3787	0.44	19.8	9.8
Atbashy	5540	113.7	2.1	4090	0.44	7.4	6.0
Alabuga	3710	126.7	3.4	4185	0.79	4.0	8.3
Naryn	58200	1369.7	2.3	4136	0.64	4.4	7.4

Source: Glacier Inventory of the USSR, 1977

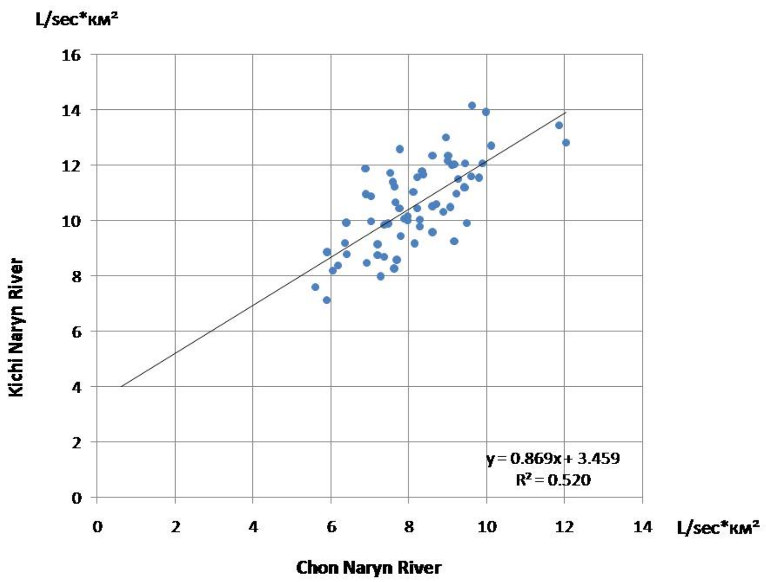


Figure 28 Communication of modules of the Chon Naryn and Kichi Naryn runoffs.
Source: processed from Meteocenter data in Bishkek.

Glacier runoff changes within a large range from 6.0 to 11.3 l/s·km^2 (Figure 28), depending on the ratio of the area in each elevation of the catchment (H_{avg}) to the elevation of the ELA (H_f). Correlation of the runoff module (M_o) and H_{avg}/H_f ratio is very close, it has a correlation coefficient equal to 0.90±0.01, and can be used in calculations for all tributaries of Naryn River. The dependence M_o= f (H_{avg}/H_f) is dynamic, glacier runoff varies at rising or decreasing in the ELA.

Dikih (1999) obtained the following dependence for the basin of Naryn River:

$$M_o=45.0\ H_{avg}/H_f - 27.4$$

Using different values for elevation of the ELA (H_f) in this dependence, runoff was calculated, corresponding to certain climatic (air temperature and precipitation) values, which the position of the ELA corresponds to.

Before calculations of the glacier runoff at varying climatic conditions, it is necessary to evaluate the current regime of temperature and moisturization of the glaciation zone. Using data of meteorological stations in the basin of Naryn River and adjacent territories, air temperature of the glacier zone was defined during the period from May to September, i.e. during the months of the melt runoff generation.

An altitudinal limit for observations of the air temperature is at the altitude of Tian Shan Meteorological Station (MS) (3614 m), temperature values above such elevation were obtained by the extrapolation method. These air temperature values can be used at calculations of the snow and ice melting layer at different altitudinal elevations according to the recommended formula (Dikikh A., 1999):

$$A=1.33(T_s+9.66)^{2.85}$$

A: a melting layer (mm), T_s: an average summer temperature at elevation, for which melting is calculated.

On obtained dependences of ice and snow melting on air temperature, based on precipitation data in zones with different elevations, as well as on the basis of ELA, the runoff volume from the glacial zone is differentiated into several types:

- From melting of seasonal snow in the ablation zone (at glacier tongue);
- From direct melting of ice;
- From melting of precipitation in the accumulation zone.

Glacier runoff of the Chon Naryn and Kichi Naryn rivers was calculated based on long-term annual average values of air temperature and precipitation (Table 10).

Table 10 Total and glacier runoff in the Naryn catchment

River – observation station	Average annual discharge (m^3/sec)	Volume (mln m^3)	Glacier runoff (mln m^3)			Share of glacier water in the total runoff (%)	Share of glacier water in summer runoff (%)
			From snow melt	From glacier melt	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
Kokomeren – Sarykamysh vill.	102.0	3217	44.5	64.9	109.4	3.4	6.0
Atbashy – Jangyztal village	33.1	1044	33.2	68.0	101.2	9.7	22.4
Alabuga – Koshtobo vill.	31.0	978	54.4	75.5	129.9	13.2	25.5
Naryn – Uchkurgan vill.	432.0	13624	378.6	665.9	1244.5	9.1	16.7

Source: M. Duishonakunov et al., 2013 (Chon Naryn and Kichi Naryn rivers), Dikih A., 1999 (other rivers).

A portion of glacier components in the total volume of flow makes up 30.7% for Chon Naryn River and 23.9% for Kichi Naryn River (Duishonakunov et al., 2013). A stable reduction of glacier areas, recorded currently, (Duishonakunov et al., 2013; Hagg et al., 2012) is stipulated by two reasons – air temperature increase and the reduction of precipitation in the high mountainous zone. According to calculations made by Dikih (1999) up to 46% of snow reserves are evaporated in the high mountainous zone during November-April from the snow surface. Naturally, that increase of temperature within winter months and the increased value of evaporation causes the balance of glacier mass to be deteriorated, and becomes steadily worse. As glaciers in this situation are released from snow much earlier, the period and intensity of melting is extended, therefore, glacier degradation rates are growing. The Chon Naryn and Kichi Naryn river basins is characterized by developed glaciation (up to 69% of the total glacier areas of Naryn basin), therefore the flows of such rivers have a significant influence on the water content of Naryn River in general.

6 CONCLUSIONS AND PERSPECTIVES: IMPACT OF CLIMATE CHANGE ON WATER AVAILABILITY, NATURAL HAZARDS AND ECONOMY IN KYRGYZ REPUBLIC

6.1 Glaciological-hydrological conclusions and economic perspectives

Kyrgyz Republic is mainly an agrarian country, and thus water is its most important natural resource. It originates from the often glacier covered mountain ranges and its abundance is a vital component for the agriculture and the production of hydro-electric power, for Kyrgyz Republic as well as some neighboring countries. The environmental and economic planning for a sustainable livelihood depends on the water availability and a sustainable water management.

As shown in the earlier chapters, the total area of glaciers of the Chon Naryn and Kichi Naryn catchments of the Naryn basin decreased significantly between about 1965 and 2010, with a total glacier retreat of 21.3%, due to increasing summer temperatures and decreasing precipitation. This glacier shrinkage varied with the regional climate and differed among glaciers of different sizes according to the altitude. 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.

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 Kyrgyz Republic and Uzbekistan and Tajikistan. 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.

After the Chon Naryn, the KichiNaryn catchment is the second major tributary of the Naryn River by amount of glacier coverage. The reductions of the glacier areas 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 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 237 MW. Construction of the Akbulun hydropower station was started in May 2013.

The confirmed 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 most important issues in this region because the majority of the water supplied from Central Asian mountains is used within the irrigation zones of the arid flat plains. This demand will increase in the future due to food and energy-security concerns in the region, and this might even lead to water wars among nation states.

Through the investment of foreign companies in mining and hydropower energy in Kyrgyz Republic, there has been steady development of industrial production, agriculture and trade for a few years. Development of priority sectors, such as tourism, mining of gold, hydro energy exchange with neighboring countries and agriculture will continue to stimulate the economy of Kyrgyz Republic.

The Kyrgyz Republic has abundant water resources. The total volume of more than 2000 km^3, the share of which is about 50 km^3 in river flows, about 15 km^3 in ground water, more than 1500 km^3 in lake water and 650 km^3 in glaciers (Mamatkanov, et. al., 2006). Kyrgyz Republic exports water to irrigate the neighboring states Uzbekistan, Kazakhstan and Tajikistan. The natural sources of drinking water allow Bishkek companies to obtain water from artesian wells and to deliver products to the market. There are several universities and also numerous international NGOs and development institutions, that are concerned with the questions of a sustainable water management (MinEco, 2011, Herrfahrdt, E. et al., 2006, Dear C., et al., 2013).

The agricultural sector remains important as a source of income for the Kyrgyz people with agriculture accounting for more than 35% of GDP. This sector employs a large part of the working population. Irrigated agriculture, which comprises more than one million hectares of

*Figure 29 Irrigation channel at Sokuluk region for cash crop, mainly corn, wheat (*09.2013).

*Figure 30 A private investor at Sokoluk has installed several large green houses for cash crop vegetables, the money comes from a bank loan (22.*09.2013).

Figure 31 The view inside the green hous shows modern irrigation systems (22.09.2013).

arable land in Kyrgyz Republic, is a major component of the rural economy (Figure 29). The main areas for agricultural production are at plant growing, gardening and livestock farming, and the main products are barley, wheat, corn, rice, haricot, sugar-beet, potatoes, cotton, tobacco, apple, apricot, pear and beef, lamb, horsemeat, milk products etc. The future of the agricultural industry in Kyrgyz Republic seems positive, as the country can deliver affordable high quality primary products. However, the use of often ineffective irrigation systems often means waste of water that might become critical when the production is increased. Foreign direct investment but also of national businessman can play an important role in the development of the agricultural industry, which are the main export products of the country. A promising approach is the installation of large green houses for the production of cash crop (Figure 30, 31). Many enterprises lack the experience of modern management, investment and financial resources to adequately compensate qualified staff - all this can bring investors. An approach for a sustainable agricultural planning and land management is given in series of publications (Shigaeva, J. et al., 2013; KAFC, 2012; NatStat, 2011; World Bank, 2004; FAO AQUASTAT, 1997).

Further, considerable sources of economic growth are expected to lie in expanded exploitation of Kyrgyz Republic's non-agricultural natural resources: hydropower, gold and coal. Large glaciers and powerful snow fields of mountain ranges give rise to many rivers, dense network covering the entire territory of the Kyrgyz Republic. Originating at high altitudes these rivers differ with steep slopes, fast-flowing and possess considerable energy capabilities. According to the calculations, the total hydropower potential of 172 surveyed rivers and streams with discharge from 0.5 to 50 m^3/sec is more than 80 billion kWh per year (Mamatkanov, et al., 2006). The Ministry of Industry, Energy and Fuel Resources of the Kyrgyz Republic conducted activities to attract investment in the construction and development of small hydropower stations. The hydropower potential is discussed by several governmental sessions, ministries, NGOs, international seminars (MoE, 2009; NEP, 2010; MinEnergo, 2011)

In Central Asia water problems are on the rise. To prevent conflicts, water allocation and use, and in particular the role of agriculture as major water user, have become very important questions in the development discourse in recent years (Abdullaev, et al., 2009, Mamatkanov, et al., 2006).

In the Central Asian high mountains, glacier hazards such as glacier lake outburst floods (GLOFs) and glacier ice avalanches often cause damages in downstream regions (Baimoldoev and Vinohodov, 2007). Large numbers of GLOF events were investigated in the northern Tian Shan (Kubrushko and Staviskiy, 1978). Recently, a big flood occurred on 7 July 1998, with an outburst from the Archa Bashy glacier lake in the Alay Range. The flood killed more than 100 persons in Shahimardan village (UNEP, 2007).

Clearly, glacier-related hazards can have catastrophic downstream consequences, including killing people and livestock, destroying infrastructure, and farmland. However, the current investigations and the existing documentation are not enough concerning other glacier hazards, ice avalanches, and their consequences for the Kyrgyz Republic. In the last years, the size of the glacier lakes has been increasing (Narama, Kääb et al, 2010). In a previous study with C. Narama, we researched the outburst of West Zyndan glacier lakein the Terskey range, Tian Shan, on 24 July 2008 (appendices A-06). The lake area was 4.22 hectares before the outburst flood, and was reduced to 0.83 hectares. The GLOF event reduced the water volume by 437,000 m^3 (Narama, Duishonakunov et al., 2010). We reported on the causes, processes, and damages of the outburst floods and included the results of many interviews with local people.

Certainly, more detailed research is required to improve the information on glacier lake outbursts. This must be done especially in the regions where up to now these events are not well documented and have occurred infrequently. Great care has to be taken, because glacier lakes can develop very fast, especially under the present conditions of rapid changes in mountain glaciers and permafrost. These events have the potential to cause extremely high economic damages.

The results of this thesis may help to bring more detailed knowledge concerning water availability for agriculture and hydropower, but also for the transboundary water management under climate change conditions. However, manifold future studies are necessary in order to give a more detailed quantitative outlook concerning the effects of glacier area changes on the water balance in Kyrgyz Republic. I will try to continue some more mass balance studies in connection with CAIAG. This is a very urgent but also difficult and time-consuming task. The gained data has then to be included in the "World Glacier Inventory" as a Kyrgyz contribution to the global perspective.

6.2 Conclusions and perspectives concerning permafrost hazards and infrastructure

Besides water as the most important natural resource, Kyrgyz Republic possesses an impressive mountain landscape with glaciers that implies a considerable potential for tourism. A third resource is gold that has been mined for years at Kumtor gold mines. However, several other findings of very promising gold occurrences exist. The development of tourism as well as of existing and new gold mines demands a safe infrastructure. Here, the existence of frozen ground may bring drawbacks in very different ways, and also pose environmental problems.

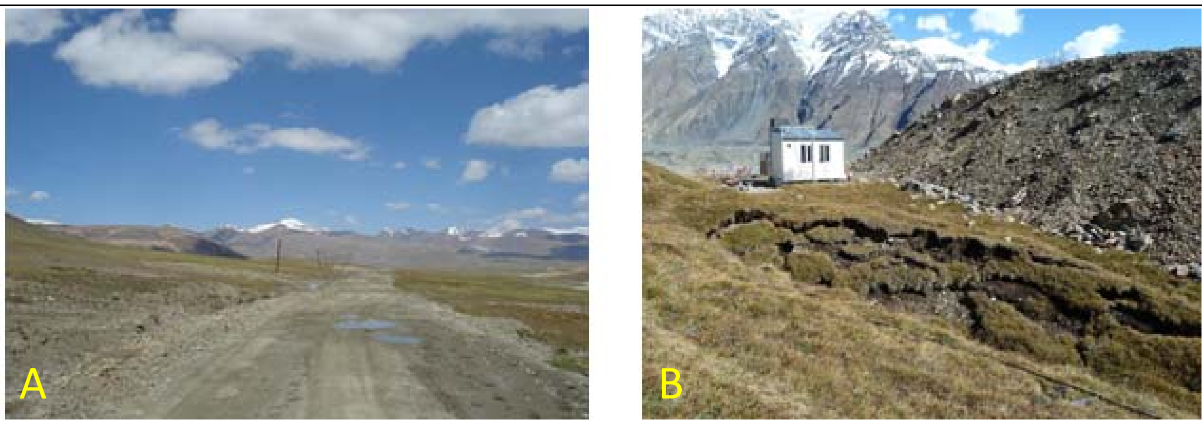
In general, permafrost of the Naryn basin slackens landscape dryness to some extent. As a matter of fact, ground ice as a water-tight stratum prevents filtration of surface and atmospheric water, and contributes to increase ground moisture. Besides, dew (condensation of water vapours from air) penetrating into the soil, and thawing in summer also contributes to the increase of moisture. Disappearance of permafrost on Tian Shan syrts would result in disappearance of bogged areas and in a significant reduction of the meadow area. From this point of view, availability of permafrost is a positive phenomenon.

Any evident direct correlation of vegetation with permafrost in the Tian Shan was not reported, with some minor exceptions. It is caused by the fact that usually a permafrost level (except for bogged areas and peatlands) occurs at the depth of more than 1.2 to 1.5 m, and a root system of vegetation penetrates only at the depth of several tens of centimeters.Permafrost has influence on mountain vegetation in two ways. On the one side, it contributes to some increase of soil moisture and, accordingly, is favourable for vegetation development. On the other hand, heaving processes and thermokarsting this extremely dry region often leads to soil salination and vegetation dieback. There is no doubt, that dependence between permafrost and vegetation cover is much more diversified, but it requires special investigations.

Permafrost influences the fauna of the Tian Shan mountain areas as well. It is recorded that marmots select warm areas for their burrows, where active permafrost is missing (or relict permafrost may exist in greater depth). This is usually in depressions with fine sediment accumulation and with snow cover in winter. Thus, ground-ice of the Tian Shan Mountains has influence on the development of many specific landscape components and their dynamics.

Studies of ground ice and cryogenic phenomena are of great practical significance. We would like to emphasize works in mountains, for which the knowledge of permafrost conditions is especially important. Most often road (Figure 32) builders have to come across areas with permafrost. They need information not only on the depth of ground ice occurrence and ice content, but also on solifluction, heaving and fracture phenomena.

Figure 32 (A) Roads and electric lines in the mountain valleys of Arabelsuu catchment. Often destroyed roads and falling electricity poles to different directions are seen.
(B) One of the buildings of the Global Change Observatory – Central Asia Station "Gottfried Merzbacher" on permafrost, Central Tian Shan with slump due to thermokarst. A lateral moraine of Inilchek glacier can be seen in the background.



Source: *(A) 20 August, 2011, M. Duishonakunov, (B) August 2011, L. King.*

Construction of buildings for different purposes (cultural centers and bases for cattle-breeders, meteorological and other scientific stations (cp. Figure 32), alpinist camps) and especially their heating systems requires most careful selection for construction. We know cases of unfortunate buildings' construction on permafrost where better locations without icy grounds could have been chosen.

In many parts of the Alps, hazardous bedrock instabilities occur more often during the past 30 years (King et al., 2013). In many cases, permafrost degradation played a central role for instability (e.g. in 1987 the Val Pola rockslide, Italy), at other events, the role of permafrost degradation is more complex or unpredictable (e.g. in 1991 the Randarockfall, Wallis, Swiss Alps). Problems encountered with the construction of touristic infrastructure in the Alps are exemplarily described by King et al. (2013).

Kyrgyz Republic wants to be a tourist state, and as our political leaders like to say this has the second highest priority. Tourists are attracted magnificent and unspoiled natural beauty of the country (Figure 33, 34, 35 and 36). The tourism sector of the Kyrgyz Republic is of big interest as a promising sector for the economy capable to develop the country. The Kyrgyz government has identified tourism as a priority sector for its development program. The potential for tourism and its development is studied especially by research groups at the University of Central Asia, Kyrgyz National University and Department of Tourism (KCBTA, 2006; Watanabe, T., 2008; Jyrgalbekov, T., 1996; Dudashvili, C., 2004).

The upper Naryn catchments are also part of the touristic locations of the Kyrgyz Republic. But before the building of touristic infrastructure, the permafrost conditions need to be investigated in the field. It could be a possibility to benefit from the experiences of the tourism industry in the Swiss Alps where tourist places are built under nearly similar conditions (mountain permafrost). Here, the infrastructure erected on permafrost consist of hotels, restaurants and mountain huts, station buildings of railways, funiculars, ski lifts and installations for artificial snowing the ski-runs. Some problems with these constructions due to permafrost degradation are shown in (King, L., 2013). At the Kleinmatterhorn mountain station at an altitude of 3820 meters, today's MAAT ranges between -6 °C and -8 °C. During the construction of a tunnel in 1981 bedrock temperatures were at -12 °C. Over the past 30 years, these bedrock temperatures have risen to about -2.5 °C, due to the heat brought into the tunnel by heating of the facilities and by the more than 490, 000 visitors per year walking through the permafrost tunnel. In an elevator shaft, the temperature even rose above freezing point close to the surface causing melt-water, and refreezing in the shaft, thus blocking the elevator movement (King, L., 2013).

The running of underground connections needs also investigations on ground temperatures. This then will allow selecting the optimal location of pipes, e.g. water pipes for artificial snowing of ski runs. Construction of communication lines and power transmission lines requires identification of dangerous areas, susceptible to solifluction, thermokarst and heaving. Many examples could be listed here.

*Figure 33 The “Kyrgyz Seaside Resort” at the northern shore of Yssyk-Kul has been well developed by Kyrgyz Gold Company in post-sovjet time. There are 850 beds, the area of the resort with parks and facilities is 65 ha. The hotel employs 235 persons. Left: Entrance to hotel complex “Kyrgyz Seaside Resort”; Right: a partial view of the recreation parks belonging to “Kyrgyz Seaside Resort” (*16.09.2013)

*Figure 34 Golden Sands Pension, the water comes from the mountain range in the background that forms the border to Kazakhstan (*17.09.2013)

*Figure 35 Hospital and health services at “Kyrgyz Seaside Resort” (*17.09.2013)

Figure 36 Karakol Ski base located at an altitude of 2300 meters at the North Slope of the Terskey mountain range. Hotel "Kapris". Source: own (16.02.2009).
The ski season starts in November and lasts until April. All this time, you don't have to worry about the snow conditions – it is cold enough and the snow covers the ground with layer, 1.5 to 2.5 meters thick.

Data on thickness and temperature of ground ice are especially important for the drilling of water wells. Sinking of wells, not taking into account their frozen ground conditions can result in large, useless financial costs. Several cases of wells freezing and failure are known in Tian Shan.

At the implementation of mining works it is also necessary to pay attention to the frozen condition of not only soft sediments but also solid rock. Frozen rocks can complicate mining works when rock blasting is required for mining. But competent utilization of such properties requires knowledge of permafrost conditions in each special case. For instance, the team of Kumtor Gold Mine Company faced several engineering design challenges including weather, permafrost and an artificial cut within a glacial moraine with ice lenses (Figure 37). Kumtor Gold Mine is an open-pit gold mining site in the Upper part of Chon Naryn catchment at an altitude of 4000 meters in permafrost. It is the second-highest gold mining operation in the world after Yanacocha gold mine in Peru. The mine started operation in 1997 and produced more than 180 000 kg of gold up to the end of 2006 (The Gazette of Central Asia, 29 June, 2012).

As mentioned, during gold mining in the Kumtor mine the team faced several engineering design challenges. These difficulties will increase due to more economic development of remote mountain areas and also the climate change condition. Therefore, the further development of gold resources is discussed in many parliament sessions of Kyrgyz Republic,

Figure 37 (A): Kumtor Gold Mine open pit, 4000 m a.s.l.; (B): removing of Davydov glacier in order to get to the gold bearing rocks ; (C): Redepositing of glacier ice.
Source: July 2011, M. Duishonakunov.

NGOs, local and scientific people etc. (Safirova, E., 2010; Bogdetsky, V., et al., 2005; Robert, E. Moran, 2011; IGC Kumtor, 2011. December 2011).

As the knowledge of permafrost existence and the involved geocryological hazards is almost totally missing in Kyrgyz Republic, the results of this thesis may also bring new ideas to a sustainable development in these fields.

Detailed mapping of frozen soft rocks and the study of their physical condition is very important for identification of probable mudflow origination sites. And this, in its turn, will allow to planning most effective measures for the protection of populated settlements against probable catastrophic phenomena. Formation of the surface and underground water in high-mountain areas cannot be understood without talking into account a hydrological role of ground ice.

Future studies are urgently needed in a new project with more detailed studies concerning the effect of topography on the distribution of permafrost and ground ice. This future project should also include the hazards involved with different warming climate scenarios. The project has to be imbedded into the activities of the CAIAG, Kyrgyz National University etc, as the assessment of natural hazards belongs also to its duties. The results have to be communicated globally within the International Permafrost Society (IPA). Kyrgyz Republic became a member of IPA during this dissertation work, and I became the national correspondent for Kyrgyz Republic thanks to my engagements within the present work.

7 SUMMARY

The Kyrgyz Republic is the only Central Asian state, where the water resources are fully generated on its own territory. The water originates from the often glacier covered mountain ranges and its abundance is a vital component for the agriculture and the production of hydro-electric power. The mountainous Kyrgyz Republic is an essential “water tower” for irrigated arable farming on arid plain territories (Figure 38). In view of the climate change discussion, this study investigates the water resources of the Naryn catchments in form of glaciers and permafrost (ground ice), and its relevance as water resource and hazard factor for the development of Central Asian semiarid regions.

Figure 38 Agriculture needs irrigation. Water is from the mountains nearby, however investments are needed for more productivity. (photo near Balikchi, north side of lake Yssyk-Kul; 24.08.2011).

Detailed studies showed a significant decrease of the total glacier area in the up-stream Naryn area by 21.3% (1965 to 2010), due to increasing summer temperatures and decreasing precipitation. The largest glacier shrinkage occurred in the Naryn range (28.9%) because of the dominance of small-scale glaciers on north-facing slopes. Continuing glacier shrinkage will result in water and energy deficiencies in the region. Strong glacier retreat can also produce glacier lake outburst floods (GLOFs), which may cause hazards in downstream areas. The state of these glaciers needs to be monitored scientifically for a sustainable use of regional water resources, and for the economic planning.

The current climate is also favorable for the development and existence of permafrost and ground ice. During the period 1930 to 2010, the mean annual air temperature was -7.6°C at an altitude of 3614 meters in the Naryn catchment. Detailed field studies proved, that permafrost is wide-spread above 3300 meters. However, permafrost islands can exist on steep northern slopes down to an altitude of 2700 meters. At altitudes of 3000 to 4000 meters, the active layer thickness is extremely variable depending of the location, exposure, slope and material. It varies from about 30 cm up to about three meters. Large cryogenic forms are connected genetically with massive ground ice. Small cryogenic forms are predetermined by seasonal freezing and can often be met outside the permafrost area.

Besides water as the most important natural resource, the Kyrgyz Republic possesses an impressive glacierized mountain landscape that implies a considerable potential for tourism (Figure 39, 40). A third national resource is gold that has been mined for years at Kumtor gold mines. However, several other findings of very promising gold occurrences exist. The development of tourism as well as of industry demands a safe infrastructure. Here, the existence of frozen ground may bring drawbacks in different ways, and also poses environmental problems.

The economic development of the high mountain areas in Kyrgyzstan needs more detailed research of the glacier development as water towers, as well as the detailed study of the permafrost conditions. The underestimation of the role of the glacier development, the ground ice conditions and the frost action can lead to significant financial losses and risks, in mining works as well as in construction activities for the infrastructure in general and especially tourism development.

Figure 39 Bishkek is the fascinating entrance gate to Kyrgyzstan, easy to reach. The city center offers many well kept recreation parcs, large hotel capacities and cultural activities (21.09.2013).

In Central Asia water problems are on the rise. The Kyrgyz Republic exports water to irrigate the neighbouring states Uzbekistan, Kazakhstan and Tajikistan. To prevent conflicts, water allocation and use, and in particular the role of agriculture as major water user, have become very important questions in the development discourse in recent years, and will continue to be in the future. The results of this thesis may help to bring more detailed knowledge concerning water availability for agriculture and hydropower, but also for trans-boundary water management under climate change.

Figure 40 Tourism in Djenish, south side of lake Yssyk-Kul. The tourist enjoy horse riding in an unspoiled nature and sleeping in yurts or in a pensionat nearby (Usubaliev, 19.08.2011).

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APPENDICES

A-01	Temperature profile (30 meters) at Borehole 48/1-B, 3630 m a.s.l., Kumtor Valley (moraine sediment)
A-02	Thermistor installation at Taragay valley (3650 m a.s.l.) in the Chon Naryn catchment.
A-03	(A) Rock glaciers at the north slopes of Uchemchek Mountain (peak is at 4339 m a.s.l.). Widespread permafrost is proven also in the Uchemchek mountain range. The blue line shows the boundary of rock glaciers. (B) Rock glaciers at the north slopes of Jetimbel Mountain ranges (peak at 3750 m a.s.l.).
A-04	Massive supersaturated ground ice of non-glacial origin in the south slope of Terskey mountain range at 3850 m a.s.l. (ice occupies up to 80% of volume).
A-05	Ground temperature variability in the study sites.
A-06	The Zyndan glacier lake had an outburst flood on 24 July 2008. (A) West Zyndan glacier lake after the lake outburst. (B) Car swept into the river. (C and D) 0.2 to 1.0 m diameter boulders deposited on the rainfed field brought by Zyndan flood.

Appendix A-01

Temperature profile (30 meters) at Borehole 48/1-B, 3630 m a.s.l., Kumtor Valley (moraine sediment)

29 November 1986		18 January 1992	
Depth (m)	Temp. (°C)	Depth (m)	Temp. (°C)
1.6	-0.7	1.6	-4.9
3.2	-1.3	3.2	-2.9
5.0	-2.0	5.0	-2.3
10.0	-3.1	10.0	-2.6
15.0	-3.1	15.0	-2.7
20.0	-2.6	20.0	-2.5
30.0	-2.3	30.0	-2.2

Source: Gorbunov, et. al. 1998

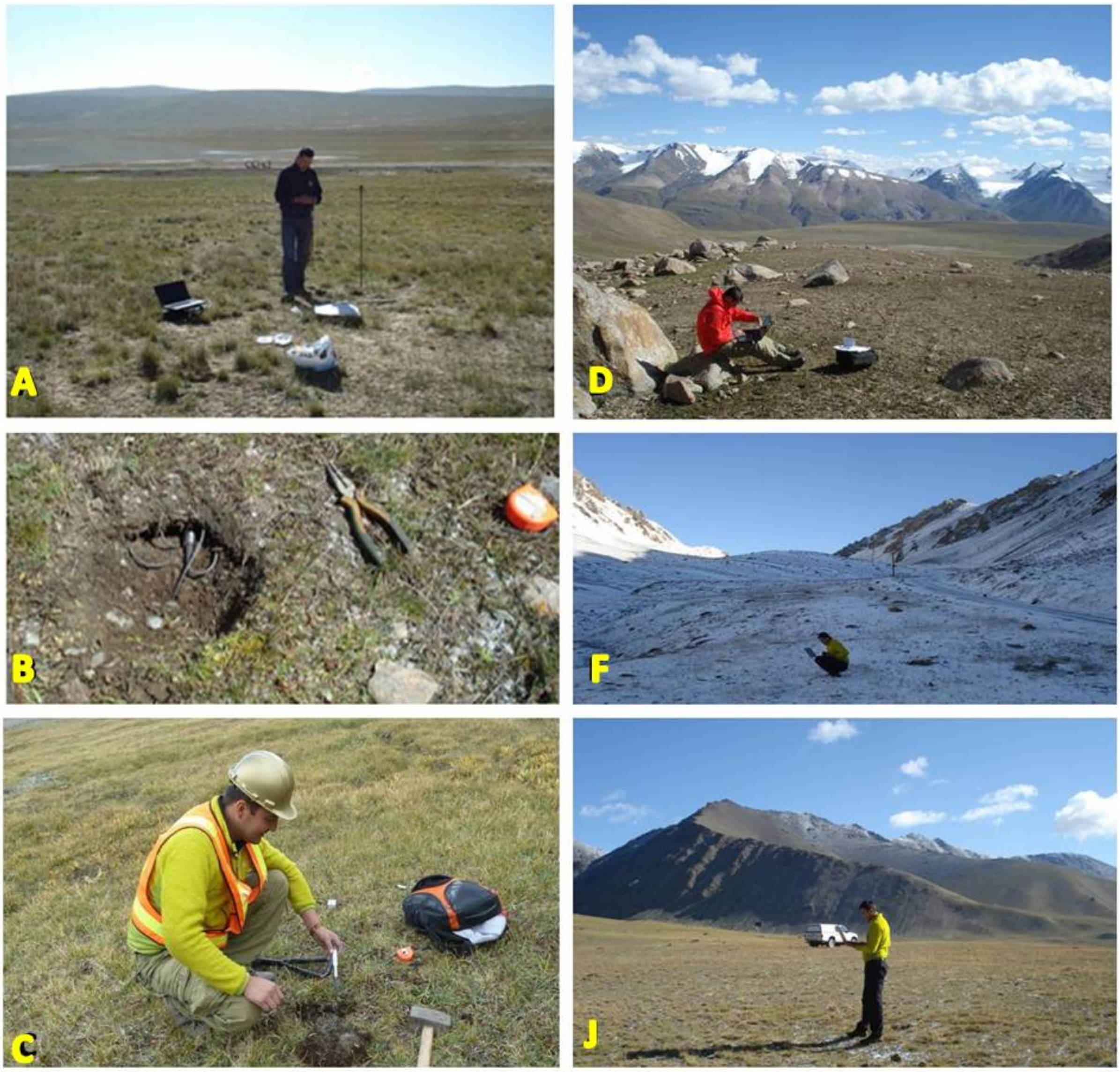
Temperature profile (30 meters) at Borehole 101, 4092 m a.s.l., Territory of the Goldmine "Kumtor" (bedrock)

14 December 1986		17 January 1992	
Depth (m)	Temp. (°C)	Depth (m)	Temp. (°C)
2.0	-1.3	2.0	-3.2
5.0	-2.0	5.0	-1.8
10.0	-2.7	10.0	-2.3
15.0	-3.1	15.0	-2.8
20.0	-3.1	20.0	-2.9
25.0	-3.1	25.0	-2.9
30.0	-3.1	30.0	-3.0

Source: Gorbunov, et. al. 1998

Appendix A-02

Thermistor installation at Taragay valley (3650 m a.s.l.) in the Chon Naryn catchment.
A, B and C show the holes for the wireless mini thermistors knocked down with a 2.5 meter steel rod and a hammer. The logger is covered with a grass sod.
D, F and J show wireless data downloading of thermistors at different study sites.



Source: own

Appendix A-03

(A) Rock glaciers at the north slopes of Uchemchek Mountain (peak is at 4339 m a.s.l.). Widespread permafrost is proven also in the Uchemchek mountain range. The blue line shows the boundary of rock glaciers.
(B) Rock glaciers at the north slopes of Jetimbel Mountain ranges (peak at 3750 m a.s.l.).

Source: own

Appendix A-04

Massive supersaturated ground ice of non-glacial origin in the south slope of

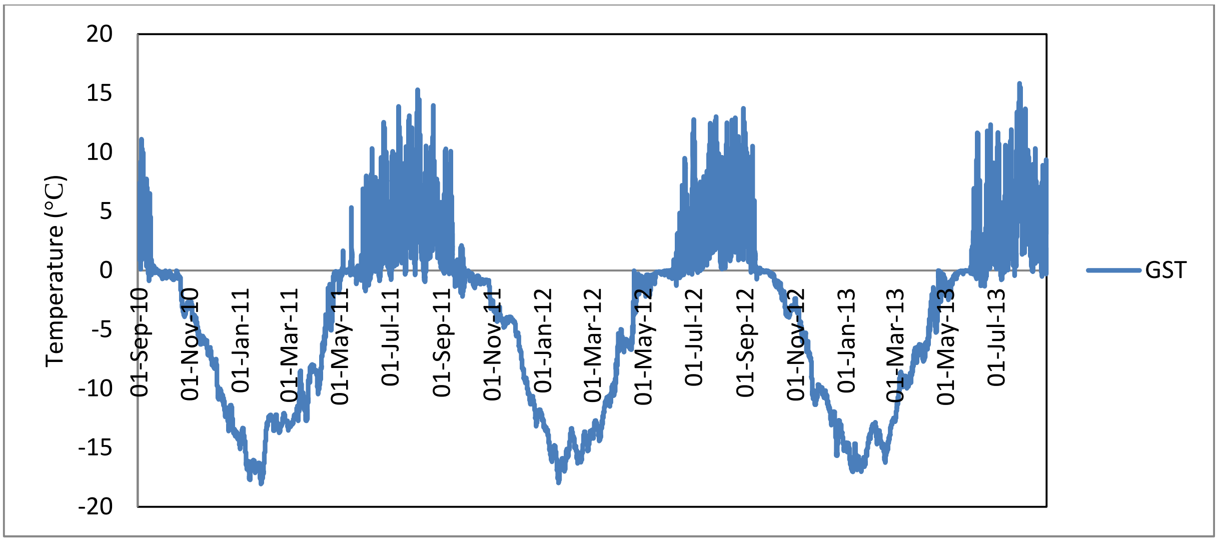
Terskey mountain range at 3850 m a.s.l. (ice occupies up to 80% of volume).

Source: own

Appendix A-05

Ground temperature variability in the study sites

Temperature Logger – A50209 at 4042 m a.s.l. (01.09.2010-31.08.2013)



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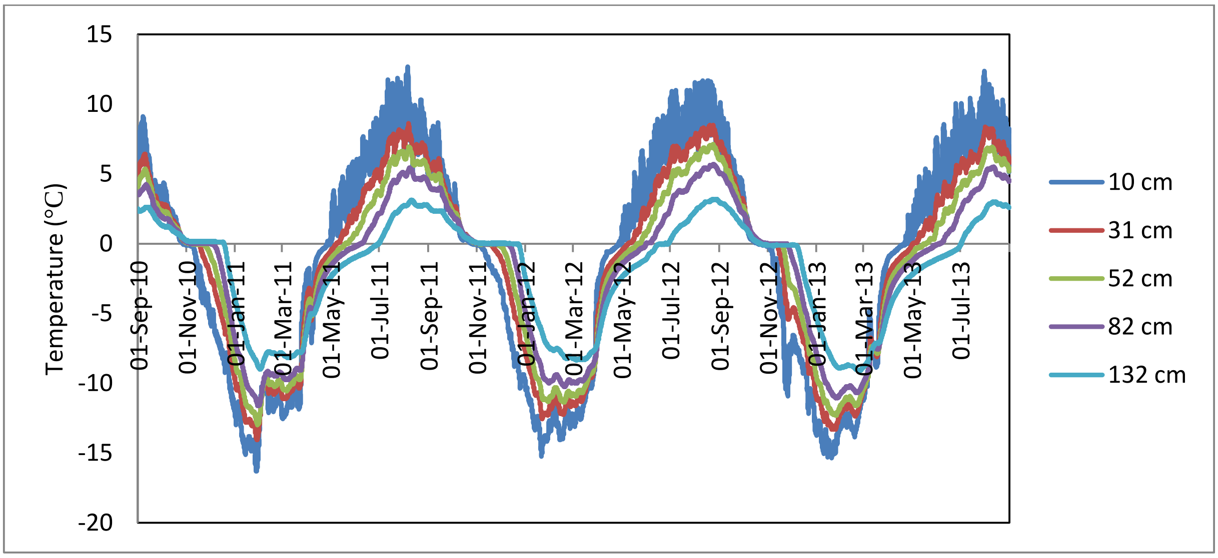
Temperature Logger – A10247 at 3650 m a.s.l. (01.09.2010 – 31.08.2013)



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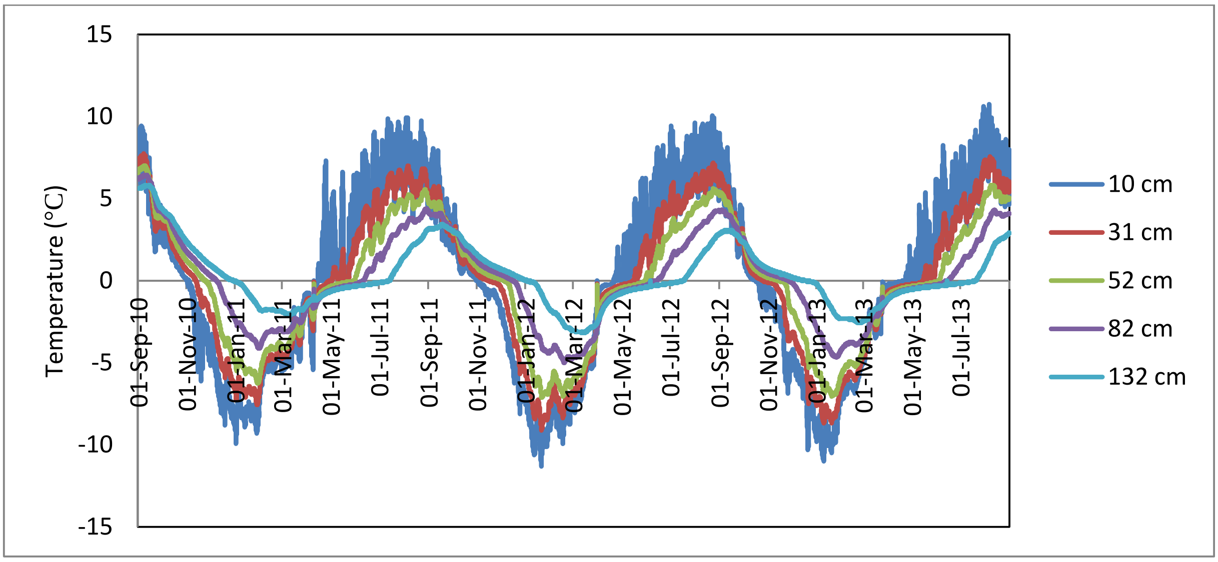
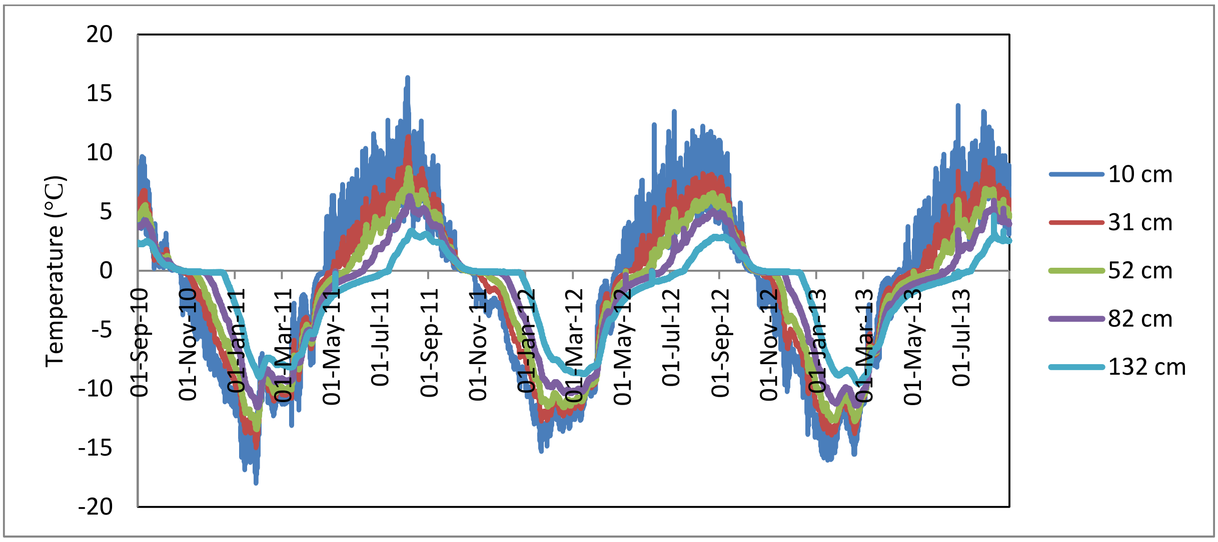
Temperature Logger – A10238 at 3781 m a.s.l. (01.09.2010 – 31.08.2013)



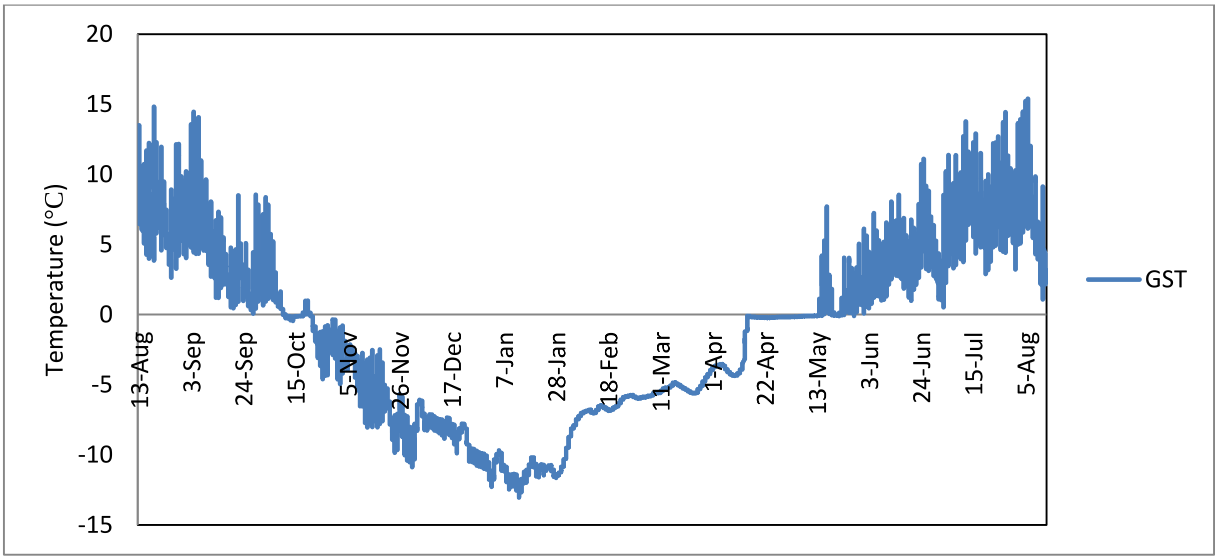
Source: own

Temperature Logger – A10222 at 3865 m a.s.l. (01.09.2010 – 31.08.2013)



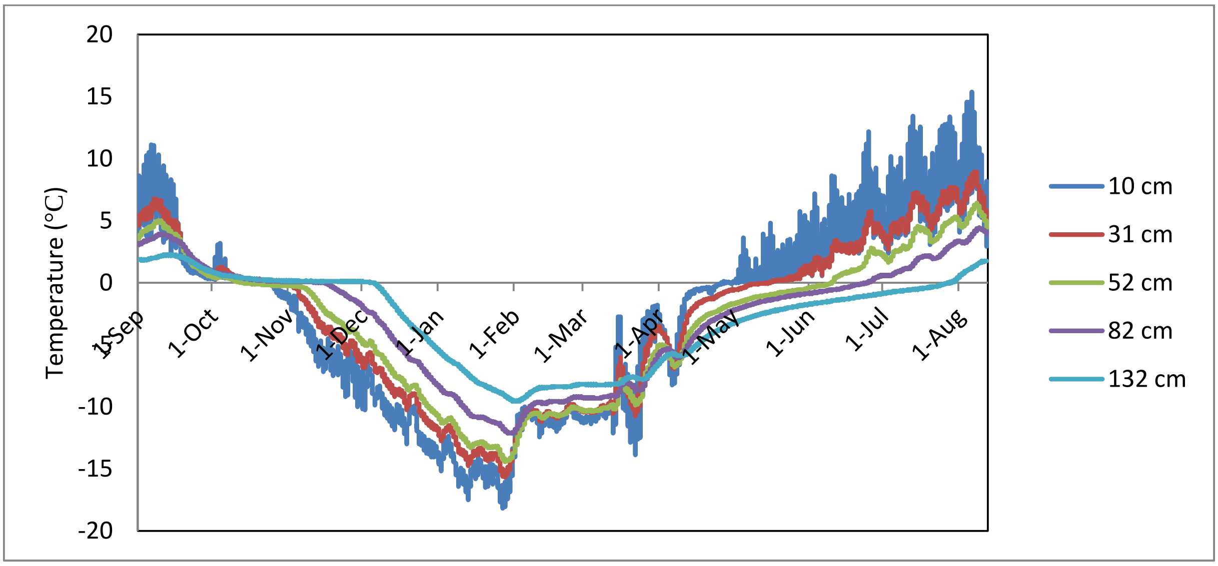
Source: own

Temperature Logger – A50200 at 3645 m a.s.l. (Average for 13.08.2010 – 13.08.2013)



Source: own

Temperature Logger – A1023C, 3727 m a.s.l. (Average for 01.09.2010 – 30.08.2013)



Source: own

Appendix A-06

The Zyndan glacier lake had an outburst flood on 24 July 2008.
(A) West Zyndan glacier lake after the lake outburst.
(B) Car swept into the river.
(C and D) 0.2 to 1.0 m diameter boulders deposited on the rainfed field brought by Zyndan flood.

Source: 27 July 2008 by M. Duishonakunov

Erklärung

Ich habe die vorgelegte Dissertation selbständig und ohne unerlaubte fremde Hilfe und nur mit den Hilfen angefertigt, die ich in der Dissertation angegeben habe. Alle Textstellen, die wörtlich oder sinngemäß aus veröffentlichten Schriften entnommen sind, und alle Angaben, die auf mündlichen Auskünften beruhen, sind als solche kenntlich gemacht. Bei den von mir durchgeführten und in der Dissertation erwähnten Untersuchungen habe ich die Grundsätze guter wissenschaftlicher Praxis, wie sie in der „Satzung der Justus-Liebig-Universität Gießen zur Sicherung guter wissenschaftlicher Praxis“ niedergelegt sind, eingehalten.

……

Ort, Datum Unterschrift