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Surface area dynamics of Gunt River Basin mountain lakes (the Pamirs, Tajikistan)

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This article is the translation of the article "Dinamika ploshchadi zerkala gornyh ozer bassejna reki Gunt (Pamir, Tadzhikistan)" [Динамика площади зеркала горных озер бассейна реки Гунт (Памир, Таджикистан)" published on November 10th, 2022.

ABSTRACT

The article discusses mountain lakes posing threat to downstream settlements and infrastructure based on the example of Lakes Rivakkul and Nimatskul in the Gunt River Basin. In recent decades, the number and area of lakes have been growing at an accelerated rate due to the shrinking of glaciers in the target basin home to over 600 such reservoirs. The elaboration of recommendations for the installation of early warning equipment to inform population about high-mountain lake outbursts is critical for the sustainable development of the Central Asian Region. The study aimed to investigate the surface area dynamics of 2 (two) mountain lakes in the Gunt River Basin during 2000-2019. Using remote sensing data, summary data were collected on their water supply, location and surface area. The paper presents the findings obtained based on Landsat 7-8 imagery (August and September 2000-2019). The harvested data showed that 2006 witnessed the maximum increase in the area of Lake Nimatskul, whereas the same was observed for Lake Rivakkul in 2010. During the study period (from 2000 to 2019), Lake Nimatskul demonstrated a gradual surface area decrease from 0.513 to 0.462 km^2, while Lake Rivakkul remained more stable. It was established that the surface area dynamics of mountain lakes are closely related to meteorological parameters, and that surface and underground runoff stabilized lake surface area and water level.

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1. Introduction

Outbursts of mountain and glacial lakes – posing a significant natural, ecological and hydrological threat – are characteristic of many highland regions around the world, including the Republic of Tajikistan (RT).

This research aimed to examine the surface area (surface) dynamics of mountain lakes as well as assess the corresponding potential danger. Rendering the possibility of comprehensive hazard assessment in large areas, remote sensing represents the most optimal and expedient method for studying hard-to-reach high-altitude zones (Huggel et al., 2002).

Numerous studies by the specialists from near and far abroad confirm the thesis that most high-altitude lakes can be easily identified on multispectral satellite images by Landsat, Sentinel-2A, etc. In particular, the majority of South Asian countries (India, Nepal, Bhutan, and Pakistan), as well as China have been executing modern glaciation studies, including continuous cataloguing of high-altitude lakes and collecting basic information about them in certain river basins. The study results of high-mountain lakes located in Central Asia are presented in the works by Vinogradov (1977, 1980); Tukeyev (2002); Batyrov, Yakovlev (2004); Yerokhin, Zaginayev (2020a, 2020b); Konovalov (2009), Chernomorets (2007a, 2007b); Shafiyev (2018); Pirmamadov (2020) and others.

In Tajikistan, there are 1,449 lakes with the total surface area of 716 km^2 and 80% of them located in mountainous and highland areas at the absolute elevation of 2,300-5,100 m ASL. It deserves noting that the territory of the Pamir Mountains is characterized by frequent mudflows, 22% of which are glacial found to have the most devastating consequences (Assessment Reports, 2006).

The studies of the distribution of high-altitude glacial lakes in the Amu Darya River upper reaches mainly aim to protect the territory and communities exposed to natural disasters associated with mountain lake outbursts. The facilities exposed to the potential impacts of lake outbursts include hydroelectric power plants (HPPs) built within the limits of the Gunt River Basin and the city of Khorog, the capital of Tajikistan's Gorno-Badakhshan Autonomous Region (GBAR) (Tukeyev, 2002).

The issue of exploring mountain lakes is highly relevant for inhabited areas along river valleys. Hard-to-reach mountain lakes are mainly studied using remote sensing methods and reconnaissance expeditions (Kidyaeva et al., 2018).

The countries of Central Asia, including the RT, have been developing their respective mountain-piedmont zones, building and operating roads of international and strategic importance, all subject to natural water-related disaster risks and other hazardous natural phenomena. Thus, when designing such facilities, it is necessary to properly consider the zones of probable avalanches, mudflows, floods and other natural disasters. Outbursts of high-mountain lakes represent dangerous and destructive phenomena occurring at high elevations.

Mudflows and outburst floods represent potentially dangerous sources of significant irreparable social and economic damage often accompanied by human deaths.

It stands noting that the natural disaster risks mentioned above largely restrain the development of high-elevation hydropower. In particular, two large HPPs (Pamir-1 and Khorog) on the Gunt River providing the entire GBAR with electricity are subject to hazardous hydrological processes and require constant monitoring to ensure safe operation of these vital facilities for GBAR's economy.

Monitoring of mountain lake surface area dynamics and water level fluctuations manifest significant elements of such monitoring allowing to draw conclusions about the trends contributing to the improvement of technologies for assessing the likelihood of their potential breakthrough (Bolch et al., 2011; Kidyaeva, 2018).

Multiple researchers around the world, including in Central Asia, have been utilizing remote sensing satellite data to study the changes in surface water area (Sagin et al., 2015; Das et al., 2015; Sagintayev et al., 2012).

Based on the above, the main purpose of this research – conducted during 2000-2019 – was to investigate the dynamics of mountain lake surface area.

2. Research site and objects

The Gunt River is the second largest (296 km long) tributary of the Pyanj River with the catchment area of 13,700 km^2. Fig. 1. shows the detailed map of the Gunt River Basin. The study objects were Lake Rivakkul (3,456 m ASL) and Lake Nimatskul (4,566 m ASL).

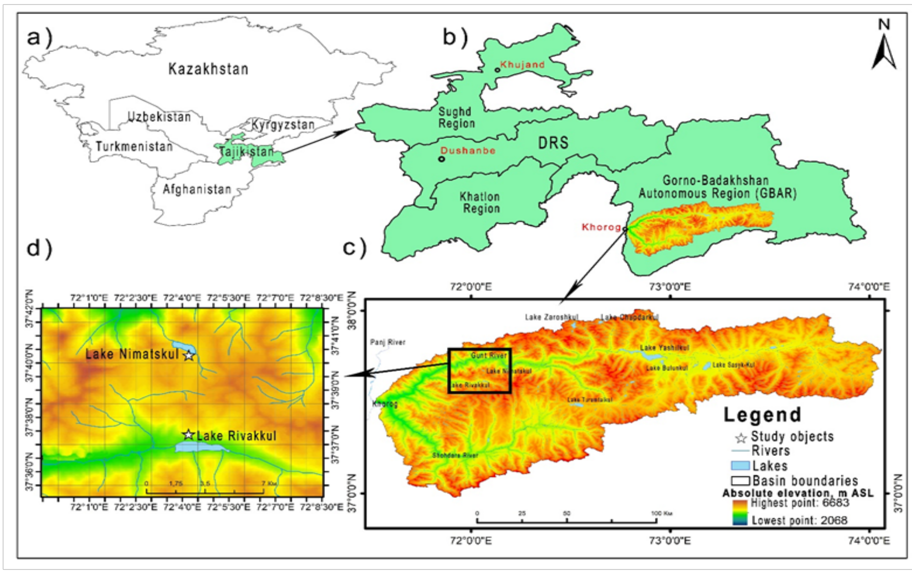

Figure 1. Map of Gunt River Basin inside Central Asia (proprietory): a) Map of Central Asia; b) Map of Tajikistan; c) Gunt River Basin; d) Lake Nimatskul and Lake Rivakkul.

Located in the southern part of the Pamirs, from north to south the Gunt River Basin stretches for 90 km in its western and central sections, for 50 km in its eastern section, and for 220 km from west to east. In the north, the mountain ranges of the Rushan and Northern Alichur Ridges serve as the basin border with the Bartang and Murghab River Basins; in the south, the Shakhdara and Southern Alichur Ridges separate the target and the Pamir-Pyanj River Basins (see Fig. 1.).

In the west, the research territory adjoins the basins of short steep-falling tributaries of the Pyanj River. In the east, short ridges and low mountain ranges separate the target basin from the basins of the left-bank tributaries of the Aksu River belonging to the Murghab River upper reaches. Administratively, the basin's territory belongs to the GBAR with its center in the city of Khorog located at the Gunt mouth (USSR Glacier Catalogue, 1979).

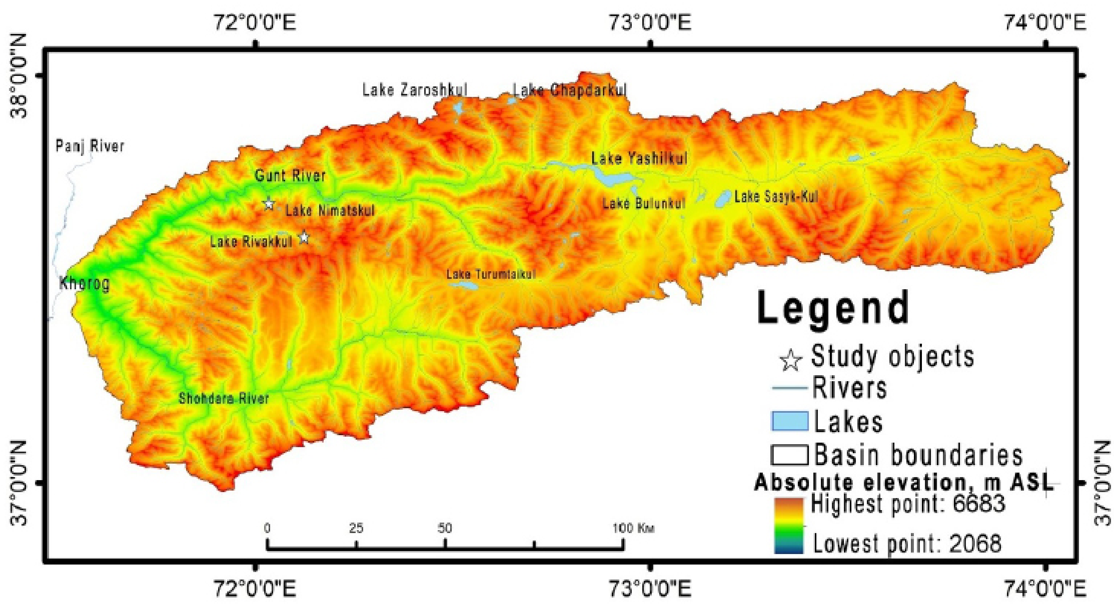

Figure 2. Map of Gunt River Basin (proprietory).

Mountain ranges inside the Gunt River Basin reach 5,000-5,500 m, including Karl Marx (6,726 m), Engels (6,507 m) and Patkhor (6,080 m) Peaks. The steep slopes of local mountain peaks are cut with deep narrow river valleys, with their lower sections dropping to 2,050 m of absolute elevation. Local rivers are rather violent and form waterfalls in certain places (USSR Glacier Catalogue, 1979).

The Gunt River Basin is home to over 600 large and small mountain lakes. Multiple lateral valleys – including the Chapdara and Shazuddara Valleys in the north, and Rivakdara, Pishdara, Vashedzdara, Nimatsdara Valleys, etc. – descending into the Gunt Valley have glacial lakes (see Fig. 3.). A significant number of these lakes are dammed with rock fragments transported by the glacier and moraine, creating an impression of sufficient stability. However, some of these natural dams contain ice, the melting of which may create catastrophic situations.

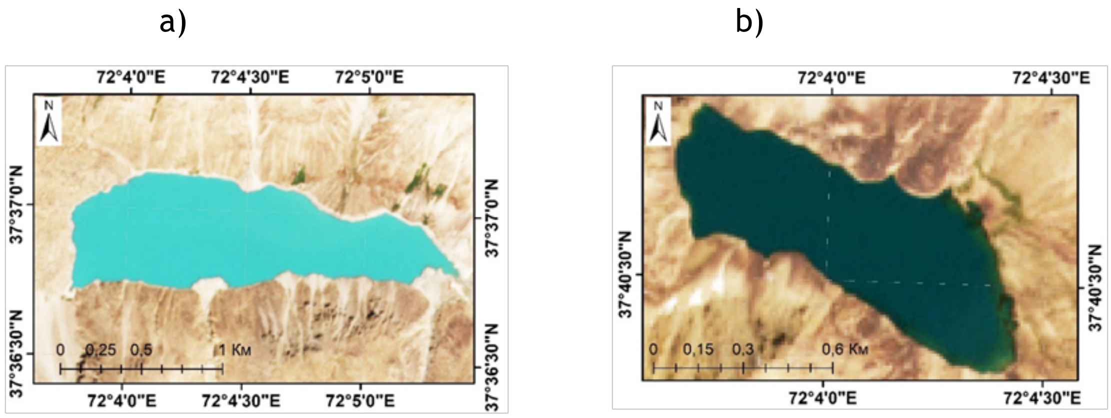

Figure 3. Sentinel satellite imagery: a) Lake Rivakkul; b) Lake Nimatskul.

In this sense, the Rivak Valley is unique as its large mountain Lake Rivakkul is blocked with a composite dam (moraine line). Two filling periods and outbursts were registered for this lake in the past.

It bears mentioning that several smaller glacial lakes in the valley's upper section have been gradually growing potentially leading to outburst risk. In the event of such a critical situation, Lake Rivakkul can play the role of a damping waterbody reducing the risk of critical wave formation triggering a dangerous hydrological phenomenon of flood. In its turn, Lake Nimatskul is considered a potentially hazardous natural object (Shafiyev, 2018).

2.1. Climate

In the Gunt River Basin, climate observations are carried out at 2 (two) meteorological stations, specifically the Bulunkul Station located in the river's upper reaches, and Khorog Station in its lower reaches. The area of the village of Bulunkul (3,744 m ASL) is considered one of the coldest in the Eastern Pamirs characterized by dry and cold summers and winters with low precipitation in the form of snow. Sometimes, winter air temperature may drop to -63°C, and rise to +11.2°C in summer. Due to remoteness (over 80 km) from the study area, the data of the Bulunkul Weather Station were not included in the analyses.

The Khorog Weather Station is located at the altitude of 2,075 m ASL in the center of the city of Khorog. Local climate is dry and sharply continental. The coldest winter month is January with the mean air temperature of -7.9°C; the warmest summer month is July with the temperature rising up to +22.8°C. The mean annual precipitation is 250-300 mm.

As commonly known, river and/or lake water content directly depends on the fluctuations of climatic parameters. Thus, in order to determine the relationship between lake surface area changes it is necessary to analyze their relationship with meteorological data.

Fig. 4. and 5. show summer precipitation and air temperature curves in the target basin by years.

a) b)

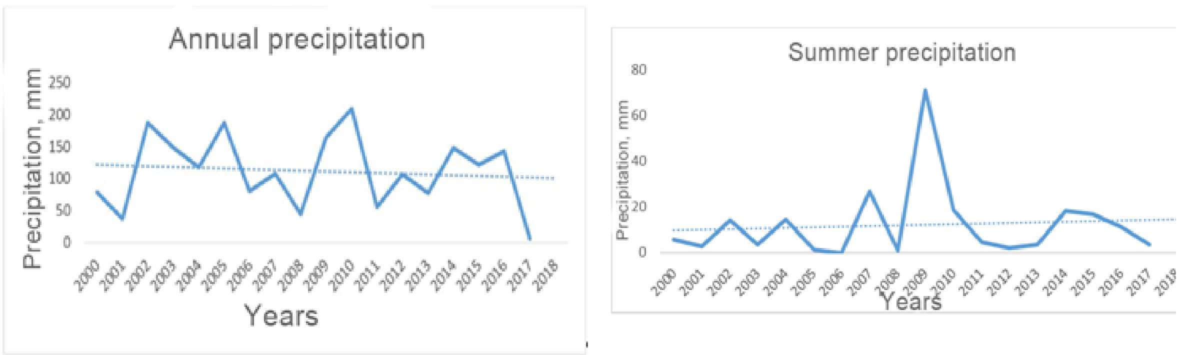

Figure 4. Precipitation curves: a) Annual precipitation; b) Summer precipitation (Khorog Weather Station, 2000-2018 (Mirzokhonova, 2021).

a) b)

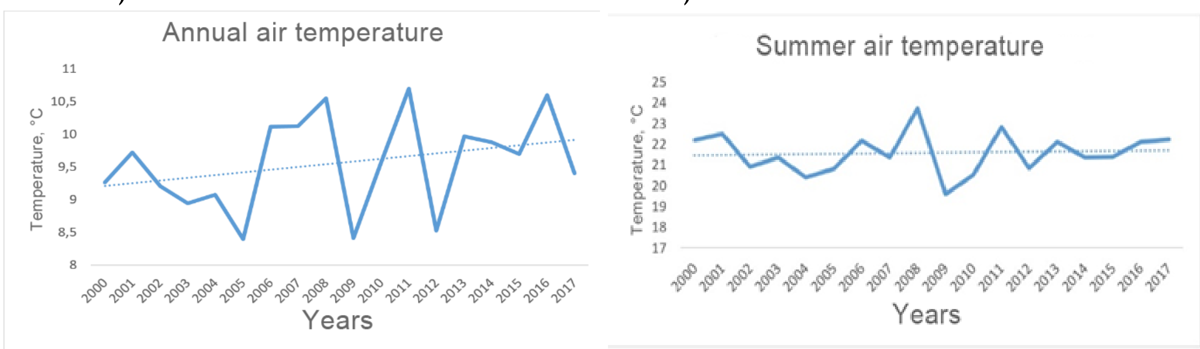

Figure 5. Air temperature curves: a) Annual air temperature; b) Summer air temperature (Khorog Weather Station, 2000-2018 (Mirzokhonova, 2021).

3. Research methods

To determine the changes in the surface area of Lakes Rivakkul and Nimatskul, open source space images of different spectral and spatial resolutions from the Landsat 7 ETM + and Landsat 8 OLI satellites were harvested from the US Geological Survey (USGS) website (Piotrovsky, Zengina, 2018).

The images included multi-zone image channels with 30 m spatial resolution supplemented with a panchromatic channel (15 m resolution). The selected satellite imagery corresponded to late summer and early fall, because these are the periods when the snow cover melts completely allowing to calculate lake nourishment for a particular year. In total, over 10 (ten) multitemporal images for 2000-2019 were processed for the study area (see Table 1.) with the interval of 1 (one) year (Ananicheva et al., 2006).

While processing satellite images, certain hardware-related distortions were detected due to the ETM+ camera malfunction. However, the regular interferences did not affect the interpretation quality during the manual interactive decryption.

Table I. Landsat satellite imagery by year

№	Date	Satellite	№	Date	Satellite
1.	August 24, 2000	Landsat 7 ETM+	6.	August 25, 2012	Landsat 7 ETM
2.	August 30, 2002	Landsat 7 ETM+	7.	August 14, 2014	Landsat 8 OLI
3.	September 04, 2004	Landsat 7 ETM+	8.	August 28, 2016	Landsat 8 OLI
4.	August 30, 2008	Landsat 7 ETM+	9.	August 29, 2018	Landsat 8 OLI
5.	August 20, 2010	Landsat 7 ETM+	10.	September 03, 2019	Landsat 8 OLI

4. Results

The research results are presented in figures, tables and diagrams. Fig. 6. and 7. demonstrate the (color-coded) contours of the target lakes during the studied years. The data on their surface area dynamics are given in Table 2. The calculation error for the surface area of Lake Nimatskul amounted to 0.05 km2 and 0.009 km^2 for Lake Rivakkul.

The decrease in the surface area of both lakes was confirmed by the trend lines (see Fig. 8.). Based on the data obtained (Table 2.), the maximum area increase at Lake Nimatskul was detected in 2006, and in 2010 at Lake Rivakkul. It was identified that during 2000-2019 Lake Nimatskul demonstrated the gradual surface

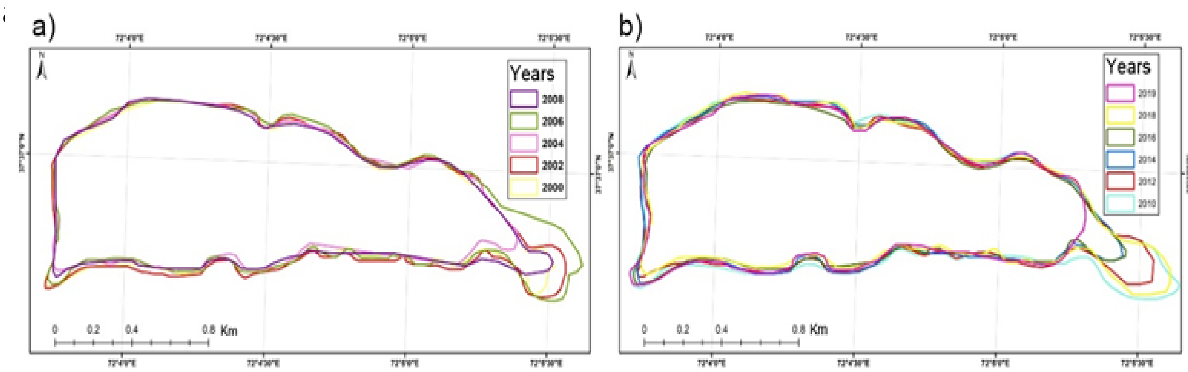

Figure 6. Dynamics of Lake Rivakkul: A) During 2000-2008; B) During 2010-2019.

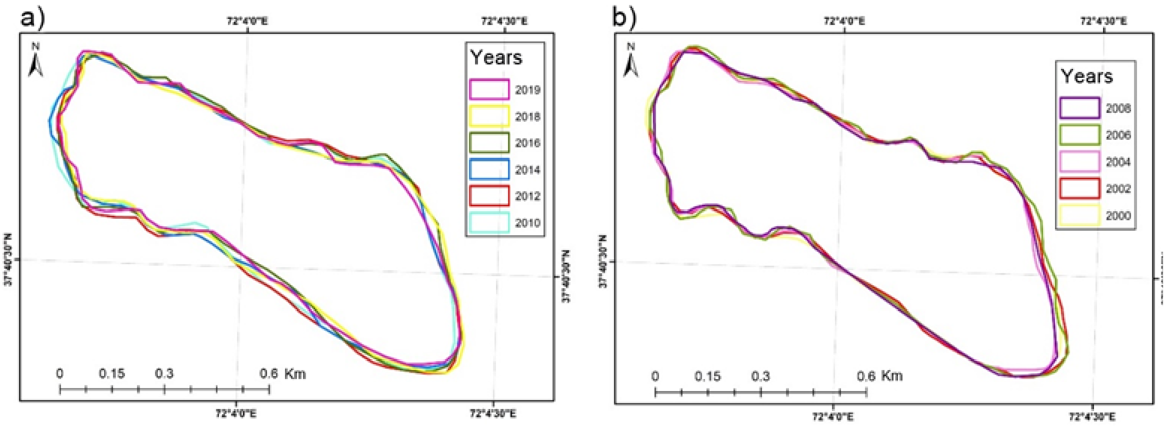

Figure 7. Dynamics of Lake Nimatskul: A) During 2000-2008; B) During 2010-2019.

Table II. Surface area dynamics of Lakes Nimatskul and Rivakkul (2000-2019)

Lake/year	Lake surface area by years (Landsat, km^2)										
	2000	2002	2004	2006	2008	2010	2012	2014	2016	2018	2019
Nimatskul	0.513	0.511	0.496	0.515	0.499	0.484	0.500	0.477	0.485	0.470	0.462
Rivakkul	1.295	1.378	1.246	1.390	1.251	1.419	1.337	1.333	1.260	1.265	1.267

The diagram in Fig. 8. was built based on the data describing the surface area changes in the target lakes (see Table 2.) during 2000-2019.

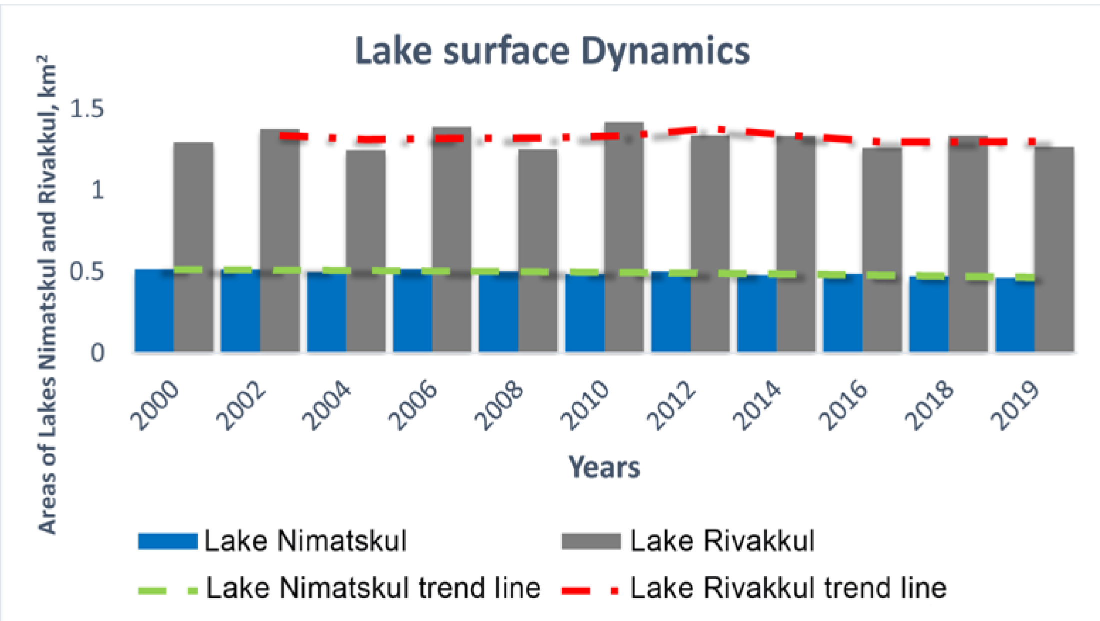

Figure 8. Surface area dynamics of Lakes Nimatskul and Rivakkul (2000-2019).

5. Discussion

The research findings confirm the results of similar studies (Bajracharya and Mool, 2009; Kidyaeva et al., 2018; Chernomorets et al., 2007a, 2007b). The conclusion that in the presence of surface runoff long-term water level fluctuations in mountain lakes are stable, and in its absence – or in case of restructuring of interglacial, filtration and other drainage channels of adjacent glaciers – large-scale changes in lake water balance emerge, which may provoke their outburst, is justified (Kidyaeva et al., 2013).

The analysis of air temperature and precipitation curves, i.e. the factors leading either to expansion or shrinking of lake surface area (see Fig. 4., 5. and Table 2.), showed that during the years of higher precipitation, the surface area of the target lakes also increased and, vice versa, decreased with lower precipitation. Based on the data in Fig. 6., Lake Rivakkul demonstrated an area decrease on its right-bank edge due to the fact that its depth there is low and, depending on meteorological parameters, contraction of the lake's surface area in summer. It was established that during 2000-2019, the area of both target lakes decreased, and that in both of them underground runoff was present.

Thus, the presented research results unambiguously suggest the relevance of remote sensing technologies for investigating surface area dynamics of mountain lakes.

6. Conclusion

The study's scientific novelty lies in the fact that it was for the first time that satellite imagery was applied to assess the surface area of Gunt River Basin mountain lakes. In the future (in further studies), based on the obtained analytical data and availability of modeling software, it becomes possible to elaborate their possible outburst model.

The obtained research results suggest that the application of remote sensing data can make a significant contribution to the study of mountain lake dynamics, and it can be recommended for use in geological, hydrological, and glaciological observations.

The results of the analyses of multi-time and multi-zone space imagery under the study point to a direct link between the changes in lakes' area and their nourishment. Lakes Nimatskul and Rivakkul have only underground runoff, as a result of which their water levels remain stable.

Thus, the use of remote sensing materials can and should form the basis for the operational methods of monitoring the surface area dynamics of mountain and glacial lakes, including field missions.

The need to develop recommendations on installing early warning equipment to inform the population about high-altitude lake outbursts is critical for the sustainable development of the Central Asian region.

7. Analyses of uncertainties and limitations

The majority of mountain lakes in the Gunt River Basin are hard to access making field research missions almost impossible. In addition, the lack of equipment to analyze mountain lakes also complicates the work, since it takes longer to obtain any data. Yet, it stands highlighting that field research should not be excluded from the overall system of comprehensive studies.

Remote sensing methods offer great opportunities to explore hard-to-reach highlands, but the spatial resolution (30 m) of Landsat satellite images in the 90's either makes the study of small lakes impossible or leads to significant calculation errors. Access to higher-quality satellite imagery and deployment of unmanned aerial vehicles (UAVs) would substantially simplify these tasks.

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