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ГИС инвентаризация приледниковых озер Алтая в пределах России, Монголии и Китая

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Со времени Малой ледниковой эпохи, высотный и широтный диапазон распространения криогенных образований Земли неуклонно сужается и выражается в прогрессирующем сокращении гляциосферы. Подчиняясь глобальным климатическим тенденциям, оледенение Алтая (Русского, Монгольского, Китайского) на протяжении полутора столетий находится в стадии устойчивой регрессии, а ледники его основных центров демонстрируют отрицательный баланс массы и уменьшают занимаемую площадь. Характерным элементом ландшафтов перигляциального пояса Большого Алтая, как области с активно деградирующим оледенением, являются комплексы полигенных и полиморфных озерных водоемов, количество которых возрастает пропорционально темпам сокращения оледенения. Сравнительный анализ материалов космической съемки с 1966 по 2020 гг. показывает, что большая часть из них образовалось за последний полувековой период. Приледниковые озера по праву рассматриваются как источник формирования гляциальных селей, обладающей огромной разрушительной силой. Именно поэтому, данный тип озер относится к особо опасным источникам стихийных бедствий. В настоящее время не существует подробного каталога приледниковых озер Алтая, поэтому чрезвычайно важно выполнить их инвентаризацию и на основе комплексного анализа получить данные о потенциально опасных озерах, представляющих угрозу населению нижележащих речных долин.

Для систематизации, аналитической обработки и отображения пространственно координированных данных о приледниковых озерах Алтая нами разработана геоинформационная система «GL Altai». В качестве основного программного обеспечения ГИС был выбран комплекс программных средств Microdem/TerraBaseII V12.0 и Global Mapper V 16.0® . Структура разработанной нами ГИС включает: банк данных, программно-аппаратный комплекс и средства создания оперативных материалов для разработки прогнозных заключений. Банк данных ГИС состоит из картографического архива, тематических баз данных в формате DBase и материалов дистанционного зондирования. Векторные цифровые карты в ГИС «GL Altai» представлены в формате Shape-файлов. Наличие цифровой топографической основы позволило привести к единой системе координат цифровые тематические карты и материалы дистанционного зондирования. В качестве цифровой модели рельефа использованы планшеты Aster GDEM, SRTM матриц третьего поколения и DTED level 3. Современное озерное покрытие горно-ледниковых бассейнов Алтая картировалось по прямым признакам дешифрирования мультиспектральных и панхроматических космоснимков высокого и сверхвысокого разрешения: Канопус-В МСС, Ресурс-П Геотон Мультспектр и монохромных космических изображений с пространственным разрешением от 1 до 3.5 м. за период с 2017 по 2020 гг. Все имеющиеся сцены в формате GeoTiff были преобразованы в единую картографическую проекцию (45 и 46 зона UTM, WGS84). Пространственное положение водоемов середины 60-х годов XX века картировалось по монохромным геотрансформированным и геореферированным электронным скан-копиям отпечатков космоснимков миссии Corona (KH-2, KH-3). Основные гидрографические характеристики водоемов (площадь акватории, длина береговой линии, отметка уреза) рассчитывались программными средствами ГИС. Объемы озерных вод рассчитывались по зависимостям К. Хюгелля и С. Эванса.

К настоящему времени выполнена ГИС инвентаризация приледниковых озер Юго-восточной части Русского Алтая и основных центров оледенения Монгольского Алтая. Трем приледниковым водоемам присвоен ранг критической опасности.

GIS inventory of glacial lakes in the Altai Mountains within Russia, Mongolia and China

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Since the Little Ice Age, the altitudinal and latitudinal range of the Earth's cryogenic formations has been steadily narrowing and expressed in a progressive reduction of the glaciosphere [1]. Subject to global climatic trends, the glaciation of the Altai (Russian, Mongolian, Chinese) has been in steady regression for a century and a half, and the glaciers of its main centres demonstrate a negative mass balance and decrease in the area occupied [2,3,4,5] . A characteristic element of landscapes of the Altai periglacial belt, as an area with actively shrinking glaciation, are complexes of polygenic and polymorphic lake water bodies, the number of which increases in proportion to the rate of glaciation reduction. The uneven distribution of lakes across the mountain-glacial basins of the Altai is dictated by their morphological features: most of the lake water bodies are confined to the gentle precipices of valley and car-valley glaciers with well-defined marginal moraine complexes, which act either as natural dams or provide conditions for the development of thermokarst limnogenesis. In basins dominated by glaciers of flat-top or slope type, there are no conditions for the formation of water bodies. A comparative analysis of the space survey materials from 1968 to 2020 shows that most of them were formed in the last half-century. Lakes of the deglaciation belt are represented by the following morphogenetic types:

1. Glacial lakes. Glacial lake basins are formed in the ablation zone of valley glaciers in thermoerosional or thermokarst depressions of the glacial terrain. This type of lakes belongs to ephemeral formations; the hydrographic characteristics of this type of lakes (water area, volume) change annually with a steady upward trend due to their thermal impact on the occupied depression and natural transformation of the glacial surface. When critical volumes are reached, after a short period of time, glacial lakes empty, with a more or less pronounced degree of catastrophism.

2. Moraine lakes are formed in intra-marine depressions at the stage of active regression of valley glaciers. Most often they are confined to areas of widening and deepening of inter-moraine flow channels. Their number on large end-marine complexes may reach several dozens. The bottoms and sides of lake depressions are composed of moraine-containing ice, ice-bearing moraine or frozen varieties of moraine sediments. Water volumes in moraine lakes can reach considerable values, depending on the local topography and balance characteristics of water bodies. The development and time of existence of this type of lakes is controlled by the intensity of thermoabrasion impact on the lake basin and cryolithological properties of sediments composing the sides and bottoms of the occupied depression.

3 Lakes dammed by rock glaciers. The origin of this type of lakes is related to blocking of the main glacier melt-water channel by the margins of the rock glaciers rising from tributary valleys of the first order or from the sides of the main valley. The vast majority of the lakes in question were formed during the maximum stage of the Little Ice Age, their stable volumes being controlled by features of the local topography, indicators of the solid runoff of the main watercourse (as the main factor of aggradation of the lake reservoir) and regime characteristics of the underrun rock glacier.

4. Moraine-dammed lakes are located hypsometrically above the marginal moraine complexes of the Little Ice Age and, as a rule, occupy the depressions excavated by valley glaciers during the transgressive stage of the Little Ice Age. Dams of these lakes are represented by moraine ramparts composed of frozen loose clastic weakly water-permeable rocks. Most of the moraine-dammed lakes have surface runoff, more rarely the source is through filtration of water through the lake dam. Moraine-dammed lakes are time-stable accumulators of regulated glacier runoff and are an important element of water redistribution in mountain-glacial basins.

5. Rigel and kar lakes occupy the lowest parts of glacial kars and cirques, separated by a rock or moraine rigel. Kar lakes are formed during the final stage of glaciation degradation and are fed by atmospheric precipitation on the surface of the catchment. The stable volume of karst lakes in time is ensured by the height of the rock or moraine transom and the regime of atmospheric precipitation.

6. Zander lakes are small and unstable in time reservoirs with insignificant depths, formed in local depressions of relief within prelimes of retreating glaciers.

Glacial lakes are usually classified as distant geological hazards (in terms of distance rather than time) as they originate in high altitude areas, far from populated areas. They are predominantly located in the highlands, in uninhabited areas. Glacial lakes contain a store of water which under certain conditions can have an enormous destructive force. Therefore mountain lakes should be classified as particularly dangerous sources of natural disasters. The most dramatic event was the outburst of the Maashey moraine-dammed lake in July 2012 . The outburst flood caused significant damage to the infrastructure of the Ulagan district: destroyed 4 bridges on the Maashey River and Chuya River, and indefinitely delayed the building of a hydroelectric power station on the Chuya River, important for the local population.

There is currently no detailed catalogue of glacial lakes in the Altai, so it is crucial to carry out an inventory and survey of glacial lakes to obtain data on potentially dangerous lakes that could trigger floods and cause harm to the population of the downstream river valleys.

For systematization, analytical processing and display of spatially coordinated data on glacial lakes in the Altai, we have developed the GIS «GL Altai» (Fig. 1). Microdem/TerraBaseII V12.0 and Global Mapper V 16.0 software package was chosen as the main GIS software. The structure of our developed GIS includes: data bank, hardware-software complex and tools for creation of operational materials for development of forecast conclusions. The databank serves as the information basis of the GIS, its composition and structure were determined by the composition of input and output data required to solve the functional tasks of the research topic. The GIS databank consists of a map archive, thematic databases in DBase format and remote sensing materials. The vector digital maps in the GIS are in Shape-file format. The availability of a digital topographic base made it possible to bring digital thematic maps and remote sensing materials into a unified coordinate system. Aster GDEM, SRTM matrix third generation and DTED level 3 are used as digital elevation model.

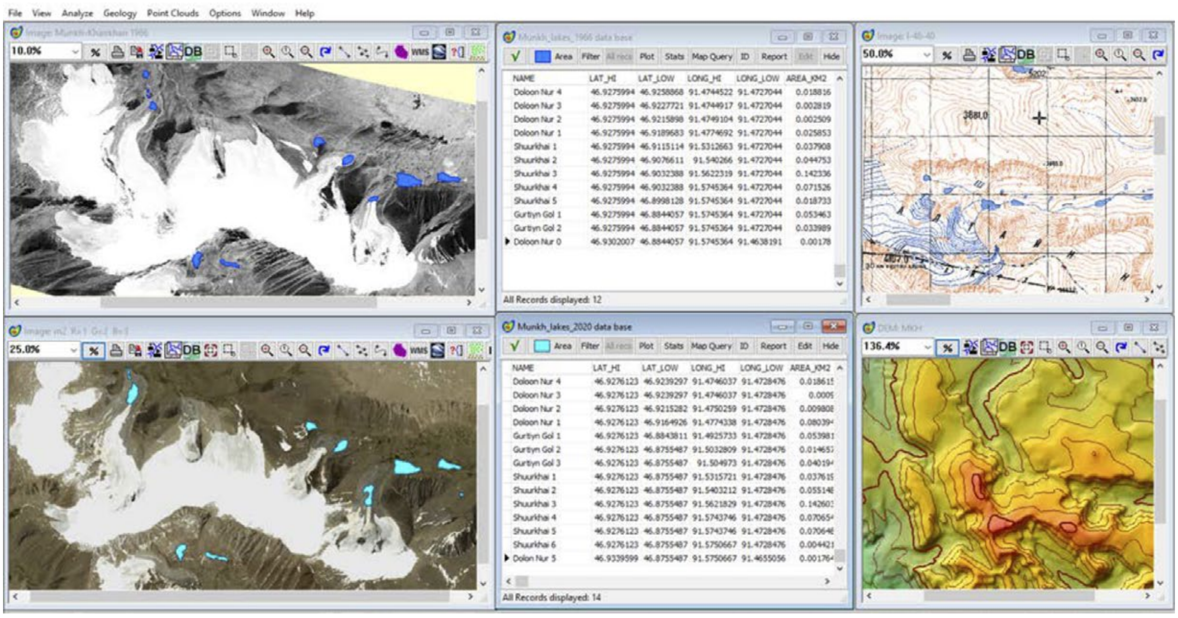

Fig.1
«GL ALTAI» GIS Interface with the thematic project "Glacial Lakes of the Munkh- Khairkhan Range".

Glacial lake mapping was performed by digitizing with Microdem/TerraBaseII V12.0 tools in Stream mode using raster pattern of summer scenes of multispectral Canopus-B MSS, Resurs-P Geoton multispectral and monochrome satellite images (scenes obtained using authorized access to the file archive of Roscosmos Geoportal's DPC, https://gptl.ru/) with spatial resolution of 1 to 3.5 m for the period from 2017 to 2020. All available scenes in GeoTiff format were converted into a single map projection (46 UTM zone, WGS84), geotransformed using Aster GDEM matrices and coordinates of reference points prepared during the field expedition research. The spatial position of the lakes for the time interval of the 1960s was mapped using monochrome geotransformed and geo-referenced electronic scans of Corona satellite imagery (materials were ordered and obtained through authorized access to the USGS GDEM file archive, https://earthexplorer.usgs.gov/).

The lake coverage of the mountain-glacier basins was mapped using direct signatures from high and ultra-high resolution multispectral and panchromatic satellite imagery. The main decoding features of lake water bodies were: smooth phototone and specific monotone or expressive structure of water images; oval shape of lakes and confinement of water bodies to low relief elements. Lakes were mapped when their shape became visible. The main hydrographic characteristics of the lakes (water area, shoreline length, and shoreline elevation) were calculated using GIS software. The lake water volumes were calculated in two ways: by C. Hugel's [6] dependence using formula (2) and by formula (3) proposed by S. Evans [7].

$$V = 0{,}104 \cdot A^{1{,}42} \quad (2),$$

$$V = 0{,}035 \cdot A^{1{,}5} \quad (3),$$

where V is water body volume, m^3, A is water body area, m^2.

To verify the obtained values, a bathymetric survey of potentially hazardous lakes was carried out. Measurements were taken with GPSMAP 585 Plus sonar with built-in GPS receiver. The echo sounding results were processed in Garmin Quickdraw Contours, from which depth maps of the water bodies were generated and their true volumes were established. The discrepancy between the measured volumes and those calculated using formula (2) was on average ±15%, and ±12% using formula (3).

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Lithological-geochemical and biological response of lacustrine sedimentation systems to weather-climatic changes (on the example of Gorny Altai lakes)

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The formation of bottom sediments in freshwater lakes depends on the external conditions that determine the inflow of sedimentary material from the catchment area. In many cases, lacustrine bottom sediments are paleoarchives that make it possible to obtain climate reconstructions of high time resolution. Special interest to researchers around the world present bottom sediments with annual layers (varves), which provide a high level of detail and accuracy of reconstructions [Zolitschka, 2015].

The high time resolution allows a direct comparison of the obtained proxies with the data of regional meteorological observations over the last century with the finding of climate indicators and the construction of transfer functions for the reconstructed parameters.

The study objects were three freshwater lakes located in the Central Altai physical-geographical province, at the northwestern end of the Katunsky ridge (Gorny Altai) - Kucherlinskoe, Srednee and Nizhnee Multinskie.

Bottom sediment cores were obtained using a hammer tubes and a box-corer. The use of a box-corer made it possible to obtain the upper layer of modern (last century), weakly consolidated sediments with practically no loss or damage. Thus, the top of the cores was dated by the year of sampling, which made it possible to build accurate and correct time series for the recent decades [Darin, 2019].

Scanning microanalysis of bottom sediments samples were carried out at the Siberian Center for Synchrotron and Terahertz Radiation at the experimental station "Elemental Analysis" according to the method [Darin,