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Mountain Resilience: A Tool for Mudflow Risk Management in the Ile Alatau Mountains, Kazakhstan

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The densely populated central part of the Ile Alatau mountains is one of the most mudflow-prone areas of Kazakhstan. Implementation of protection measures, early warning systems, and risk management plans is crucial to protect livelihoods and infrastructure from damage caused by mudflows. Increasing harm and damage from mudflows in recent decades—due to more frequent events, as well as increased economic development of the area—has made the establishment and implementation of a mudflow risk management system a priority. The effectiveness of such a system largely depends on the scientific validity of the management plan and hence is determined by the level of knowledge of the physical processes triggering such events. This knowledge is based on information that must be collected, analyzed, and systematized. However, such data are not easy to access; they are scattered over different archives and research institutes or simply missing. In recent years, scientific monographs, articles, and reports have been published that attempt to collect and systematize data on mudflow phenomena in general. These efforts provide a basis for further work but are often not readily available for use. This article presents the updateable, interactive, intelligent information system "Mudflow phenomena of the central part of the Ile Alatau" that links cartographic information with data on mudflow formation centers. This system concentrates and collates existing knowledge, making it accessible to stakeholders and decision-makers who can turn this knowledge into suitable applications for adaptive and sustainable risk management.

Keywords: *mudflow risk management; mudflow database; mudflow formation center; GIS technology; interactive map; Kazakhstan.*

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Introduction

The mountainous areas of Kazakhstan, which cover about 13% of the country's territory, are vulnerable to mudflows. About 70% of these areas belong to medium and high mudflow hazard categories. There are more than 300 basins where mudflow activity is registered, with more than 5600 mudflow centers and 967 moraine–proglacial lakes, which pose a potential threat to one third of the population (Medeu et al 2018, Baymoldayev et al 2018).

About 1100 mudflow events have been recorded in Kazakhstan since 1887, including more than 20 catastrophic ones (Medeu et al 2020). Protection against mudflows requires timely implementation of risk management, which, in turn, is based on the availability of data about mudflows and the factors controlling them. An effective strategy for the implementation of protection, early warning systems, and risk-reduction plans would promote sustainable development of the areas exposed to mudflows and adaptation to climate change. In Kazakhstan, issues related to the assessment and management of mudflow risks have been addressed since the 1990s, focusing on the Ile Alatau mountain range. Nationwide assessments (Kapitsa et al 2017; Medeu et al 2019) evaluated current levels of risk (eg high, moderate, or low) posed by glacial lake outburst floods (GLOFs) and mudflows and potential future changes in risks.

Observed and projected climate change (including an increase in air temperature and a shift toward liquid precipitation at progressively higher elevations) and melting of glaciers could lead to an increase in the frequency of mudflows of pluvial and glacial genesis. In the 1930–2020 period, summer air temperature increased in the northern Tien Shan at a rate of 0.10–0.26°C per decade, according to data from regional meteorological stations. Positive trends in summer temperatures were also noted in other regions of the Tien Shan (Kutuzov and Shahgedanova 2009; Narama et al 2010; Sun et al 2010; Wang et al 2011; Hoelzle et al 2019; Barandun et al 2020; Shahgedanova et al 2020). In the future, the development of mudflows is expected to intensify because of an increase in the elevation of the zero isotherm, resulting in more widespread rainfall (as opposed to snow) in the mountains, where loose clastic sediment is abundant (Stepanov and Yafyazova 2017; Medeu et al 2022; Mussina et al 2022).

Successful adaptation to the current and future risks posed by mudflows requires a detailed, regularly updated, and easily accessible database of mudflow activity. Such a database should include exact locations and descriptions of mudflow initiation points (eg mudflow centers in the form of incisions, potholes or moraine lakes, and inside moraine channels), their current state, and information on past events, including their quantitative characteristics, formation factors, and damage caused. It is important to provide spatially distributed information to model the development of mudflows and assess or predict damage. Spatiotemporal databases of mudflow activity based on geographic information systems (GIS) are used worldwide. They enable detailed analysis of physical characteristics of terrain, meteorological, and socioeconomic data to assess the hazard potential, risks, and impacts of mudflows and to inform governments and agencies responsible for relief and recovery activities. At the international level, recognition of the importance of such data has led to the development of the Emergency Events Database (EM-DAT 2020), which is widely used by development and relief agencies to mitigate against the impact of disasters on vulnerable populations.

There are various examples of the use of GIS technology for risk management. The US National Centers for Environmental Information (NOAA 2022) are a leading authority on environmental information. Canada's GIS-based Multi-Agency Situational Awareness System (MASAS; Government of Canada 2020) facilitates the sharing of reliable situational awareness based on real-time positioning in the Canadian emergency management community. This system is designed to act as a central hub for critical information and integrates data from various sources. It can be used via desktop and mobile Internet browsers, downloading data through the Representational State Transfer (REST) feature of ArcGIS and using MASAS GIS data layers in ArcGIS, which improves communication and information flow.

The US Federal Emergency Management Agency and Canadian agencies use a GIS-based tool (Hazus; FEMA 2020) to estimate the physical, social, and economic impacts of natural disasters. The visualization system illustrates the boundaries of locations at high risk of earthquakes, floods, fires, and hurricanes. Hazus is used for emergency response, early warning, and disaster loss reduction and recovery with minimal losses.

Recently, a dataset of GLOFs was established by the International Centre for Integrated Mountain Development for the Hindu Kush Himalayan region. It included locations, timing, associated processes, and downstream impacts. The dataset (ICIMOD 2022) includes 660 individual GLOFs that occurred during the period of 1833–2022. These can be integrated with other geospatial datasets to assess risks, drivers, and future projections of GLOFs.

In Kazakhstan, Moldakhmetov et al (2013) and Mussina and Zhanabayeva (2016) considered using GIS technology in the management of mudflow risks and proposed a unified electronic database spatially referenced on real terrain. Sagintayev and Kerimkulov (2017) proposed the development of GIS databases for managing natural hazards and disasters (eg floods and mudflows). The development of an operational, accessible, georeferenced database system or information platform in Kazakhstan that stores and presents data would enable efficient operational decisions facilitating the work of disaster relief agencies and decision-makers and would be useful to practitioners and researchers.

A digital database containing information on and relevant to mudflows has been developed using data from long-term monitoring by the Kazakhstan State Agency for Mudflow Protection (KSAMP) known in Kazakhstan as Kazselezaschita. This article presents an interactive database for the central part of the Ile Alatau, where GLOF and non-GLOF (glacial, pluvial, hybrid, seismic, anthropogenic, etc) mudflows have been registered. These often occur throughout the mountainous and foothill regions of Central Asia. The functionality, structure, and design of the database can be expanded to the whole of Central Asia.

Study area, materials, and method development

Study area

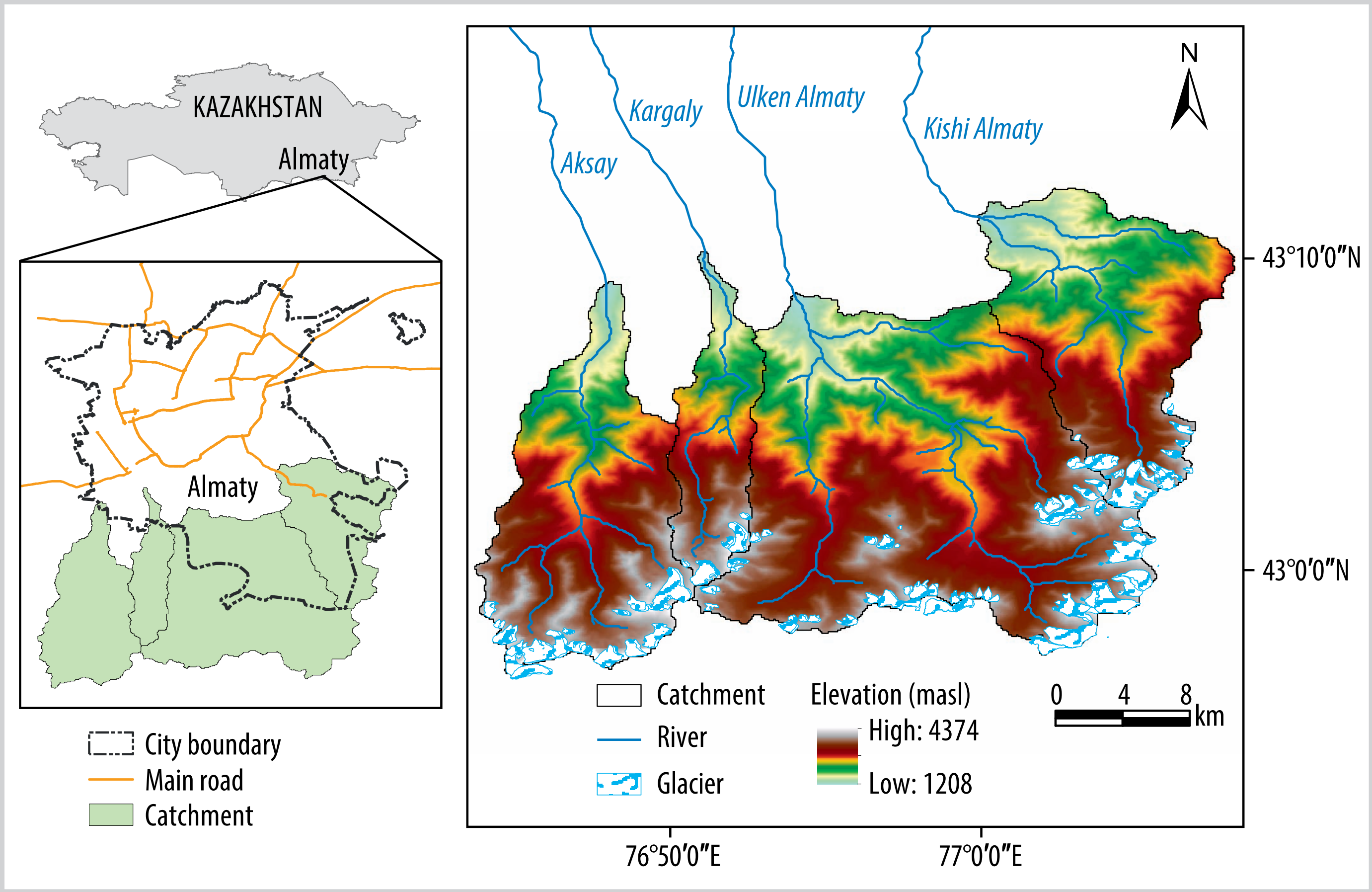
The Ile (Zailiyskiy) Alatau is a mountain range in the northwestern Tien Shan extending for 360 km along the border between Kazakhstan and Kyrgyzstan (Figure 1). The river basin geology in the mountains is represented by granites and porphyries mostly covered with Quaternary sediments, which are the predominant solid component of mudflows (Parker 2000). The region is characterized by strong seasonal variations in temperature and precipitation, and the mudflow season extends from May to September when temperatures are above freezing. The central part of the Ile Alatau is the most mudflow-prone region of Kazakhstan. Mudflow activity in the study area is related to seismic, glaciological, and hydrometeorological conditions. In the study area, mudflow phenomena are among the most active exogenous processes that can abruptly alter the topography and morphology of the mountain river basins.

Almaty, Kazakhstan's largest city with 1.8 million people (Agency for Strategic Planning and Reforms of the Republic of Kazakhstan Bureau of National Statistics 2021), lies in the foothills of the central Ile Alatau. Although settlements and economic development in this area are expanding because of its favorable climate, water resources, and attractive mountain environment, it is vulnerable to mudflows. Almaty is located on the fan of mudflows, and both its suburbs and city center have been devastated by mudflows, for example, in 1921, 1956, 1973, 1977, 1999, 2006, and 2015. The valleys of all 4 mountain rivers flowing through the city—Kishi Almaty, Ulken Almaty, Kargaly, and Aksay (Figure 1)—are characterized by high mudflow activity (Medeu 2009). Their headwaters are in the glacierized area at an elevation of 3300–3400 masl, and the mountainous parts of the catchments, where mudflows develop, occupy 1083 km^2 of the northern slope of the Ile Alatau.

Steep gradients allow mudflows to propagate into the populated foothills. The Kishi Almaty is particularly high risk because of its steep channel (Yafyazova 2012). Most of the city of Almaty is situated on the Kishi Almaty's mudflow fan (Yafyazova 2007).

About 50 cases of mudflows were recorded during the 20th century in the Kishi Almaty and Ulken Almaty river

FIGURE 1 Study area. Maximum and minimum elevations correspond to heights of river catchments in the highlands and a mudflow protection structure that is nearest to Almaty, respectively.



basins; 5 of these were catastrophic and caused considerable damage. The most devastating mudflow occurred in 1921 in the Kishi Almaty catchment because of heavy rainfall. The mudflow, traveling along the Kishi Almaty channel, caused enormous damage to Almaty, whose population at the time was 45,000, and killed more than 500 people. The total volume of the mudflow was estimated to be 10×10^6 m^3 and its maximum discharge reached about 900 m^3/s. A record amount of solid material (more than 3×10^6 m^3) was carried down the mountains and through the city (Medeu et al 2020).

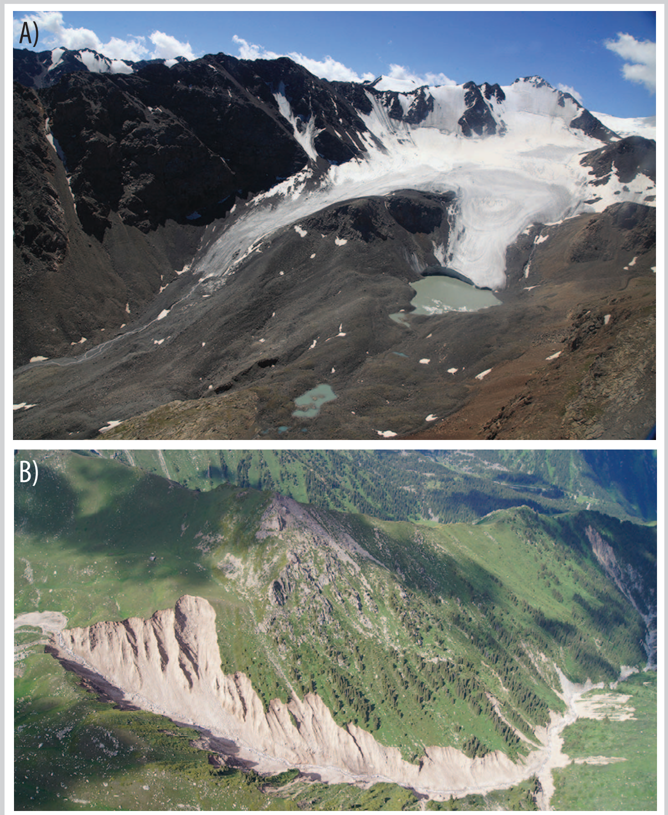
In the Ulken Almaty catchment, the most devastating mudflow occurred in 1950 and resulted from heavy rainfall. It caused severe damage to property and infrastructure in the river catchment. The maximum discharge was estimated to be 1000 m^3/s (Baymoldayev and Vinokhodov 2007).

More recently, in 2015 and 2019, mudflows in the Kargaly river basin resulted from prolonged positive anomalies in summer air temperature. In 2015, a 150,000-m^3 mudflow reached the point where the river exits the mountains and is stopped by a protective dam. However, the flood after the mudflow, discharged through the unregulated locks at a flow rate of 30 m^3/s, eroded the old mudflow deposits on the fan below the dam. As a result, a secondary mudflow developed, which passed through Karagayly village and damaged 456 houses, destroyed 7 bridges and 27 power transmission pylons, and necessitated the evacuation of more than 1000 people from the danger zone (Medeu et al 2015).

Historical mudflow data

The first information about mudflow phenomena in Kazakhstan was published by Mushketov (1890), who described mudflows caused by an earthquake in 1887. Descriptions of the catastrophic mudflow formed in the Kishi Almaty river basin in 1921 have been published by several researchers (Korzhenevsky 1921; Gorodetsky 1936; Medeu et al 2016). This event prompted the organization of a mudflow observation network in the region. The established monitoring became more systematic in 1929, when the Kazakh Meteorological Bureau was established under the Kazakh Autonomous Soviet Socialist Republic, and in 1931, when the meteorological bureau merged with the hydrological bureau. The activities of the hydrometeorological service focused primarily on observations of, research on, and warning about mudflows. During the 1970s–1980s, mudflow research increased, led by the Kazakh National Institute of Hydrometeorological Research. The observation network expanded significantly and the Main Mudflow Protection Service was formed (Baymoldayev and Vinokhodov 2007). Materials on mudflow monitoring and research on past mudflows were published in the form of scientific papers and technical reports, forming an extensive archive. Following the collapse of the Soviet Union, there was a sharp decline in the 1990s in mudflow research, and the network of mudflow observations declined too. Since the beginning of the 21st century, the

FIGURE 2 Mudflow formation centers. (A) Glacial mudflow center: moraine lake in the Ulken Almaty river basin, 23 July 2017. (B) Pluvial mudflow center: gully in the Ulken Almaty river basin, 30 July 2015. (Photos by Zhanar Raimbekova)



mudflow monitoring network has continued to function and is run by KSAMP.

Historical data on mudflow occurrences over more than 100 years in the river basins of the city of Almaty, collected and archived by KSAMP, were analyzed to develop an interactive database. This record was complemented with data from field studies from the last 30 years. The previous data were mostly available in Soviet archives and were primarily localized in situ data. During the investigation period from 1931 to 2020, about 282 pluvial mudflow events and 103 glacial mudflows were observed in the study area.

Remote sensing data on mudflow formation centers

Sections of mountain river basins where conditions for mudflow formation occur are called mudflow centers (Perov 2003). Clastic sedimentary rocks accumulate in the mudflow center, concentrating runoff and creating sufficient bias for the development of shear or transport-shear mudflow processes and thereby for the formation of high-density mud (debris) flows.

Analysis of the KSAMP database allowed us to characterize the genesis and type of mudflows in each basin (eg glacial or pluvial), identify mudflow centers, suggest mechanisms for mudflow initiation, and estimate the volume and frequency of mudflows.

Due to a lack of high-resolution digital elevation model (DEM) data for the central part of the Ile Alatau, terrain information was obtained in this study by digitizing the 1/5000 scale contours on the aerial and ground survey photos. With aerophotogrammetry and onsite measurements of the terrain over the period 1970–2018, information at an accuracy 1/1000 was obtained by the KSAMP services.

Helicopter reconnaissance was used to photograph and video record the study area on 30 May 2019 and 14 August 2020. These observations were supplemented using repeat satellite imagery analysis to identify mudflow features, such as mudflow formation centers, changes in glacial lake size, and riverbed scouring. Landsat TM and ETM+ satellite images with a resolution of 30 m were used in mudflow formation center delineation. We applied a well-established semiautomated approach using the TM3/TM5 band ratio to generate the outlines. Misclassified areas, such as snow patches, cast shadows, and lakes, were corrected manually using false-color composite (TM bands 5, 4, and 3) on the Landsat imagery. All images were obtained for cloud-free conditions and for the ablation period when the extent of snow cover was minimal to reduce potential uncertainly in the mudflow center boundary delineation because of seasonal snow cover. Changes in the extent of mudflow centers were assessed using images from 2019 and 2020 and analyzed according to their surface area.

Changes in the number of mudflow centers that occurred because of climate change in mudflow catchments from the glacial cirques to the mudflow fan zone were consistently evaluated, and new centers were identified based on satellite imagery and field research.

Research methodology

GIS technology provides a set of programs that enable mapping, systematization, and analysis of spatial data. The creation of a database on mudflow phenomena will allow interested organizations and services to obtain up-to-date and interactive information on mudflow phenomena in the central part of Ile Alatau as a digital template. The cartographic unit of this interactive system is the mudflow center, which is where information on mudflow phenomena is stored on the interactive map in the database system. In this work, mudflow centers are divided into 2 types. Moraine–glacial lakes and grottoes are classed as centers of glacial mudflows and GLOFs. Gullies and potholes were taken as the centers of pluvial mudflows (Figure 2).

The research methodology consisted of the following steps:

- Collection of data on registered and recovered mudflow phenomena in Kazakhstan and mudflow centers, according to the criteria of location (with obligatory indication of GPS coordinates), typology by genesis, and relief shape;
- Creation of a digital map of mudflow centers identified through aerial photographs taken by the Kazakh Hydrometeorological Research Institute in the 1970s;
- Identification of new mudflow centers based on satellite images and field studies;
- Determination, using remote sensing data, of the main morphometric characteristics of mudflow centers (ie width, length, depth, area, and volume of loose clastic sediments).

Analysis of mudflow data: determining parameters of glacial and pluvial mudflows

Determining GLOF parameters: The maximum discharge $Q_{\max}$ likely in the event of a lake breakthrough was estimated using the Popov (1986) method in Equation 1 and the Haeberli (1983) method in Equation 2.

$$Q_{\max} = 0.0048 \times V^{0.896} \quad (1)$$

$$Q_{\max} = {}^{2}V/_{t} \quad (2)$$

where V is the volume of water in the lake in cubic meters, and t is the time equal to 1000 seconds.

The discharge value according to Equation 2 assumes the worst-case scenario of a breakthrough due to a sharp overflow of the lake because of the collapse of rocks, a glacier, an avalanche collapse into the lake, or a landslide. Equation 1 was obtained based on the dependence of the maximum flow rates on the volumes of breakthrough floods in the Ile Alatau.

For lakes where no bathymetric survey has been carried out, the volume of lake water was estimated based on its empirical dependence on the area of the lake water surface (Kapitsa et al 2018), obtained from 37 bathymetric surveys for the period 2011–2020:

$$V = 0.229 \times F^{1.290} \quad (3)$$

where F is the lake water surface in square meters.

Calculating probabilistic maximum characteristics of pluvial mudflows: Maximum flow characteristics of rarely recurring pluvial mudflows are calculated using reduction formulas and formulas of limiting intensity for various values of expected precipitation (RussianGost 2003). The calculations are based on the reduction dependence of the maximum runoff modulus on the underlying factors that determine it: the average height of the catchment area, the flood runoff layer, and so forth. The formula for determining the daily maximum flood runoff modulus is as follows:

$$q_{1\%} = \frac{r \times A_{1\%} \times \delta}{(F+1)^{n}} \quad (4)$$

where r is the coefficient of flow regulation by lakes and reservoirs, $A_{1\%}$ is a value proportional to the maximum inflow modulus, δ is a coefficient considering the influence of forest cover and waterlogging of the catchment area, F is the catchment area enclosed by the desired section in km^2, and n is the exponent characterizing the reduction (decrease in the flood risk coefficient depending on the catchment area).

Their values were obtained using the coefficient of transition from $Q_{1\%}$ (the daily maximum discharge with a provision of 1%) and $H_{1\%}$ (the maximum daily precipitation layer with a provision of 1%) to discharge and precipitation layers with other provisions.

To calculate the daily maximum discharge of rainfall floods in the rivers of Almaty, a formula limiting the intensity of runoff was applied:

$$Q_{1\%} = 16.67_{\varphi\psi_{\tau}} H_{1\%} F \quad (5)$$

where φ is the combined coefficient of maximum flow, ψ_{τ} indicates the reduction of precipitation intensity for the τ calculated time, $H_{1\%}$ is the maximum daily precipitation layer with a provision of 1%, and F is the catchment area in km^2.

Stages of database creation

The database uses 3 basic concepts: base map, cartographic unit, and descriptive information.

- Base map and additional layers: The base map is built on the Shuttle Radar Topography Mission DEM of the study area. It can be changed by selecting a topographic map of the area, or OpenStreetMap. Other layers, such as zero isotherm, glaciers, rivers, catchments of different orders, moraine lakes, and mudflow centers, can be added.
- Cartographic unit (main unit on the map): This shows mudflow centers of (1) pluvial genesis, such as gullies, potholes, and centers of dispersed mudflow formation. and (2) glacial genesis, such as moraine lakes (if it is possible to identify them by type), intramoraine channels, and niches.
- Descriptive information of mudflows centers: Symbols on the map link to more in-depth information on the mudflows.

The different types of geographical reference data can be conveniently represented by GIS tools as a system of graphical, textual, and media files with hyperlinks to a larger interactive map. The complex data structure and its larger data volume require intuitive and user-friendly visualization. In this work, we used the updated, interactive, intelligent information system NextGIS Quantum GIS (QGIS) software platform and environment (GIS-Lab.info). QGIS Desktop (under the name NextGIS QGIS) is included in the Unified Register of Russian Computer Programs and Databases (NextGIS 2020). However, it is not the original but rather a modified version with extended functionality created by a Russian company. The map base can be created from vector data (area maps and city plans), remote sensing data (space and aerial survey materials), fieldwork data (geodetic and navigation measurements), and other sources.

Creating a QGIS project with raster and vector layers allows adaptable styles, grouping, and hierarchy and visibility settings. After successfully importing the project into NextGIS, a web map with the defined extents appears.

Every hyperlink on the web map includes the following: (1) attributes, (2) description of mudflow centers or moraine lakes, and (3) attachments (Figure 3). The attributes contain information on the name and/or number of the mudflow center, coordinates, basic morphometric characteristics, and statistical parameters. The attachments include media files, with the hydrometeorological situation described for a specific date, obtained during both ground and aerial surveys.

The high-level GIS approach is summarized in the flowchart in Figure 4. As can be seen from the figure, setting up the proposed system consists of 5 steps that require input data on the status of mudflow centers, followed by output data in steps 6 and 7. The figure shows what kinds of data are required for the first 5 steps of creating the system:

1. Construct a GIS inventory of historical data and assessing the hazard level of the different mudflow centers based on measurable criteria.

FIGURE 3 Structure of the database on mudflows.

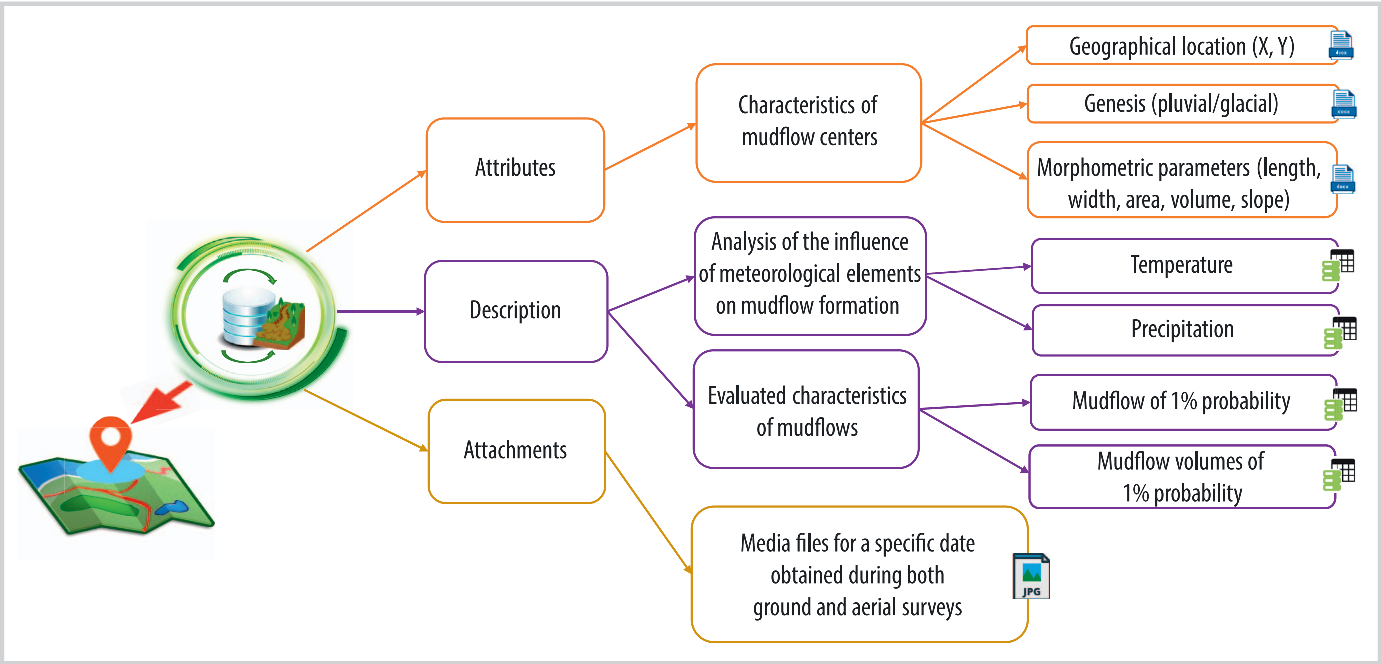
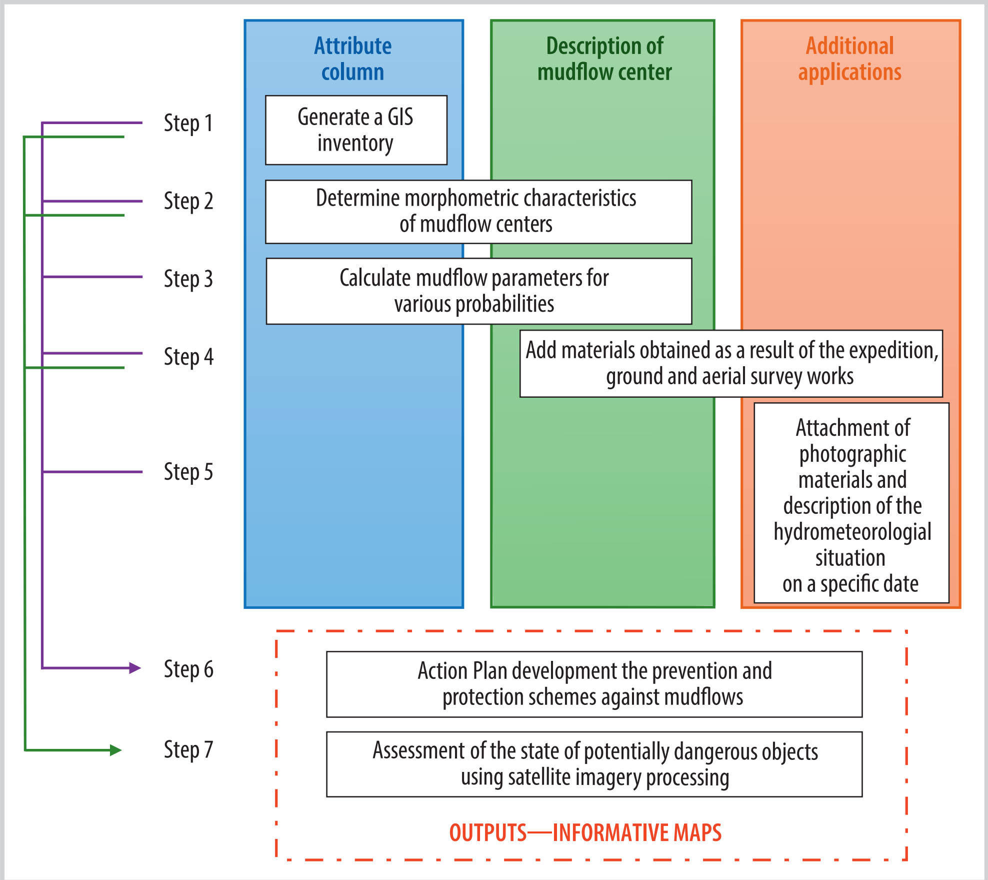


FIGURE 4 Steps to establish the interactive, intelligent information system on mudflow hazards and risks.



2. Add current state data on the underlying surface and the morphometric characteristics of the mudflow centers determined based on satellite images to ascertain the capacity and type (category) of mudflows.
3. Add new and refined morphometric characteristics of the mudflow centers to estimate parameters of mudflow at different probabilities of occurrence (eg catastrophic and rare mudflows) and their probability of occurrence. In

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this step, the spatial (ie geographical) variability of mudflow center locations, probability of formation, and expected mudflow parameters are taken into account, in combination with the geospatial inventory of archived data.

4. Add materials obtained as a result of expeditions, fieldwork, and aerial surveys, which provide information about mudflow formation centers.
5. Add the results of field and aerial surveys, which provide information on the hydrometeorological situation on a specific date, illustrated by photographs. This facilitates the identification of hotspots of mudflow formation and passage.

The output data in steps 6 and 7 (ie action plan and informative maps) are obtained from these steps (Figure 4). The database allows an action plan for mudflows to be developed with prevention and protection schemes. It also allows the state of potentially dangerous objects to be assessed using satellite imagery processing for hard-to-reach places where field and aerial surveys are not possible.

The creation of an interactive information system requires continuous computer processing of the data on mudflow phenomena. This is mainly done using a statistical method for processing and analyzing the data. The proposed steps to create a computer database work best for a region of interest when published information has been previously digitized.

Results

The interactive system described earlier has produced a first analysis of the patterns of mudflow hazards and risks (Figure 5):

- An interactive map of mudflow centers in the central part of the Ile Alatau, which indicates new, potentially dangerous mudflow centers identified by remote sensing data. The mudflow centers in the central part of the Ile Alatau are distributed as follows: Of the total number of mudflow centers, 19% are in the midlands, 9% are in the lowlands, and 34% and 38% are steep-slope highlands and rocky-glacial highlands, respectively.
- Refined morphometric data (length, width, depth, area, volume, and slope) on mudflow centers, with images of the sources obtained during field research. During the analysis of the results, a regularity of the distribution of mudflow types in various mountain belts was revealed. Mudflows occurring in the highlands are the most powerful and catastrophic. High-density mudflows formed in the midlands are usually smaller, which is associated with a decrease in the stock of friable material and sometimes with a decrease in slopes and better afforestation and saturation of the slopes. Low-density mudflows are most often distributed in the lowlands and sometimes within the middle mountains.
- The limiting values of the probable maximum water flow rates for each mudflow center in the study area are established to predict the formation of mudflows.
- Estimated characteristics (mudflow and mudflow-forming flood discharges, mudflow mass and mudflow-forming flood volume, velocity, density, level or height of mudflow billow, diameters of grain composition, duration, and distance of mudflow passage) for previously recorded mudflows.
- Retrospective review of past mudflows in the studied basins, indicating dates, centers, formation factors (genesis), mechanism of origin (types), capacity, damage caused, and availability of mudflow protective structures and monitoring systems.

On an interactive map of this system, where the cartographic unit is the mudflow center, all of the preceding information is associated with centers by a system of hyperlinks that provide relevant information in dialog windows with systematized data on glacial (blue circles) and pluvial (pink circles) mudflow centers (Figure 5). The cursor can be moved to obtain all of the preceding information for another center. This demonstrates the simplicity and convenience of using the proposed system.

Discussion and lessons learned

One of the main principles of data organization is interconnection between elements of the system, which makes it easy for both specialists and nonspecialists to navigate it. One of the advantages of this system is that it is easily updated. All mudflow-related information should be collected during aerial and field surveys and recorded in the system by specialists. During the mudflow danger period, the system can be supported with satellite images, which provide accurate information about the current state of mudflow centers of both glacial and pluvial genesis.

The development of such a system is complex, long, and labor intensive. It involves 3 important stages:

- Conceptual: collecting, analyzing, and editing data requirements;
- Logical: transforming data requirements into data structures;
- Physical: defining data storage features, access methods, and so forth.

In the global database system, there is still no international consensus on best practices for collecting data that can provide information on mudflow events, despite its evident importance.

The interactive map should contain the following:

- Search functions and advanced search information;
- Highlighting and clipping functions to select a study area, basin, or territory;
- Data-saving functions for one mudflow center or its groups.

The availability of these functions increases the practical significance of the proposed system and makes it an effective tool for decision-makers. Because the decision-makers assessing mudflow hazard and risk in Kazakhstan are KSAMP specialists who have access to daily monitoring data about mudflow-prone areas, only they will update and support the database.

Several GIS programs are used to visualize the data: QGIS is a platform with an interface that allows users to manually add labels to relevant items. The platform is heavily based on ArcGIS. In addition, the use of ArcGIS Pro allows complete

FIGURE 5 Fragment of the updateable, interactive, intelligent information system.

information about the mudflows to be obtained with a single click because of the dashboard function.

A disadvantage of the established interactive system is the scarcity of data on which the meteorological conditions for the formation of mudflows were analyzed. In the study area, data from only 2 functioning meteorological stations were available. However, the stations do not fully reflect the hydrometeorological situation in the area. A solution to this is the use of the Climatic Research Unit Time Series (CRU TS; Harris et al 2020; CRU and NCAS 2022). CRU TS provides publicly available data on the mean monthly temperature in the near-surface layer of the atmosphere and monthly precipitation totals for $0.5° \times 0.5°$ grid nodes. Processed data from this array will help to identify meteorological factors in the formation of mudflows, increase the accuracy of the hydrometeorological information, and improve the quality of mudflow forecasts.

Conclusions

A database based on GIS technologies on mudflow events and risks has been developed for the mountain regions of Central Asia. The structure and operating mode of the updateable, interactive maps provide a tool for managing mudflow risks. The creation of this intelligent information system for information on mudflow phenomena will provide a sound foundation for making prompt and effective decisions in the event of mudflow phenomena, thereby minimizing financial costs. The creation of a mudflow database will have economic and social effects. The database will reduce the financial costs of data collection and analysis in the development of mudflow risk management systems, and it will help to highlight the most effective methods of protection, ensuring the reduction of material damage from mudflows. The user-friendly and intuitive visualization will help to disseminate information among the population to increase awareness of mudflow threats. This will allow people to organize their own protection against the negative impact of mudflows and will reduce social tension. The information can be used to solve scientific and practical problems to reduce the vulnerability of the population and economic, cultural, and recreational infrastructure. Systematic data collection and visualization will allow new patterns of mudflow formation to be identified and methods to be improved for calculating and forecasting mudflows and protecting against them. The system will help to integrate scientific data into the decisions made about mudflow prevention, mitigation, and adaptation and therefore contribute to the sustainable development of mountainous and foothill areas. The template we have developed is applicable to other regions at risk of mudflows in Kazakhstan and Central Asia where the formation of glacial and pluvial mudflows of various types is being observed and recorded.

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