Science of the Total Environment 592 (2017) 228–242

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Glacial lake inventory and lake outburst potential in Uzbekistan

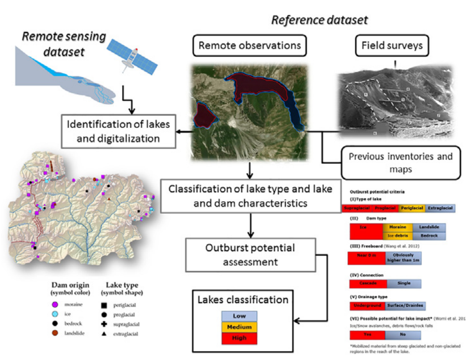
Maxim A. Petrov [a], Timur Y. Sabitov [a,b,*], Irina G. Tomashevskaya [a], Gleb E. Glazirin [a], Sergey S. Chernomorets [c], Elena A. Savernyuk [c], Olga V. Tutubalina [c], Dmitriy A. Petrakov [c], Leonid S. Sokolov [c], Mikhail D. Dokukin [d], Giorgos Mountrakis [b], Virginia Ruiz-Villanueva [e,f], Markus Stoffel [e,f,g,**]

[a] Institute of Geology and Geophysics, Glacial-geology lab, Olimlar St. 49, 100041 Tashkent, Uzbekistan
[b] State University of New York College of Environmental Science and Forestry, Baker 402, 13210 Syracuse, NY, USA
[c] Lomonosov Moscow State University, Faculty of Geography, 1 Leninskie Gory, 119991 Moscow, Russia
[d] High-Mountain Geophysical Institute, pr. Lenina, 2, 360030 Nalchik, Russia
[e] Dendrolab.ch, Institute for Geological Sciences, Baltzerstrasse 1+3, CH-3012 Berne, Switzerland
[f] Institute for Environmental Sciences, University of Geneva, 66 Bvd Carl Vogt, CH-1205 Geneva, Switzerland
[g] Department of Earth Sciences, 13 rue des Maraîchers, CH-1205 Geneva, Switzerland

HIGHLIGHTS

- A new inventory of mountain and glacial lakes in Uzbekistan is presented based on hi-res satellite imagery.
- We classify lakes according to their potential outburst hazard.
- 15% of all lakes are classified as potentially highly dangerous.
- Ongoing climate change may increase outburst flood hazard from mountain and glacial lakes in Uzbekistan.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 16 January 2017
Received in revised form 7 March 2017
Accepted 8 March 2017
Available online xxxx

Editor: D. Barcelo

Keywords:
Glacial lake outburst floods (GLOF)
Uzbekistan
Mountain lakes
Glacier shrinkage
Outburst assessment
Lakes inventory

ABSTRACT

Climate change has been shown to increase the number of mountain lakes across various mountain ranges in the World. In Central Asia, and in particular on the territory of Uzbekistan, a detailed assessment of glacier lakes and their evolution over time is, however lacking. For this reason we created the first detailed inventory of mountain lakes of Uzbekistan based on recent (2002–2014) satellite observations using WorldView-2, SPOT5, and IKONOS imagery with a spatial resolution from 2 to 10 m. This record was complemented with data from field studies of the last 50 years. The previous data were mostly in the form of inventories of lakes, available in Soviet archives, and primarily included localized in-situ data. The inventory of mountain lakes presented here, by contrast, includes an overview of all lakes of the territory of Uzbekistan. Lakes were considered if they were located at altitudes above 1500 m and if lakes had an area exceeding 100 m^2. As in other mountain regions of the World, the ongoing increase of air temperatures has led to an increase in lake number and area. Moreover, the frequency and overall number of lake outburst events have been on the rise as well. Therefore, we also present the first outburst assessment with an updated version of well-known approaches considering local climate features and event histories. As a result, out of the 242 lakes identified on the territory of Uzbekistan, 15% are considered prone to

* Correspondence to: T.Y. Sabitov, State University of New York College of Environmental Science and Forestry, Baker 321, 13210 Syracuse, NY, USA.
** Correspondence to: M. Stoffel, Institute for Environmental Sciences, University of Geneva, 66 Bvd Carl Vogt, CH-1205 Geneva, Switzerland.
E-mail addresses: sabitov.ty@gmail.com (T.Y. Sabitov), markus.stoffel@unige.ch (M. Stoffel).

http://dx.doi.org/10.1016/j.scitotenv.2017.03.068

Debris flow
Remote sensing
GIS

outburst, 10% of these lakes have been assigned low outburst potential and the remainder of the lakes have an average level of outburst potential. We conclude that the distribution of lakes by elevation shows a significant influence on lake area and hazard potential. No significant differences, by contrast, exist between the distribution of lake area, outburst potential, and lake location with respect to glaciers by regions.

1. Introduction

Global warming is impacting cryospheric processes and accelerates glacier shrinkage around the world and in Central Asia in particular (Narama et al., 2006, 2010; Kutuzov and Shahgedanova, 2009; Bolch et al., 2012; Sorg et al., 2012, 2015; Petrakov et al., 2016). The shrinkage and wasting of glaciers in the region locally leads to the disintegration of large glaciers into smaller segments (Aizen et al., 2006), an increase of seasonal variation in river discharge (Hannah et al., 2005; Sorg et al., 2014) and related impacts on water resources, an increase in the number of mountain lakes (Narama et al., 2009), and consequently an increase of glacier-related hazards such as glacial lake outburst floods (GLOFs; Stoffel et al., 2016; Zaginaev et al., 2016). On the territory of Central Asia, GLOF processes have been reported to occur in the regions of Northern Tien Shan, Hissar-Alay, and Pamir. The most detailed studies of the mountain environment of Central Asia started in the beginning of the 20th century (Merzbacher, 1905; Korjenevskiy, 1922) and continued in the context of the State Cadaster of Hydrology during the Soviet Union period (Nikitin and Gorelkin, 1977). After World War II, when records and studies of mountain environment resumed, a considerable number of GLOFs were reported in Northern Tien Shan (Kubrushko and Shatrabin, 1982; Kubrushko and Staviskiy, 1978). Glacier-related hazards may have severe consequences downstream (Stoffel and Huggel, 2012): GLOFs have repeatedly injured and killed people and livestock, devastated farmlands and destroyed infrastructure. To prevent the negative impacts of such catastrophic events and to define lakes with potential outburst hazards, over 300 mountain lakes were observed in the region of Central Asia in-situ between 1966 and 1975. Their morphological and morphometric characteristics were obtained, and bathymetric surveys were realized (Staviskiy and Jukov, 1968; Reyzvih et al., 1971; Nikitin and Gorelkin, 1979). As a result, some of the first inventories of mountain lakes of Central Asia were published in 1967 and updated in 1980 (Nikitin, 1987). The most noticeable, recent GLOF events occurred in 1973, 1998, and 2002 when GLOFs in Northern Tien Shan (Tuyuksu), Hissarro Alay (Shakhimardan), and the Pamirs (Shahdara) killed over one hundred people in total (UNEP, 2007). In recent years, many studies concentrated in identifying mountain lakes, creating inventories (Cook et al., 2016; Emmer et al., 2016) and defining their hazard potential (Richardson and Reynolds, 2000; Huggel et al., 2002; Wang et al., 2012; Worni et al., 2013, 2014; Allen et al., 2016; Schwanghart et al., 2016; Ruiz-Villanueva et al., 2017). The notable feature of the region is that only a very limited number of studies has been realized in Western Tien Shan and Hissar Alay (Narama et al., 2010; Semakova et al., 2015). Most of the available inventories have so far been based on automatic identification of lakes in satellite data (Huggel et al., 2002; Worni et al., 2014), where spatial resolution of images was typically >30 m, thus leading to an error exceeding 40% for lakes with an area of <2000 m^2 (Semakova et al., 2015). However, small outburst volumes or modest peak-discharge values may result in dangerous debris flows in steep gradient channels (Haeberli, 1983). Such debris flows occurred, for instance, on July 7, 1998 in the Shakhimardan river catchment, Hissar-Alay, when the outburst of a small lake formed a chain of GLOFs from Archa-Bashy glacier in Kyrgyzstan and triggered a debris flow with an initial volume of 50,000 m^3, killing over 100 people in the Shakhimardan enclave of Uzbekistan (Chernomorets, 2015). On August 7, 2002, 23 people were killed in the Shahdara river catchment, Pamir, by a glacier lake outburst flood which temporarily dammed the main river.

The creation of detailed inventories of mountain lakes and assessment of their GLOFs hazard potential are thus critical activities to ensure human and livestock safety and environmental conservation in Central Asia, including the country of Uzbekistan. Accordingly, the aim of this work is to provide an inventory of mountain lakes in Uzbekistan and to assess their outburst potential. We used very high resolution (0.5 to 2 m) satellite imagery and examined features of several mountain lakes in-situ to verify the accuracy of our results against field data.

2. Area description

The territory of the Republic of Uzbekistan is divided into two unequal parts: three-fourth or 78.8% of the country are located in plains, and the remaining 21.2% are occupied by mountains and intramontane valleys. This study included all mountain areas (above 1500 m a.s.l.) of Uzbekistan, namely the Tashkent region, the Chirchik and Akhangaran river basins in Western Tien Shan, the Surkhandarya and Kashkadarya regions with the two main rivers Surkhandarya and Kashkadarya, and the Shakhimardan exclave in the Hissar-Alay range (Fig. 1). Noteworthy, about 90% of the river flow used by Uzbekistan is coming from rivers having their source in neighboring countries (Sorg et al., 2014b). The main consumer of water is irrigated agriculture, which employs over 90% of all available water resources in the region. According to data from 1997, the share of the population in rural areas was 62%.

In the four study regions, 597 glaciers with a total area of 135.4 km^2 have been observed (Semakova et al., 2015; Table 1). According to Shults (1965), the mean fraction of ice melt in annual runoff in the region was 8–9% around the mid-20th century, but since these times runoff is concentrated to a few months with increased summer runoff. In basins with pronounced glacier cover, Shults (1965) determined the proportion of ice melt to up to 22% over the year, and to 37% during the ablation period (July–September). According to more recent data, and based on results from high mountain river basins of Northern Tien Shan, glacier melt would contribute 18–28% to annual runoff and 40–70% to summer runoff (Aizen et al., 1997).

According to a recent study in the region, the rate of glacier shrinkage shows a decrease in the intensity of melting, but at the same time, glacial runoff has remained unchanged (Glazirin, 2013).

Comparison of the glacier catalogs of 1969 and 1980 (Schetinnikov, 1976; Glazirin and Glazirina, 2012) clearly shows a decrease of glaciation in the region. The elevation of glacier termini has increased in all three regions studied here. In the Tashkent region, Pskem glacier termini increased from 3390 (in 1969) to 3730 m a.s.l.

In the alpine zone of the Tien Shan Mountains, three types of permafrost zones can generally be distinguished according to altitude; these include the sub-zones of continuous, discontinuous, and sporadic or (island) permafrost (Gorbunov, 1978). Boundaries of these sub-zones have also been shown to move upward from north to south by 140 m per 1° decrease in latitude. Gorbunov (1978) indicates that the lower boundary of permafrost is at approximately the same height as the mean annual air temperature (MAAT) isotherm of 0 °C. This reflects the formation of debris covered glaciers or rock glaciers across the region (Gorbunov et al., 2004). Moraines of the Tien Shan Mountains contain between 10 and 40% water, whereas in rock glaciers, ice can occupy up to 80% of the rock-glacier volume and thus serves as a possible source of water for the lakes. In the following, we provide a detailed description of the four study regions investigated in this manuscript.

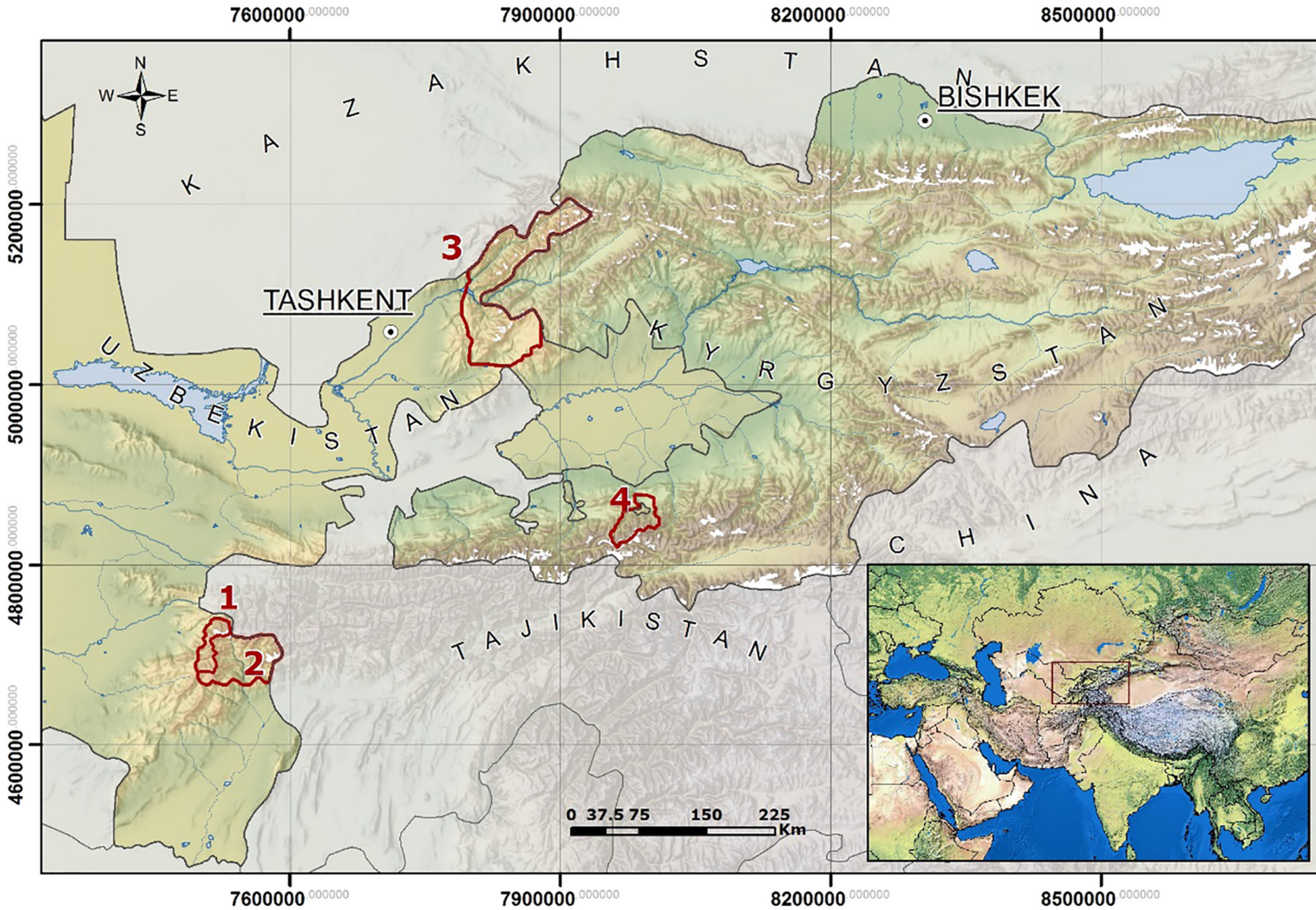


Fig. 1. Regions of Uzbekistan in which mountain lakes have been analyzed: 1 – Kashkadarya, 2 – Surkhandarya, 3 – Tashkent, 4 – Shakhimardan.

2.1. Kashkadarya region

The Kashkadarya region is located in southern Uzbekistan and home of the Kashkadarya river basin. The region extends for 300 km from west to east and 200 km from north to south, with a total area of 12,300 km^2. Mountain ranges in the Kashkadarya region are composed of Paleozoic limestones, granites, schists, and marbles. The Hissar ridge is the highest range in the Kashakadarya region and was formed during the Hercynian folding. The highest peaks are Hazrat Sultan and Chakchar with a height of 4643 m (Table 2). The zone also hosts the largest glaciers of Uzbekistan: Severtsova (length 2.3 km) and Batyrbai (2.2 km). Climate in the Kashkadarya area is continental and subtropical (i.e. summers are hot, dry and long, whereas winters are cold). Temperature minima occur in January and drop down to −29°. In summer, temperatures commonly exceed 41–42 °C and maxima can reach 48 °C. The upper portions of the catchment receive the largest amount of precipitation during spring when 45–50% of total annual precipitation is recorded. Roughly 37–40% of annual amount precipitation is recorded in winter, and about 10–15% are recorded in fall. The summer months only receives up to 2–3% of annual precipitation.

2.2. Surkhandarya region

The Surkhandarya region is located in southern Uzbekistan and comprises the Surkhan and Sherabad valleys. The surrounding mountains also form the border with Tajikistan in the North and East. In the northwestern district of Kashkadarya, the range reaches into Turkmenistan in the West and Afghanistan in the South. As the Surkhandarya region is literally surrounded by high mountains, the cold air masses from the north and north-east do not reach the study region. The largest river in the region has the name of the region – Surkhandarya – and is 196 km long; it has formed the main valley which is 5–6 km in width. Mean annual runoff is 52.2 $m^3 s^{-1}$. The mountains of the Surkhandarya region are part of the Hercynian chain and are composed mainly of limestones, shales, conglomerates, sandstones, and partly igneous rocks. Climate in the Surkhandarya region is dry and subtropical. In the plains, summer is very hot, dry and sunny Winters in the region are generally warm and short, colder in the mountains.

Average temperatures in summer are +28.4 °C in Denov and 32.1 °C in Sherabad, whereas at Termez (991 m.a.s.l), summer temperatures can exceed +50 °C. Average January temperature is +2 °C in the

Table 1
Basin area and glaciation changes for the study basins.

Glacier data	Surkhandarya	Shakhimardan	Tashkent	Kashkadarya
Glaciation, number/area 1960s [km^2] (Schetinnikov, 1976)	158/52.1	N/G	251/121.2	58/20.3
Glaciation, number/area 1980s [km^2] (Glazirin and Glazirina, 2012)	65/15.5	N/G	260/106.1	65/15.5
Change in glacier area between 1960s–2010s, % (Semakova et al., 2015)	−40	N/G	−23	−49
Glaciation, number/area 2015[km^2] (Semakova et al., 2015)	202/31.5	N/G	309/93.5	76/10.2

Table 2
Summary of the study sites.

Characteristics	Surkhandarya	Shakhimardan	Tashkent	Kashkadarya
Basin area [km^2]	20,100	90	15,300	28,400
Highest points [m a.s.l.]	4688	NG	4300	4688
Average precipitation, plain/mountain zone [mm/year]	Ng/900	200/NG	400/900	NG
Air temperature during the summer/winter for mountain zone, [C°] (Gulyamov and Vaxobov, 2013).	+50/−29	46/−3	20/−30	48/−29
Population (in thousands)/census date	≈2000/2005	≈6/1998	≈4500/NG	≈2000/2007

valleys, whereas in the mountain regions and at elevations of 2500–3000 m, −6 °C have been measured. Spring starts early, and the days get hot soon, autumn is usually warm and dry. Precipitation in Surkhandarya area falls unevenly. On mountain slopes, precipitation reaches 500–650 mm at best. On the southern slopes of Hissar, about 800–900 mm of precipitation can be expected per year. Winter precipitation dominates (46–48%) together with spring (43–44%); during autumns, only 8–10% are usually recorded, and summers are very dry with only 1–2% of annual precipitation. While some winters are snowless in the plains, and snow melts quickly once it is on the ground, in the mountains, and at altitudes above 1900–2000 m, snow falls abundantly and does not melt for several months, allowing the formation of small glaciers on the southern slopes of the Hissar ridge. According to Semakova et al. (2015), total glacier area in the region was 31.5 km^2 in 2015.

2.3. Tashkent region

The mountains around the capital of Uzbekistan can be divided into two parts, namely the north-eastern part of the Chirchik river basin and the Angren region in the south-eastern part of the Akhangaran river basin. The region includes the basins of Pskem, Chatkal, Oygaing, Ko'ksuv, Angren rivers. The region is located in the north-eastern part of the country between the Syr Darya rivers and the spurs of Western Tien Shan. From North-East to South-West, the Chirchik-Akhangaran district stretches for 280 km and covers 180 km from East to West.

The relief of the Chirchik and Akhangaran districts are rather complex. From North-East to South-West, in the direction of the Syr Darya, the relief gradually decreases. The highest elevations are located to the North-East and East while the south-western part of the zone is rather flat. The frequency of tectonic processes in the region is high. The highest point of the Chirchik-Akhangaran district is Mount Beshtor with an elevation of 4299 m (Table 2). Average temperature during summer in the mountain region is 20 °C. Minimum temperatures observed during the winter months can drop down to −30 °C. Precipitation in the plains ranges from 250 to 300 mm per year, in the foothill zone values reach 350–400 mm, in the western part of the mountains, which is exposed to cold air masses, precipitation is in the range of 800–900 mm (Gulyamov and Vaxobov, 2013). As in the other regions, the main part of annual precipitation falls in winter and spring.

The Chirchik river basin has an area of 14,900 km^2 and receives meltwaters from the Chatkal and Pskem rivers. The Chatkal river basin rises on the south-western slopes of the Talas Alatau. It flows generally West along the most western part of the Tien Shan mountain ranges between Sandalash to the North and Koksu-Chatkal to the South. The source of the Pskem region is located at the Talas Alatau glaciers in Kazakhstan and Uzbekistan.

The second largest river in the Tashkent region is the Akhangaran (7710 km^2); it originates in the Chatkal range. The entire catchment is located within the Republic of Uzbekistan. The river is a tributary of the Syr-Darya river and shows the highest discharge levels in April and May.

2.4. Shakhimardan zone

The Shakhimardan zone, in fact, is an enclave of the territory of Uzbekistan and located on the territory of Kyrgyzstan. River discharge mainly comes from glaciers located on the territory of Kyrgyzstan. Here, average temperatures for July are 22 °C, in January they range from −3° to 3 °C. >6000 persons live in this enclave (Table 2). Annual precipitation is <200 mm with a maximum in March and April, and least precipitation in summer. Winter in this zone is warmer than in the plain, snow cover does not form every winter. Summer is less hot than in the plains, but maximum temperatures can still reach 45–46 °C.

In the mountain area in this zone (above 600–1000 m a.s.l.), average annual precipitation exceeds 400 mm, and can locally be >2000 mm. Precipitation in the mountains occurs throughout the year, but peaks in April–May. Snow cover tends to persist at elevations exceeding 800–1000 m and sometimes exceeds 1.5 m. The region has received increased attention after the occurrence of a devastating debris flood in 1998 (UNEP, 2007).

3. Material and methods

3.1. Images used for analyses

Lake identification has been based on WorldView 2, IKONOS and SPOT 5 (Table 3) satellite imagery from freely available web portals including Google Earth, Bing, Yandex, Here.com, and Arc Imagery. The resolution of images varied from 0.5 m for WorldView-2 (panchromatic at Nadir) to 2.5 m for SPOT 5 imagery. Practically all images were acquired during the warmer months (June–October) and between 2010 and 2014. A majority of the images were acquired in August when snow cover was at its minimum. The original imagery was in the World Mercator projection and for accurate area estimates, we converted it to UTM projection, zone 42, on the WGS84 ellipsoid using the ArcMap software package.

Topographic data including lake heights and dam parameters were obtained from advanced datasets of combined Japanese L-band Synthetic Aperture Radars (PALSAR and PALSAR-2) on Advanced Land Observing Satellite (ALOS) and Shuttle Radar Topography Mission (SRTM). PALSAR (Phased Array Type L-band Synthetic Aperture Radar) is the L-band SAR with 10 and 100 m resolutions that are capable of detailed, all-weather, day and night observations and repeat-pass interferometry.

3.2. Image interpretation

The mountain lakes were manually identified in the high-resolution satellite imagery for all mountain regions of Uzbekistan. To identify lakes, we defined the shape, lake color, as well as the position of lakes with respect to glaciers and rock glaciers. All catchments in the mountain regions were delineated aswell. Lakes were labelled in a clockwise direction before lake contours have been digitized as ArcGIS shapefiles.

We have included all lakes identified at altitudes above 1500 m a.s.l., such that the approach covers all lakes in and next to the periglacial zone and with an area exceeding 100 m^2, which is a practical threshold for the visual search of lakes in the imagery. The approach is described in more detail below.

3.2.1. Types of lakes with regard to their position relative to the glaciers

Based on the available literature of glacier lake types, we have used the following distinction and used definitions as given below:

Table 3
Parameters of the source satellite imagery.

Name	Date (d/m/y)	Resolution (visible band/panchrom.)	Lakes quantity	Source
WorldView 2	06.07.2010 09.08.2010 11.10.2009 25.08.2013 28.08.2013 03.08.2013 05.10.2013 06.08.2013 13.06.2014 22.07.2014	1,84/0,5	231	Esri, World Map http://goto.arcgisonline.com/maps/World_Imagery
SPOT 5	12.06.2008 02.09.2008 13.09.2002	20/2.5	7	DigitalGlobe https://www.google.ru/maps/@42.2537176,71.1286938,1792m/data=!3m1!1e3?hl=ru
IKONOS	05.10.2013	3,28/0,82	4	DigitalGlobe https://www.google.ru/maps/@39.8724701,71.8021581,45292m/data=!3m1!1e3?hl=ru

Supraglacial lakes are positioned on the glacier surface and are dammed by ice (Quincey et al., 2007). Typically, they appear on stagnant flat ice due to thermokarst processes.

Proglacial lakes are situated in front and at the sides of mountain glaciers, and at the edges of nunataks. Most of the lakes in the proglacial zone are moraine-dammed (Carrivick and Tweed, 2013), however, there are ice-dammed lakes in the upper part of glaciers as well as rock-dammed lakes near nunataks.

Periglacial lakes have their name from the periglacial zone formed by past glacial activity (Łozinzki, 1909). In view of recent glacier shrinkage, we define here periglacial lakes as being at distances of up to 2 km from glacier termini, but without a direct connection to surface ice. The 2-km distance has been defined based on field observations and represents the maximum distance at which the lakes would still be situated on recent and historical moraines. Thus, the genesis of outburst events could be directly connected with glacier changes. A considerable number of the lakes are dammed by ice and debris, i.e. moraines with ice cores or rock glaciers, whereas the other types of dams also exist.

Extraglacial lakes, a term which is used in this study to define lakes at distances exceeding 2 km from present-day glacier termini. Again, the threshold used here is a region-specific distance and defined with field data. More than half of the extraglacial lakes are dammed by landslides and rock dams, however, moraine-dammed extraglacial lakes also exist due to Quaternary glaciation. Fig. 2 summarizes the lake types used in this study and how they evolve with time.

3.2.2. Type of lake dams

As a lake dam for all lakes, we defined surfaces near the lake that are positioned against the slope of the water surface and under the hydraulic pressure of the same water body. They were defined through the main features which could be interpreted in the satellite imagery and included ice dams, ice-debris dams, moraine dams, landslide dams, bedrock dams:

Ice dams are mainly structured out of glacial ice; they are a consequence of local topography, and favorable hydraulic pressure gradients (Tweed and Russell, 1999). In most settings, ice-dammed lake formation is a gradual, quasi-periodic to episodic process, linked to glacier mass balance and, ultimately, climate forcing (Clague and Evans, 2000).

Ice debris dam consists of ice and debris, or moraine material or rock glaciers. The thickness of the debris layer and glacial ice under an ice debris dam depends on the distance from the mother glacier and local geological conditions. The presence of ice dams is visible during winter

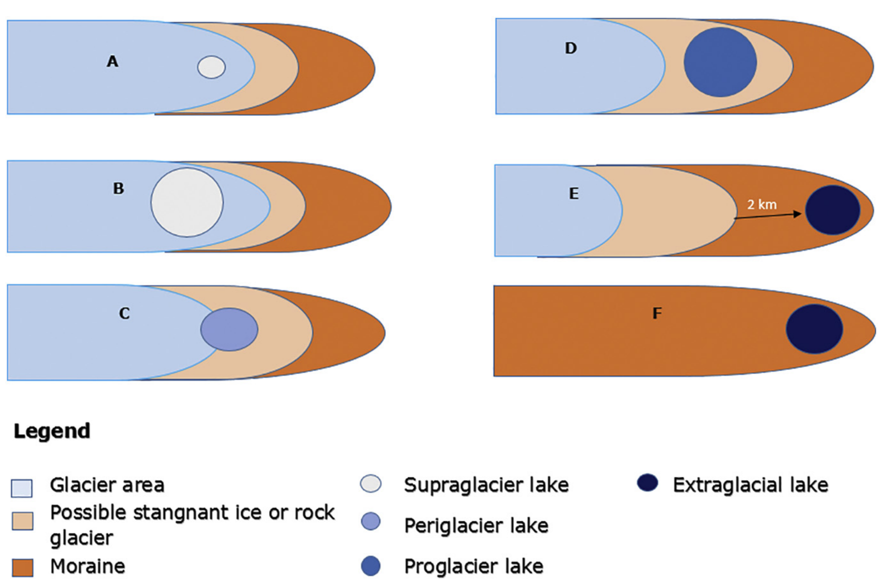


Fig. 2. Lake positions in relation to glaciers and their evolution over time, from (A) supraglacial lake situated on the surface of a glacier where the lake is dammed by glacier ice; (B) evolution of the area of the supraglacial lake; (C) modification of the supraglacial into a proglacial lake situated at the edge of the glacier and dammed by the stagnant ice; (D) After losing its connection with the glacier surface, the proglacial lake is becoming a periglacial lake; (E) With increasing distance of the periglacial lake from the active glacier, it will become (F) an extraglacier lake. In this study, the transition from € to (F) has been defined at 2 km. For details see text.

(Dokukin and Shagin, 2014).We also note transformation of terminal moraines to rock glaciers which are a common feature in Tien Shan.

Moraine dams are often remainders of previous glaciations, as debris-charged glacier snouts can become separated from rapidly ablating ice and eventually stagnate; under these circumstances, ice-free moraines serve as an effective barrier to meltwater runoff leading to proglacial lake development (Iwata et al., 2008).

Landslide dams are a product of landslides from steep slopes bordering glaciers. Landslide-dammed lakes in glacial environments are stochastic and usually associated with slope debuttressing after glacier retreat (Korup and Tweed, 2007). They form most frequently in narrow valleys bordered by steep slopes. The most common triggers are earthquakes, rainfall, and snowmelt. Repeated landslides at particular sites can form stacked dams (Chigira and Yagi, 2006).

Bedrock dams are typical in areas were the retreat of glaciers left over-deepened bedrock topography (Cook and Swift, 2012). They are considered as the most stable type of dams, but GLOF events can still occur in the case of mass-movement impact into the lake.

3.2.3. Types of connections between lakes

3.2.3.1. Closed type of drainage. This type of drainage is characterized by the nature of dam formation and the subsequent impacts on river flow. The high hydrostatic pressure of water on dam sides when inflow value from sources higher than outflow increases outburst potential. The area between the glacier and the downstream dam, becomes a source of formation of small lakes, and marshes. During intense melting, glacier discharge increases and leads to the accumulation of water in front of the dam. This process increases hydrostatic pressure on the dam walls and might cause an outburst event (Yakovlev and Batirov, 2003).

3.2.3.2. Open type of drainage. It is characterized by the fact that rivers flow without barriers. Intense flow stress erodes riverbanks and thus releases energy by increasing flow capacity, thereby decreasing outburst possibility.

We consider two possible types of configurations between lakes in this study, namely *single lakes* and *cascades* of two or more lakes (Fig. 3). The cascade position of lakes defines the outburst potential. We define hydrological connections of lakes here by using satellite imagery and DEMs.

3.2.4. Potential triggers for lake outburst

GLOF events can be triggered indirectly by rockfalls, icefalls, landslides, snow avalanches, and/or debris floods and can thus lead to dam failure and lake outburst floods (Clague and Evans, 2000; Richardson and Reynolds, 2000; Huggel et al., 2002). Steep glacier surfaces and glacier tongues can indeed be sources of such impact events. In case that source areas of potential mass-movement processes are located near the lake, they can increase the likelihood of lake outbursts. The distance of impacts for the different events was obtained from data published by Alean (1984) and Rickenmann (2005).

3.2.5. Freeboard height

The height of the freeboard is considered a crucial parameter driving or avoiding dam failure. The exact height of the freeboard is difficult to measure by remote sensing. However, with available topography, it is possible to estimate whether the height is larger than just a few meters or indeed close to zero. Therefore, relatively rough freeboard values (more than >1 or ≈0) were defined to assess lake outburst susceptibility. The value of freeboard is a decisive factor and allows further analyses of dam geometry. At the same time, it is also a restriction factor for overtopping impact waves after events. Impact waves can lead to erosion of dam, and even partial dam failure could cause destructions downstream (Carey et al., 2011).

3.2.6. Dam geometry

Dam geometry should be considered as an additional source of information which can be used for validation in case that dam freeboard is relatively high. Dam stability depends on geological factors and dam parameters. By way of example, moraine dams are more prone to collapse under high hydraulic gradients (Huggel et al., 2004; Lu et al., 1999), whereas ice dams are more sensitive to local climate and its seasonal variations (Singh et al., 2011). Stability of more solid dams will depend on erosion and regional features (Carrivick and Tweed, 2013). Crucial parameters for all dam types are the width-to-height ratio, the width of the crest and the slope of the downstream slop (Lu et al., 1999; Huggel et al., 2004). The range of these values is provided in this study to provide a first assessment of dam stability. Examples of some lake types and their parameters are presented in Fig. 3.

3.3. Assessment of lake area uncertainties and field validation

Lake area is the first and most important parameter in this study, but it is also the parameter which is most likely subject to errors in determination: the accuracy of the lake outline thereby depends on several factors, with the most important being the image's spatial resolution, as well as the visibility of the lake in the image, which is in turn defined by the snow cover and image contrast. As for the lake visibility, we ensured to take the most snow-free and highest-contrast images out of the imagery available in the different portals.

With regard to the various spatial resolution of the source satellite imagery, and in accordance with recent studies (O'Gorman, 1996; Pieczonka and Bolch, 2015; Petrakov et al., 2016), we assume that the maximum error of the area determination of lake area is in the order of half a pixel. For each lake, this error has been assessed by buffering the lake perimeter considering the area uncertainty $dS_{max} = P^{*}\varepsilon$, where dS_{max}– area error for each lake, P – perimeter of each lake *and* ε – half of the pixel dimension for each image. Therefore, the buffer width was 0.25 m for WorldView-2 imagery, 0.5 m for Ikonos, and 1.25 m for SPOT-5.

The total uncertainty in the mountain lake area assessment was then determined as the sum of all buffer areas. It amounted to 1194m^2 or 5% for SPOT5, 1000 m^2 or 0.95% for IKONOS, and 2942 m^2 or 0.5% for WorldView. The mean error for WORLDVIEW2 is 93m^2, for IKONOS 331m^2, and for SPOT5 711m^2, total uncertainty for all lakes is 0.8%.

We also assume that image geo-referencing errors in web portals had a negligible impact on lake areas, as lakes are usually situated in the flatter areas, and an absolute error of the geo-referencing should not be important in this case because each lake was always located entirely on a particular image.

However, we shall note that the mountain lakes, and in particular those located at and near glaciers, can vary substantially in area during the melting season and from year to year (Fig. 4).

Several dynamic lakes were identified at those locations for which very highly resolved, multitemporal time series of imagery was available. In this case, the maximum recorded area was used for the database.

To verify the data, we used in-situ measurements from 2004 and recent field surveys at the upper and lower Ikhnach, Shaurkul, and Ozerniy lakes, together with observations at middle Barkrak (2004, 2008, 2012, 2013, 2014, and 2015), Arashan, and Kunkermes lakes (2013, 2014, and 2015). Most of these lakes are located in the Tashkent region. Lake Kunkermes, by contrast, is located in the Kashkadarya region. The Surkhandarya and Shakhimardan regions currently have restrictions such that studies cannot be conducted in the field; validation data is therefore lacking. Details and images from these lakes are provided in the supplementary material.

During in-situ observations, lake area, volume, dam type, distance to the glacier, and outburst potential were estimated and these observations were compared with remotely sensed results.

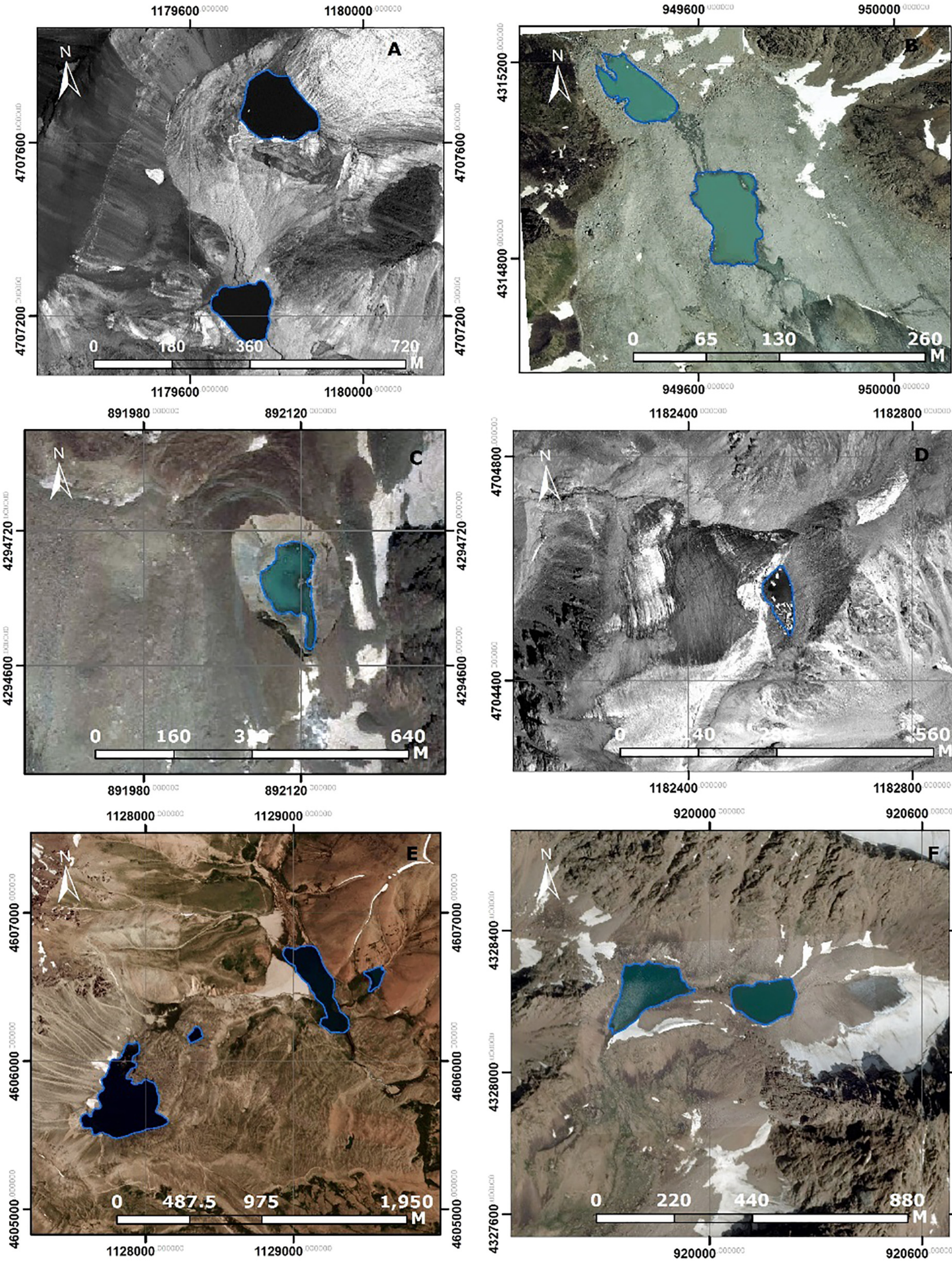


Fig. 3. Polygons define lakes boundaries:(A) Cascade of lakes in the Tashkent region, with an upper proglacial lake dammed by ice, a lower periglacial dammed by a moraine with underground drainage; (B) Cascade of lakes in the Surkhandarya region, both periglacial lakes dammed by moraines and exhibit surface drainage; (C) Single periglacial lake in the Kashkadarya region dammed by ice and debris with an underground drainage; (D) Single proglacial lake dammed by ice with surface drainage in the Tashkent region; (E) Extraglacial lakes in the Tashkent region, three of them are arranged in a chain and show surface drainage, one does not show any signs of drainage and is dammed by an ancient moraine; (F) Periglacial lakes in the Surkhandarya region, with surface drainage, and a moraine dam.

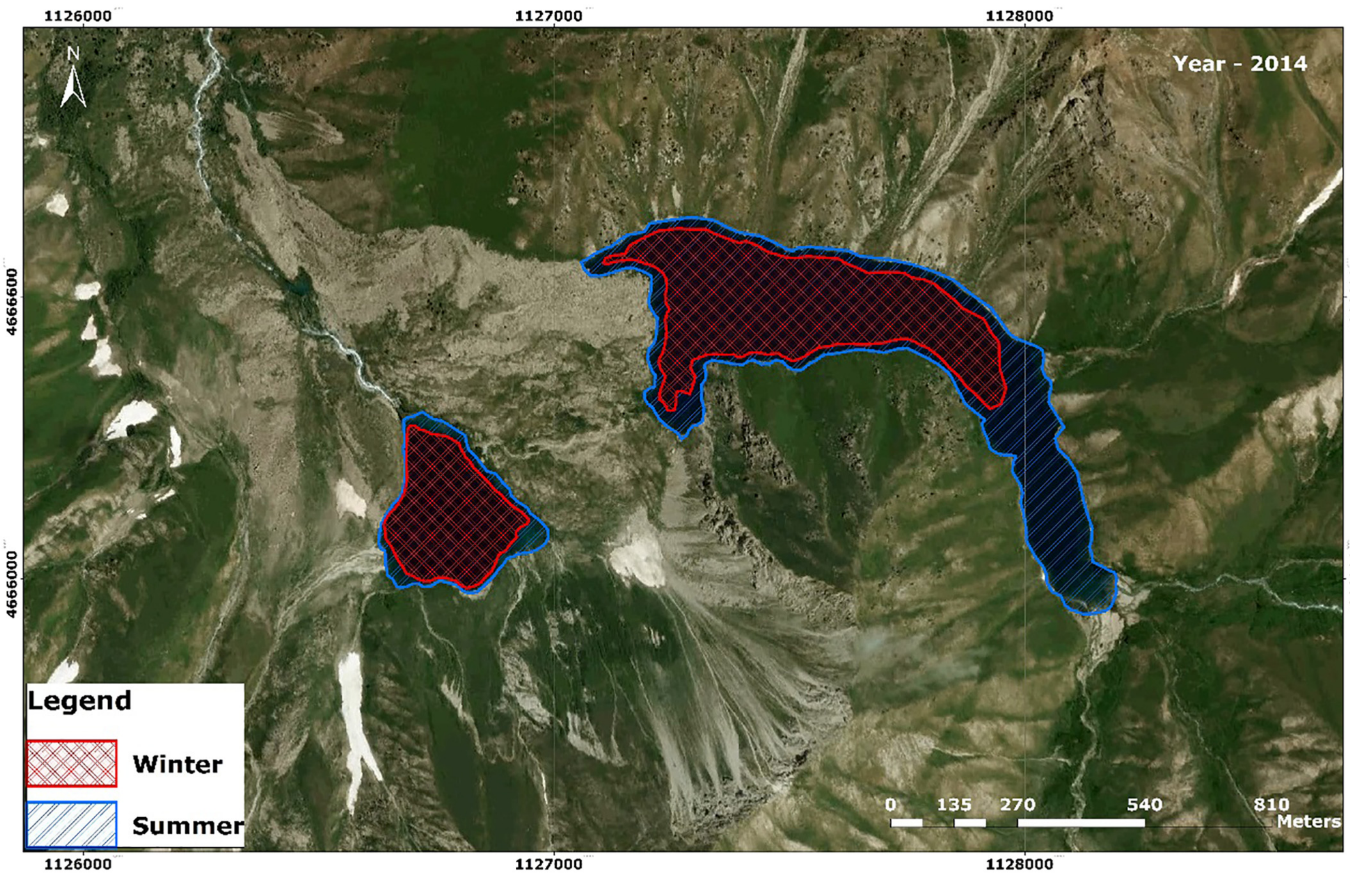


Fig. 4. Examples of the Ikhnach (h > 1500 m a.s.l.) lakes which are highly dynamic in the area between individual calendar years and within the same year (depending on the timing of image acquisition).

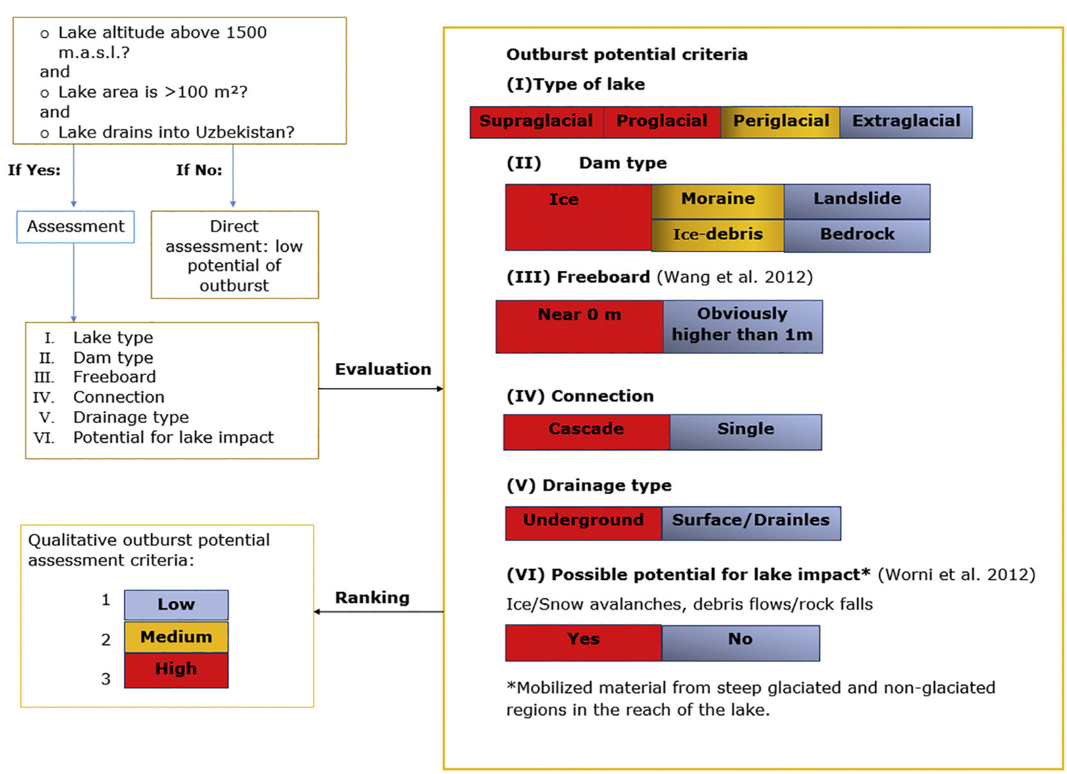


Fig. 5. Flow chart illustrating the framework used for the creation of the inventory of mountain lakes of Uzbekistan and for the classification of lake outburst potential.

3.4. Assessing outburst potential and analysis of the lake inventory

Several approaches have been combined in this study to assess the outburst potential of mountain lakes on the basis of remotely-sensed inventories (Wang et al., 2012; Worni et al., 2013; Chernomorets et al., 2015). The final, qualitative assessment of each lake was based on selected key parameters which have been considered the most relevant for the Central Asian context. The resulting decision tool for the assessment of outburst potential is shown in Fig. 5.

Based on a total of 7 main variables (i.e., lake type, dam type, freeboard, connection, drainage type, possibility for lake impact) and 3 sub-variables (dam width, width-to-height ratio, dam length) for dam geometry, an outburst potential assessment has been realized for all lakes. The final classification was summarized in 3 categories of outburst potential (1 = low, 2 = medium, and 3 = high). Evaluation of sub-variables of dam geometry depended on the freeboard value. When the freeboard was noticeable from the topography, we considered dam sub-variables as the slope, width-to-height ratio, and dam width. When the features of the dam were not noticeable, a dam did either not exist or dam parameters could not be measured, suggesting that all three sub-parameters are high and that the largest outburst potential prevailed.

The highest possible outburst potential has a value of 27, whereas the lowest possible level is 9. Lakes with values smaller than 15 were classified as having a low outburst potential, those with values ranging between 15 and 21 have a medium outburst potential, and lakes with values between 22 and 27 were considered to have a high outburst potential. Uncertainties of course exist in such an assessment, and the final values and outburst potential category do not necessarily imply that a lake is about to burst out, but that it should be of high priority for detailed investigations or monitoring (Worni et al., 2013).

For each lake, the main parameters for the outburst potential assessment (Fig. 5) were defined by two approaches, i.e. by measuring values (quantitatively) and by visually identifying (qualitatively) different variables in the image. Data from digital elevation models were then applied to assess dam parameters. All parameters were recorded in the inventory database and checked by at least 2 independent experts for all lakes. The inventory of database consists of 16 parameters, namely:

1. Lake ID
2. Coordinates, x/y in UTM projection zone 42 on a WGS84 ellipsoid.
3. Altitude m a.s.l.
4. Lake area, km^2.
5. Name of river catchment.
6. Name of key region.
7. Type of the dam.
8. Type of lake.
9. Type of drainage.
10. Connection between lakes.
11. Estimated freeboard values.
12. Estimated dam height.
13. Estimated width of dam crest.
14. Potential for mass-movement impacts into the lake.
15. Outburst potential index.
16. Outburst potential class (Low, Medium, High).

We analyzed the distribution of lakes by area, elevation and tested differences between the lakes located in different regions in Uzbekistan. Differences were tested using the non-parametric Kruskal-Wallis test, the significance was defined at p-value = 5%. Statistical analyses were realized with R and SPSS.

4. Results

4.1. Inventory of mountain lakes

In this study, 242 lakes were identified in the four key mountain regions of the Republic of Uzbekistan as illustrated in Fig. 6. About 40 of these lakes account for 60% of the area of all lakes; they are located below 3100 m a.s.l. Looking at the cumulative curve, shown in Fig. 7, we observe a sharp increase in the number of lakes once we exceed 3100 m, but also realize that the overall area of lakes at these altitudes is only about 40% of the total area. Another noticeable feature is that the area of lakes is in three elevation intervals, namely at 1700–1900, 2300–2500, and 3500–3700 m a.s.l. Most of the lakes at the lower end of the elevational range are extraglacial, landslide dammed, and have a relatively large area. The altidudinal band 2300–2500 m includes extraglacial and periglacial lakes, both typically dammed by moraines and landslides. Lakes located in the interval comprising elevations between 3500 and 3700 m are usually periglacial or proglacial and have relatively small areas.

The mean value of lake area is 13,900 m^2 and the median is 2796 m^2, whereas standard deviation is 40,640 m^2. The biggest lake has a water surface of 394,976 m^2, whereas the smallest lake has an area of 117.9 m^2. The distribution of lakes by elevation (from 1500 to 4100 m a.s.l.) shows a mean value of 3487 m and a median of 3594 m, with a standard deviation (σ) of 478 m.

The skewness of the distribution of lakes by area is positive $\Upsilon = 6.1$ (Fig. 7A) with a distribution of lakes to the right, as the highest number of lakes has a small surface. The skewness of the distribution of lakes by elevation is positive with $\Upsilon = 2.9$. Distribution of the lakes by altitude is skewed to the right as well, as the highest number of lakes is located above 3000 m a.s.l. and as most of these high-elevation lakes are at area intervals comprised between 100 and 50,000 m^2 (Fig. 7B).

Overall, 68 lakes were identified in the Surkhandarya region (Fig. 7) and are situated in the lower part of the Hissar Alay Range. Here, most lakes are found above 3300 m a.s.l. The Kashkadarya region is situated north of the Hissar Alay Range and has 39 lakes. Distribution of lakes is similar to Surkhandarya.

A total of 131 lakes were identified in the Tashkent region, with surfaces ranging from 0.1 to 0.39 km^2 (Fig. 7). Most of the large lakes are in the Tashkent region. Bodakkul and Upper Ikhnach lakes both have an area of about 0.26 km^2. The biggest lake in the region (and in the inventory) is Lake Shaurkul, situated in the north-eastern part of the Tashkent region and at an altitude of 2750 m a.s.l. Its area varies from 0.28 km^2 in winter to 0.40 km^2 in summer.

In the Shakhimardan basin, we identified 4 lakes, all of them being transboundary in nature and located on the territory of Kyrgyzstan. The biggest lakes are lakes Kurbankul' and Kokkul' with areas of 0.08 and 0.1 km^2, respectively. They belong to the extraglacial type of lakes with landslide dams. The two other lakes are located in the upper reaches of the catchment and at elevations above 3700 m a.s.l., with the highest lake in the inventory found at 4088 m a.s.l.

The largest number of lakes with high outburst potential is found in Tashkent region ($n = 48$) and the probability that a lake in this region has a high outburst potential is 36.6%. The second largest amount of lakes with high outburst potential is located in the Surkhandarya region with 35 lakes; here the probability for the occurrence of high outburst potential is 51.5%, In the Kashkadarya region, 12 lakes show high outburst potential (31.6%), whereas in the Shakhimardan zone only 2 lakes are considered to have high outburst potential.

The largest number of lakes with medium outburst potential is in the Tashkent region ($n = 67$) and the probability that a lake in this region belongs to the medium outburst potential class is 51%.

The distribution by lake type reflects the position of lakes with respect to the glacier, especially in the case of extraglacial lakes, as most of these are located at much lower altitudes than the other lake types (Fig. 8). Lake area displays maximum values for the extraglacial lakes and most of these large lakes were formed by geological processes and in the absence of glaciers. In general, the average area of proglacial and periglacial lakes is similar (7091 and 9953 m^2, respectively), whereas the area of supraglacial lakes is much smaller (2180 m^2). However, the smallest area values are observed for periglacial lakes (117 m^2), presumably as the study region is virtually lacking big glaciers (the biggest

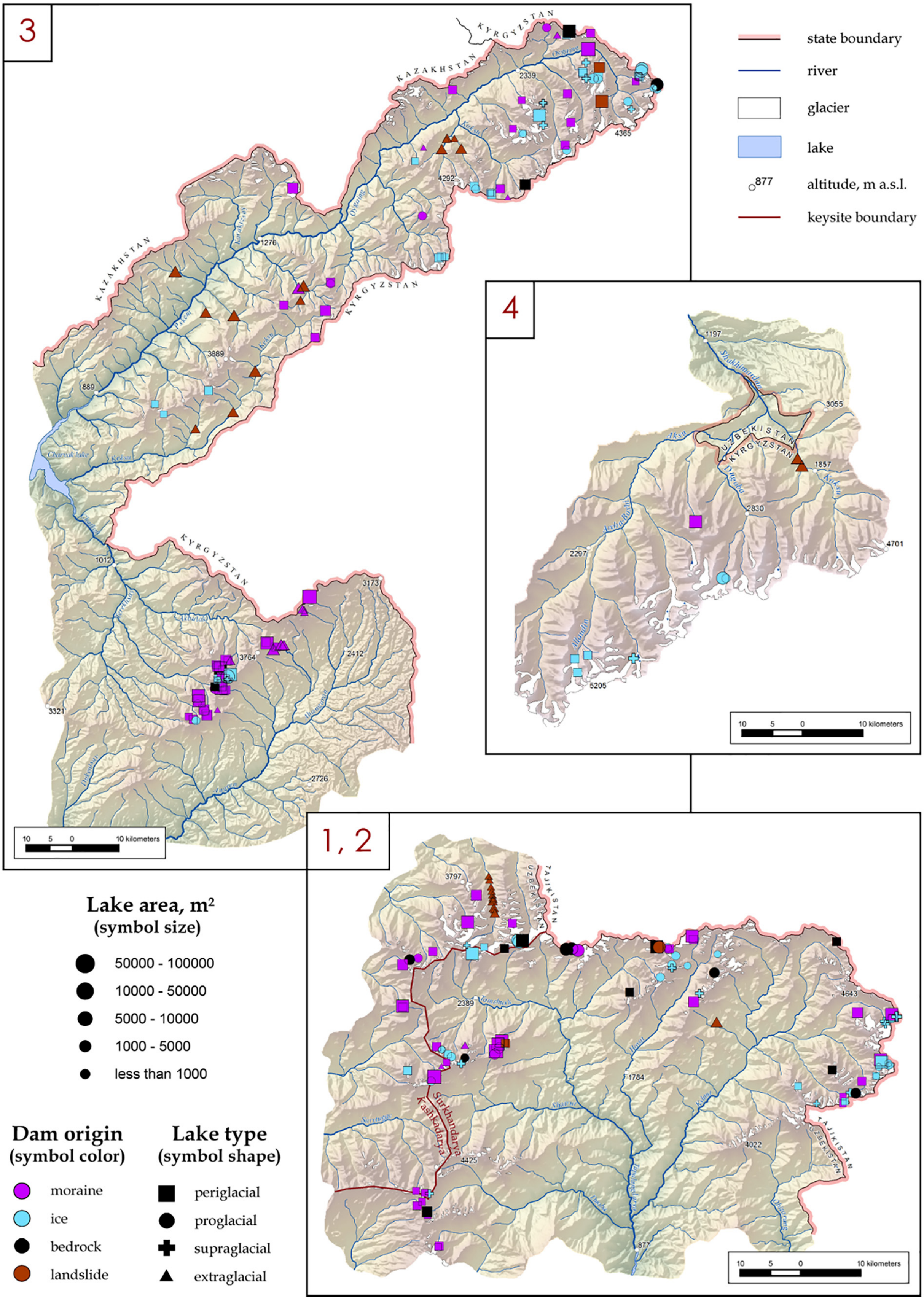


Fig. 6. Distribution of mountain lakes by regions in the Republic of Uzbekistan: 1-Kashkadarya, 2-Tashkent, 3-Surkhandarya, 4-Shakhimardan.

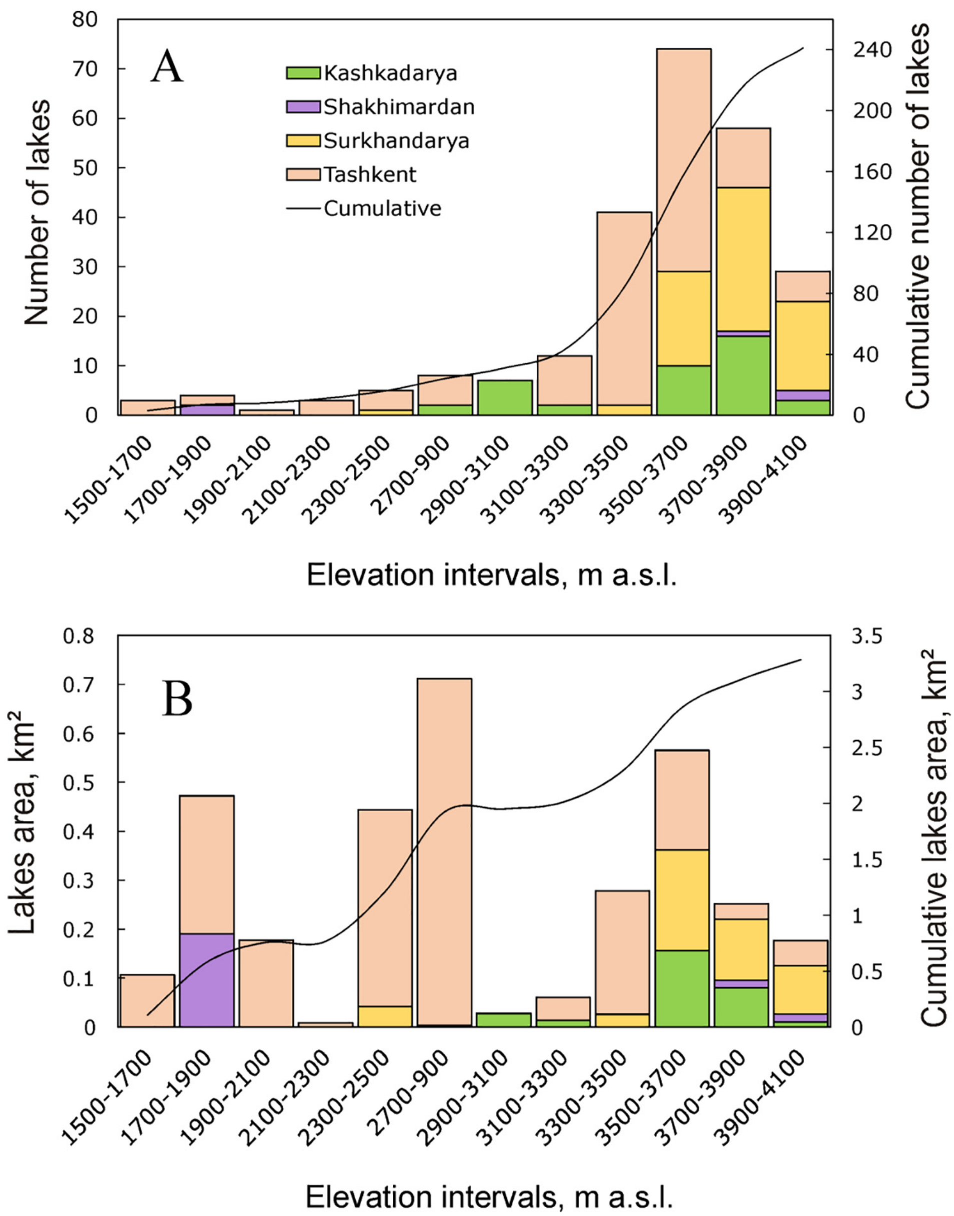


Fig. 7. Distribution of lakes in the study regions by area and elevation.

glacier in the study region, Severtsova, has an area of only 2 km^2). The highest variation of altitudes is observed for extraglacial lakes, where the lowest lake is situated at the altitude of 1500 and the highest lake at 3400 m a.s.l.

4.2. Lake outburst potential

The small number of lakes with low outburst potential ($n = 21$) are located at all altitudes, but show a concentration round altitudes of 3000 m a.s.l. Lakes with medium outburst potential generally are located at elevations comprised between 3000 and 4000 m, and also make the largest part of the database ($n = 124$). Interestingly, lakes with high outburst potential are situated at the highest altitudes of the catchments, on average at about 3400 m, and typically located in the periglacial zone (Fig. 9). A total of 97 lakes has been considered to have a high outburst potential.

The largest lakes are in general classified with low outburst potential (Fig. 10). This can be explained by the fact that lakes with a low outburst potential are typically located quite far away from the glaciers and their dams normally have relatively stable structures. By contrast, the largest number of lakes with a high outburst potential is situated in the periglacial zone and are often part of a cascade, with ice or ice-debris dams and situated on or next to the glacier.

5. Discussion

The inventory of the mountain lakes of Uzbekistan presented here and the assessment of outburst potential is the first of its kind for the wider study region and will be of great help for a more appropriate land-use and eventually emergency planning in Uzbekistan. In the past, data as the ones presented here have not been available in Uzbekistan in particular but also in Central Asia in more general terms, mainly because of security concerns and tensions between the different countries in the region (Siegfried et al., 2012). Determination of water equivalents stored in the region's glaciers (Sorg et al., 2012) and, even more so, detailed risk assessment will remain a challenge, but the present study has made a first step into the direction of lake outburst potential. The present assessment therefore complements previous work on Central Asia's cryosphere (Aizen et al., 2006, 2007; Semakova et al., 2015), and adds a cornerstone to the large set of international assessments of

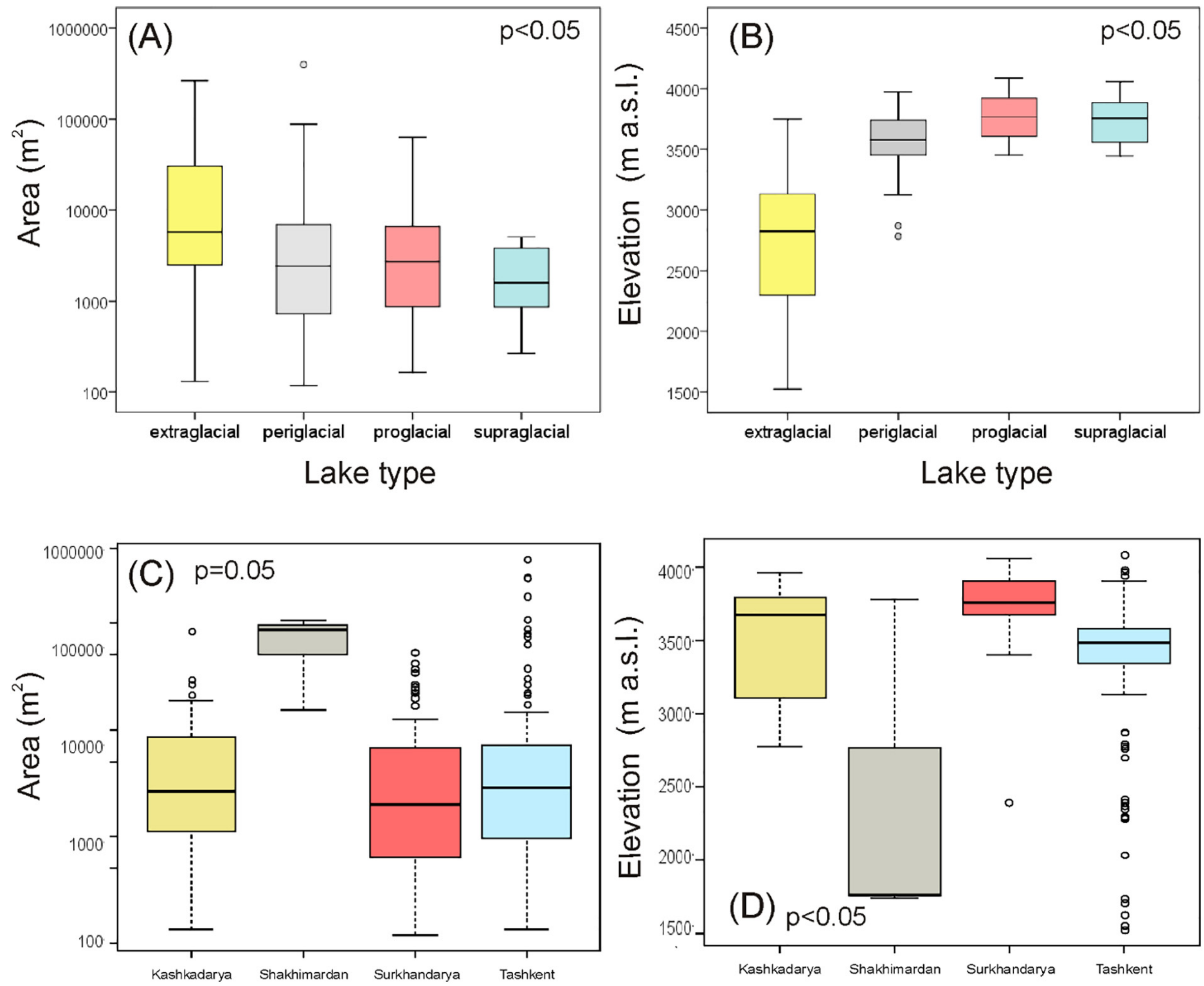


Fig. 8. Lake type distribution by (A) area and (B) elevation; Regional distribution of lakes according to (C) area and (D) elevation.

glacier lakes and their potential hazards (Reynolds, 1998; Clague and Evans, 2000; Huggel et al., 2004; Worni et al., 2013; Schwanghart et al., 2016).

As pointed out by Worni et al. (2013), evaluation and classification of lake outburst potential by remote sensing are challenging, and we thus propose an approach which takes account of these limitations (Huggel et al., 2004; Wang et al., 2012; Worni et al., 2013) and applies them to region context of Uzbekistan. However, any approach based on a set of key parameters assessed by remote sending has limitations that will be discussed in the following. One limitation is the estimation of lake area, which is ideally obtained via a detailed site survey including bathymetry, however, for large areas with a large number of lakes, and many of them in very remote areas, a field-based approach is not feasible. Nevertheless, and by contrast to many other studies, we provide a

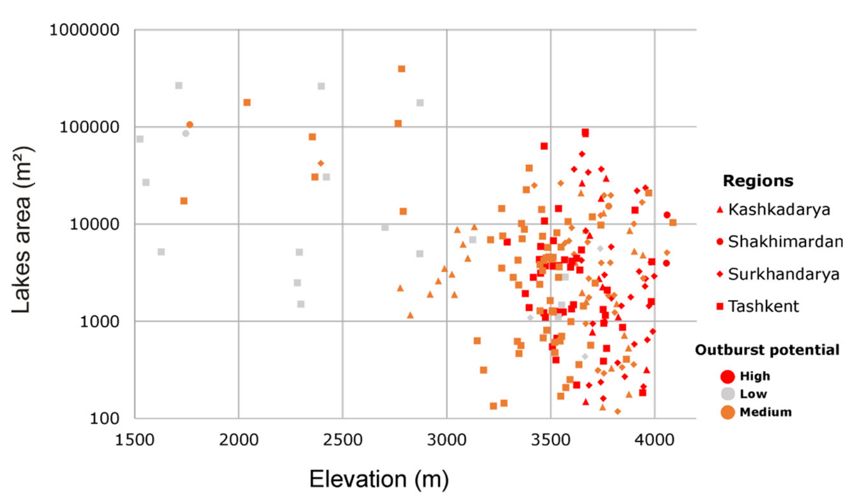


Fig. 9. Distribution of lakes according to lake area and elevation. Different colors indicate differences in outburst potential whereas different shapes point to different regions.

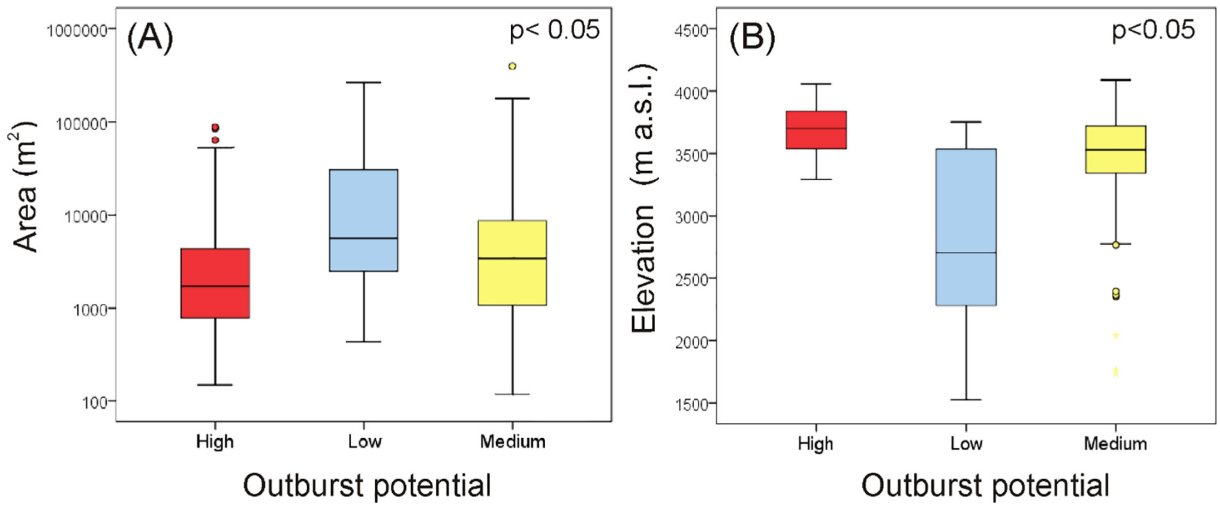


Fig. 10. Lake outburst potential distribution with relation to (A) area and (B) elevation.

validation of our remotely sensed approach with a comparably large set of measurements obtained in the field (Fig. 11). In addition, the remotely sensed classification of outburst potential was complemented with in-situ measurements (see Table S1 in the Supplementary Material).

Based on the analyses performed in Fig. 11, we can state that remote sensing applied to the assessment of lake areas provides a powerful tool to cover large spatial areas with relatively good accuracy, but that the quality of the output will depend on temporal, spectral, radiometric, and spatial resolutions (Kirby, 1995). The temporal resolution will limit the time window for which images can be obtained. The spectral resolution will be limited by the visual bands (RGB) used, whereas with bands above RGB (i.e. in near infra-red region or NIR), objects such as water could be easily identified as they reflect less energy and would appear dark. Radiometric and spatial resolutions will be limited by the design of the sensors used in the satellites. The main limitation of our approach lies, however, in the characterization of lake drainage type and dam type and geometry (e.g., height or freeboard) based on the DEM and the interpretation of satellite images. Although the approach used here is common, it includes certain inaccuracies (Fujita et al., 2008; Wang et al., 2012). Therefore, the assessment presented

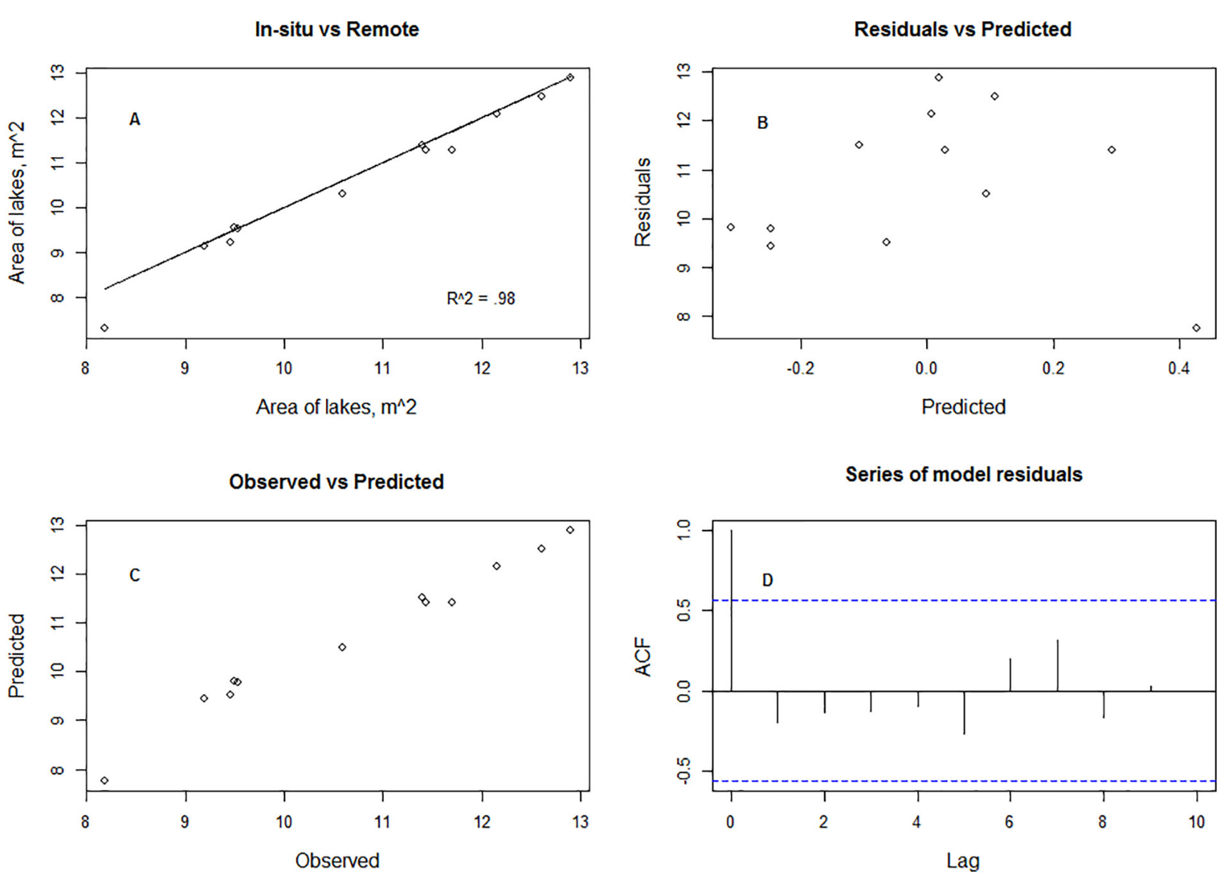


Fig. 11. (A) Plots of in-situ observed and remotely sensed lake area in a log space with 45° line of observed values; (B) Plot of residuals vs. model estimates of remotely sensed data; (C) Plot of model estimates vs observed data; (D) Autocorrelation plot of residuals.

in this study should be taken as a first-order approach to identify critical lakes with high and medium outburst potential for which further analyses (e.g. field surveys, detailed modelling, etc.) and monitoring will be needed.

The present work also adds substance to case-study type investigations of mountain lakes in the region, as the one existing for Ikhnach, Shaurkul, or Ozerniy lakes (Yakovlev and Batirov, 2003; Glazirin and Glazirina, 2012; Glazirin, 2013; Semakova et al., 2015), or regionally-focused analyses (Glazirin et al., 2013), which were, however, mostly limited to the Tashkent region. In the case of the of Oygain basin, Glazirin et al. (2013) described 30 lakes, whereas this study reports on a total of 61 lakes. Comparable differences have also been found between the present assessment and data provided by Semakova et al. (2015), who used Aster and Landsat data and therefore restricted the minimum area of water surface to 500 m^2. Differences therefore exist in the number of lakes (110 lakes) and total area (1.8 km^2) as compared to our study for which we observe only 88 lakes with a total area of 1.6 km^2.

As a result of the differences described above, we also call for a clearer definition and the approval of common protocols for future studies aiming at lake identification. The study of Glazirin et al. (2013), for instance, was based on helicopter reconnaissance, whereas Semakova et al. (2015) used an automatic identification of lakes which were then validated with a rather limited set of field data of mountain lakes. Also, the latter study assumes a maximum relative error for lakes with an area < 2000 m^2 to be 40%, whereas in our study total uncertainty of lake area for all identified lakes should be <1%.

6. Conclusions

This work represents, to our knowledge, the first attempt to apply lake outburst potential and hazard assessment of mountain lakes in the wider Central Asian region based on remotely sensed data. Noteworthy, as outburst evaluation relied partly on remotely sensed data, results may suffer from certain uncertainties. Nevertheless, the approach presented here allows a rather detailed determination of the current state of lakes with small areas and over fairly large regions. About 40% of all lakes found in this study have a high outburst potential, but the area of these lakes remains relatively small. By contrast, only 10% of the lakes have been considered to have a low outburst potential and, at the same time, larger water surface areas.

Acknowledgements

This work has been supported by a Swiss National Science Foundation Scopes grant (grant no 152301). Valuable comments and support by Ella Semakova on an earlier version much improved the quality of the paper. Russian participants acknowledge support by the Russian Foundation for Basic Research (grants no 15-05-08694 and 14-05-00768).

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2017.03.068.

References

Aizen, V.B., Aizen, E.M., Kuzmichonok, V.A., 2007. Glaciers and hydrological changes in the Tien Shan: simulation and prediction. Environ. Res. Lett. 2:045019. http://dx.doi.org/10.1088/1748-9326/2/4/045019.

Aizen, V.B., Aizen, E.M., Melack, J.M., Dozier, J., 1997. Climatic and hydrologic changes in the Tien Shan, Central Asia. J. Clim. 10:1393–1404. http://dx.doi.org/10.1175/1520-0442(1997)010<1393:CAHCIT>2.0.CO;2.

Aizen, V.B., Kuzmichenok, V.A., Surazakov, A.B., Aizen, E.M., 2006. Glacier changes in the central and northern Tien Shan during the last 140 years based on surface and remote-sensing data. Ann. Glaciol. 43:202–213. http://dx.doi.org/10.3189/172756406781812465.

Alean, J., 1984. Ice avalanches and a landslide on Grosser Aletschgletscher. Z. Gletscherkunde Glazialgeol. 20, 9–25.

Allen, S.K., Rastner, P., Arora, M., Huggel, C., Stoffel, M., 2016. Lake outburst and debris flow disaster at Kedarnath, June 2013: Hydrometeorological triggering, and topographic predisposition. Landslides 13, 1479–1491.

Bolch, T., Kulkarni, A., Kaab, A., Huggel, C., Paul, F., Cogley, J.g., Frey, H., Kargel, J.s., Fujita, K., Scheel, M., Bajracharya, S., Stoffel, M., 2012. The state and fate of Himalayan glaciers. Science 310. http://dx.doi.org/10.1126/science.1215828.

Carey, M., Huggel, C., Bury, J., Portocarrero, C., Haeberli, W., 2011. An integrated socio-environmental framework for glacier hazard management and climate change adaptation: lessons from Lake 513, Cordillera Blanca. Peru. Clim. Change 112:733–767. http://dx.doi.org/10.1007/s10584-011-0249-8.

Carrivick, J.L., Tweed, F.S., 2013. Proglacial lakes: character, behaviour and geological importance. Quat. Sci. Rev. 78:34–52. http://dx.doi.org/10.1016/j.quascirev.2013.07.028.

Chernomorets, S., 2015. Селевая опасность в бассейне реки Шахимардан (Киргизия и Узбекистан) - доклад на конференции | ИСТИНА – Интеллектуальная Система Тематического Исследования НАукометрических данных [WWW Document]. URL https://istina.msu.ru/conferences/presentations/11208275/ (accessed 2.23.17).

Chernomorets, S., Savernyuk, E., Dokukin, M., Tutubalina, O., 2015. Assessment of Glacial Lake Outburst Flood and Debris Flow Hazard in Northern Afghanistan. IGU 2015 Book Abstr. 3941 p. 1136.

Chigira, M., Yagi, H., 2006. Geological and geomorphological characteristics of landslides triggered by the 2004 Mid Niigta prefecture earthquake in Japan. Eng. Geol. 82:202–221. http://dx.doi.org/10.1016/j.enggeo.2005.10.006.

Clague, J.J., Evans, S.G., 2000. A review of catastrophic drainage of moraine-dammed lakes in British Columbia. Quat. Sci. Rev. 19:1763–1783. http://dx.doi.org/10.1016/S0277-3791(00)00090-1.

Cook, S.J., Kougkoulos, I., Edwards, L.A., Dortch, J., Hoffmann, D., 2016. Glacier change and glacial lake outburst flood risk in the Bolivian Andes. Cryosphere Discuss.:1–27 http://dx.doi.org/10.5194/tc-2016-140.

Cook, S.J., Swift, D.A., 2012. Subglacial basins: their origin and importance in glacial systems and landscapes. Earth-Sci. Rev. 115:332–372. http://dx.doi.org/10.1016/j.earscirev.2012.09.009.

Dokukin, M.D., Shagin, S.I., 2014. Features of dynamics of glacial lakes with underground drain channels (analysis of multi-temporal aerospace information). Earths Cryosphere 18, 47–56.

Emmer, A., Klimeš, J., Mergili, M., Vilímek, V., Cochachin, A., 2016. 882 lakes of the Cordillera Blanca: an inventory, classification, evolution and assessment of susceptibility to outburst floods. Catena 147:269–279. http://dx.doi.org/10.1016/j.catena.2016.07.032.

Fujita, K., Suzuki, R., Nuimura, T., Sakai, A., 2008. Performance of ASTER and SRTM DEMs, and their potential for assessing glacial lakes in the Lunana region, Bhutan Himalaya. J. Glaciol. 54, 220–228.

Glazirin, G., 2013. Key locations of naturally dammed lakes in Uzbekistan. Shak. Verl. 3–20.

Glazirin, G., Glazirina, M., 2012. Catalogue of Pamir and Hassaro-Alay Glaciation for 1980 (database of A.S.Schetinnikov). Exlib. LLP.

Glazirin, G., Shamsutdinov, V., Starygin, G., Khan, V., 2013. Inventory of glacial lakes in the territory surrounding Uzbekistan. Shak. Verl. 54–74.

Gorbunov, A.P., 1978. Permafrost investigations in High-Mountain Regions. Arct. Alp. Res. 10:283–294. http://dx.doi.org/10.2307/1550761.

Gorbunov, A.P., Marchenko, S.S., Seversky, E.V., 2004. The thermal environment of blocky materials in the mountains of Central Asia. Permafr. Periglac. Process. 15:95–98. http://dx.doi.org/10.1002/ppp.478.

Gulyamov, P., Vaxobov, X., 2013. Fizicheskaya geografiya Centralnoy Azii i Uzbekistana.

Haeberli, W., 1983. Frequency and characteristics of glacier floods in the Swiss Alps. Ann. Glaciol. 4, 85–90.

Hannah, D.M., Kansakar, S.R., Gerrard, A.J., Rees, G., 2005. Flow regimes of Himalayan rivers of Nepal: nature and spatial patterns. J. Hydrol. 308:18–32. http://dx.doi.org/10.1016/j.jhydrol.2004.10.018.

Huggel, C., Haeberli, W., Kääb, A., Bieri, D., Richardson, S., 2004. An assessment procedure for glacial hazards in the Swiss Alps. Can. Geotech. J. 41:1068–1083. http://dx.doi.org/10.1139/t04-053.

Huggel, C., Kääb, A., Haeberli, W., Teysseire, P., Paul, F., 2002. Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps. Can. Geotech. J. 39:316–330. http://dx.doi.org/10.1139/t01-099.

Iwata, S., Karma, K., Ageta, Y., Sakai, A., Narama, C., Naito, N., 2008. Glacial geomorphology in the Lunana area in the Bhutan Himalaya: moraine stages, glacial lakes, and rock glaciers. Himal. J. Sci. 2:164. http://dx.doi.org/10.3126/hjs.v2i4.853.

Kirby, R., 1995. Remote-Sensing and Image Interpretation, 3rd Edition - Lillesand,tm, Kiefer,rw. Int. J. Geogr. Inf. Syst. 9, 345–348.

Korjenevskiy, N., 1922. Turkestan fiziko-geograficheskiy ocherk (Turkestanskoye gosudarstvennoe izdatelstvo).

Korup, O., Tweed, F., 2007. Ice, moraine, and landslide dams in mountainous terrain. Quat. Sci. Rev. 26:3406–3422. http://dx.doi.org/10.1016/j.quascirev.2007.10.012.

Kubrushko, S., Shatrabin, V., 1982. Long-term prediction of glacial mudflows in Tien Shan, Data of Glaciological Studies. Data Glaciol. Stud. 43, 60–62.

Kubrushko, S., Staviskiy, Y., 1978. Glacier lakes of Kyrgyz and their role in mudflow formation. Data Glaciol. Stud. 32, 59–62.

Kutuzov, S., Shahgedanova, M., 2009. Glacier retreat and climatic variability in the eastern Terskey–Alatoo, inner Tien Shan between the middle of the 19th century and beginning of the 21st century. Glob. Planet. Change 69:59–70. http://dx.doi.org/10.1016/j.gloplacha.2009.07.001.

Łozinzki, W., 1909. Uber die mechanische Verwitterung der Sandsteine im gema ssigten klima. Bulletin International de l'Academie des Sciences de Cracovie, Classe des Sciences Mathematiques et Naturelles English translation by T. Mrozek, 1992. On the

mechanical weathering of sandstones in temperate climates. In: Evans, D.J.A. (Ed.), Cold Climate Landforms. 1–25. John Wiley and Sons Ltd., pp. 119–134.
Lu, R., Tang, B., Li, D., 1999. Introduction of debris flow resulted from glacial lakes failed. In: Lu, R., Tang, B., Zhu, P. (Eds.), Debris Flow Environ. Sichuan University Publishing House, Tibet, pp. 69–105.
Merzbacher, G., 1905. The Central Tian-Shan Mountains 1902–1903. John Murray, Lond.
Narama, C., Kääb, A., Duishonakunov, M., Abdrakhmatov, K., 2010. Spatial variability of recent glacier area changes in the Tien Shan Mountains, Central Asia, using Corona (~1970), Landsat (~2000), and ALOS (~2007) satellite data. Glob. Planet. Chang. 71: 42–54. http://dx.doi.org/10.1016/j.gloplacha.2009.08.002.
Narama, C., Severskiy, I., Yegorov, A., 2009. Current state of glacier changes, Glacial Lakes, and outburst floods in the Ile Ala-Tau and Kungöy Ala-Too ranges, Northern Tien Shan Mountains. Geogr. Stud. 84:22–32. http://dx.doi.org/10.7886/hgs.84.22.
Narama, C., Shimamura, Y., Nakayama, D., Abdrakhmatov, K., 2006. Recent changes of glacier coverage in the western Terskey-Alatoo range, Kyrgyz Republic, using Corona and Landsat. Ann. Glaciol. 43:223–229. http://dx.doi.org/10.3189/172756406781812195.
Nikitin, A., 1987. Ozera Credney Azii. Gidrometeorologicheskiy regim ozer I vodohranilisch SSSR. Leningr. Gtdrometeoizdat 106.
Nikitin, A., Gorelkin, N., 1979. K voprosu gidrometeorologicheskogo obsnovaniya ekspluataii i ohrani vodnih resursov ozer i vodohranilish Sredney Azii. Ann. CARHRI 66, 3–9.
Nikitin, A., Gorelkin, N., 1977. O dinamike ozer srednego i nijnego techeniya reki Syrdari. Ann. CARHRI 50, 22–30.
O'Gorman, L., 1996. Subpixel precision of straight-edged shapes for registration and measurement. IEEE Trans. Pattern Anal. Mach. Intell. 18:746–751. http://dx.doi.org/10.1109/34.506796.
Petrakov, D., Shpuntova, A., Aleinikov, A., Kääb, A., Kutuzov, S., Lavrentiev, I., Stoffel, M., Tutubalina, O., Usubaliev, R., 2016. Accelerated glacier shrinkage in the Ak-Shyirak massif, Inner Tien Shan, during 2003–2013. Sci. Total Environ. 562:364–378. http://dx.doi.org/10.1016/j.scitotenv.2016.03.162.
Pieczonka, T., Bolch, T., 2015. Region-wide glacier mass budgets and area changes for the Central Tien Shan between ~1975 and 1999 using Hexagon KH-9 imagery. Glob. Planet. Chang. 128:1–13. http://dx.doi.org/10.1016/j.gloplacha.2014.11.014.
Quincey, D.J., Richardson, S.D., Luckman, A., Lucas, R.M., Reynolds, J.M., Hambrey, M.J., Glasser, N.F., 2007. Early recognition of glacial lake hazards in the Himalaya using remote sensing datasets. Glob. Planet. Change, Climate Change Impacts on Mountain Glaciers and Permafrost. 56:pp. 137–152. http://dx.doi.org/10.1016/j.gloplacha.2006.07.013.
Reynolds, J.M., 1998. High-altitude glacial lake hazard assessment and mitigation: a Himalayan perspective. Geol. Soc. Lond. Eng. Geol. Spec. Publ. 15:25–34. http://dx.doi.org/10.1144/GSL.ENG.1998.015.01.03.
Reyzvih, V., Kruglovskiy, G., Nikitin, A., 1971. Prichini I usloviya proriva oz. Yashinkul'. J. TGMO 4, 48–95.
Richardson, S.D., Reynolds, J.M., 2000. An overview of glacial hazards in the Himalayas. Quat. Int. 65–66:31–47. http://dx.doi.org/10.1016/S1040-6182(99)00035-X.
Rickenmann, D., 2005. Runout prediction methods. In: Hazards, Debris-Flow, Phenomena, Related (Eds.), Springer Praxis Books. Springer, Berlin Heidelberg:pp. 305–324 http://dx.doi.org/10.1007/3-540-27129-5_13.
Ruiz-Villanueva, V., Allen, S., Arora, M., Goel, N.K., Stoffel, M., 2017. Recent catastrophic landslide lake outburst floods in the Himalayan mountain range. Progr. Phys. Geogr. 41, 3–28.
Schetinnikov, A., 1976. Ledniki basseyna reki Pskem. Leningr. Gtdrometeoizdat 121.
Schwanghart, W., Worni, R., Huggel, C., Stoffel, M., Korup, O., 2016. Uncertainties at the water-energy nexus - the case of Himalayan hydropower and glacial lake outburst floods. Environ. Res. Letter 11, 074005.
Semakova, E., Gunasekara, K., Semakov, D., 2015. Identification of the glaciers and mountain naturally dammed lakes in the Pskem, the Kashkadarya and the Surhandarya River basins, Uzbekistan, using ALOS satellite data. Geomat. Nat. Hazards Risk 7: 1081–1098. http://dx.doi.org/10.1080/19475705.2015.1023852.
Shults, V., 1965. Reki Sredney Azii, SPb. ed. Gidrometeoizdat.
Siegfried, T., Bernauer, T., Guiennet, R., Sellars, S., Robertson, A.W., Mankin, J., Bauer-Gottwein, P., Yakovlev, A., 2012. Will climate change exacerbate water stress in Central Asia? Clim. Chang 112:881–899. http://dx.doi.org/10.1007/s10584-011-0253-z.
Singh, S., Bassignana-Khadka, I., Singh Karky, B., Sharma, E., 2011. Climate Change in the Hindu Kush Himalayas (ICIMOD report) (ICIMOD report).
Sorg, A., Bolch, T., Stoffel, M., Solomina, O., Beniston, M., 2012. Climate change impacts on glaciers and runoff in Central Asia. Nat. Clim. Change 2, 725–731.
Sorg, A., Stoffel, M., Huss, M., Rohrer, M., 2014. The days of plenty might soon be over in glacierized Central Asian catchments. Environ. Res. Lett. 9. http://dx.doi.org/10.1088/1748-9326/9/10/104018.
Sorg, A., Kääb, A., Roesch, A., Bigler, C., Stoffel, M., 2015. Contrasting responses of Central Asian rock glaciers to global warming. Nat. Sci. Rep. 5:8228. http://dx.doi.org/10.1038/srep08228.
Staviskiy, Y., Jukov, N., 1968. Nekotorie svedeniya ob ozerah Maliy I Bol'shoy Kulun. J. FGMO 104–111.
Stoffel, M., Huggel, C., 2012. Effects of climate change on mass movements in mountain environments. Prog. Phys. Geogr. 36:421–439. http://dx.doi.org/10.1177/0309133312441010.
Stoffel, M., Wyzga, B., Marston, R.A., 2016. Floods in mountain environments. Geomorphology 272, 1–9.
Tweed, F.S., Russell, A.J., 1999. Controls on the formation and sudden drainage of glacier-impounded lakes: implications for jökulhlaup characteristics. Prog. Phys. Geogr. 23: 79–110. http://dx.doi.org/10.1177/030913339902300104.
UNEP, 2007. UNEP: Global Outlook for Ice and Snow. p. 235.
Wang, X., Liu, S., Ding, Y., Guo, W., Jiang, Z., Lin, J., Han, Y., 2012. An approach for estimating the breach probabilities of moraine-dammed lakes in the Chinese Himalayas using remote-sensing data. Nat. Hazards Earth Syst. Sci. 12:3109–3122. http://dx.doi.org/10.5194/nhess-12-3109-2012.
Worni, R., Huggel, C., Stoffel, M., 2013. Glacial lakes in the Indian Himalayas — from an area-wide glacial lake inventory to on-site and modeling based risk assessment of critical glacial lakes. Sci. Total Environ. 468–469 (S71–S84) Changing water resources availability in Northern India with respect to Himalayan glacier retreat and changing monsoon patterns: consequences and adaptation. 10.1016/j.scitotenv.2012.11.043.
Worni, R., Huggel, C., Clague, J.J., Schaub, Y., Stoffel, M., 2014. Coupling glacial lake impact, dam breach, and flood processes: a modeling perspective. Geomorphology 224, 161–176.
Yakovlev, A., Batirov, R., 2003. Monitoring of mountain glaciers and glacial lakes using ASTER space images. First Int. Conf. Hydrol. Water Resour. Asia Pac. Reg. APHW 1042–1047.
Zaginaev, V., Ballesteros-Cánovas, J.A., Erokhin, S., Matov, E., Petrakov, D., Stoffel, M., 2016. Reconstruction of glacial lake outburst floods in northern Tien Shan: implications for hazard assessment. Geomorphology 269:75–84. http://dx.doi.org/10.1016/j.geomorph.2016.06.028.