JOURNAL OF WATER AND LAND DEVELOPMENT

e-ISSN 2083-4535

Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2025.156048
2025, No. 67 (X–XII): 156–162

Morphological and morphometric analysis of debris flow sites using satellite imagery in the Ile Alatau Mountains, Kazakhstan

Yuisya Lyy*[1)], Yerkebulan Khalykov[1)], Akhmetkal Medeu[1)], Maulen Togys[1)], Tatyana Kirenskaya[1)], Kuralay Orazbekova[1), 2)], Aidana Kamalbekova[2)]

[1)] Institute of Geography and Water Security, Seifullin Ave 458/1, 050000, Almaty, Kazakhstan

[2)] Al-Farabi Kazakh National University, Faculty of Geography and Environmental Sciences al-Farabi Ave., 71/19, 050040, Kazakhstan

* Corresponding author

RECEIVED 03.04.2025 ACCEPTED 03.09.2025 AVAILABLE ONLINE 12.12.2025

Highlights
- In the Ile Alatau Ridge, 86 debris flow sources were identified.
- Morphometric characteristics of debris flow sources were determined.
- A map of debris flow sources was compiled.
- A classification of debris flow sources was developed.

Abstract: Debris flows in mountainous regions around the world pose a significant threat to human lives, infrastructure, and local ecosystems. The study of the morphology and morphometry of debris flow sites is essential for assessing debris flow hazards and developing protective measures. The paper examines methods for interpreting debris flow sites using satellite imagery in the Ile Alatau Range of the Northern Tien Shan (Kazakhstan). Mapping of debris flow sites was carried out through manual interpretation of Google Earth images in the most debris flow-prone basin of the Ulken Almaty River. Morphometric characteristics of 86 debris flow sites were determined using ArcGIS software. Distributions of the debris flow sites by area, length, slope, and altitude were obtained. The area of the sites ranges from 0.2 to 4.7 km^2. The distribution shows a pronounced positive skew. Site lengths vary from 640 to 7,500 m and their distribution is also strongly positively skewed. The mean slope of the debris flow sites ranges from 6° to 33° and shows significant negative skewness. The altitude of the sites ranges from 1,300 to 3,860 m a.s.l., with a weakly negative skew in distribution. Approximately 70% of the debris flow sites are located within the elevation zone of 2,000–3,500 m a.s.l. The study demonstrated the high effectiveness of remote sensing methods for mapping and inventorying debris flow sites. These data are used for debris flow hazard assessment and the development of protective measures. The proposed methodology can be applied in other mountainous regions of Central Asia.

Keywords: debris flow sites, debris flows, morphometric parameters, Northern Tien Shan, space image interpretation

INTRODUCTION

Debris flows are short-lived but highly intense hydrological processes characterised by the rapid movement of a mixture of water, debris (ranging from fine particles to large boulders), and soil along ephemeral channels or mountain slopes under the influence of gravity. These flows typically occur during intense rainfall, rapid snow and ice melt, seismic events, rock mass failures, or dam breaches in valleys with abundant loose debris (Kozlovsky, 1984). Debris flows are among the most destructive

© 2025. The Authors. Published by Polish Academy of Sciences (PAN) and Institute of Technology and Life Sciences – National Research Institute (ITP – PIB).
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/)

natural hazards in mountainous regions (Hürlimann, Rickenmann and Graf, 2003; Adhikari and Koshimizu, 2005; Xu *et al*., 2012; Cui *et al*., 2013; Sepúlveda *et al*., 2015).

Kazakhstan ranks among the leading countries of the former USSR in terms of the activity and magnitude of debris flow occurrences. Approximately 13% of the country's territory (360,000 km^2) is exposed to the formation and destructive impact of this hazardous exogenous process. Over 900 debris flow basins have been identified across Kazakhstan, where more than 2,000 debris flows have been recorded since 1841, including over 10 catastrophic events (Medeu *et al*., 2016). The mountain regions of the Ile Alatau are particularly prone to debris flow activity.

The formation of debris flows is controlled by orographic, tectono-geomorphological, geological-lithological, soil-vegetation, anthropogenic, and especially hydrometeorological conditions (Sergeyeva, Volobuyeva and Krivosheyeva, 2012). The high mobility of debris flows allows them to travel at speeds exceeding 30 km·h^{-1}, transporting rock fragments over considerable distances due to their flow consistency (Iverson, 1997). As debris flows advance, they can erode material from the channel bed and banks, increasing both in volume and destructive capacity (Hungr, McDougall and Bovis, 2001).

Debris flow sites and glacial lakes play a key role in determining the dynamics, intensity, and spatial extent of debris flows in mountainous terrain. These sources are zones of accumulation of loose detrital material susceptible to mobilisation by external triggers such as intense precipitation, glacial melt, or seismic activity.

The role of glacial lakes in debris flow formation is linked to their instability; outbursts can release large volumes of water, which, when mixed with loose debris, initiate powerful debris flows.

Remote sensing methods significantly improve the accuracy of debris flow forecasting and the development of preventive strategies. Satellite technologies enable the monitoring of vast areas with high temporal resolution, making them indispensable tools for studying debris flow processes. Multi-year satellite data are particularly valuable for observing changes in terrain, tracking the dynamics of existing glacial lakes and debris flow sites, identifying new hazardous zones, and forecasting debris flow processes' development. Combined with GIS analysis and modelling, such methods provide broad opportunities for studying debris flow sites (Mussina and Zhanabayeva, 2016).

In recent decades, remote sensing technologies have revolutionised debris flow research, providing researchers with large-scale, continuous observations over extended time periods. Satellite and aerial imagery can be used to map debris flow pathways, identify vulnerable zones, and monitor changes in soil cover, debris flow sites, and glacial lakes that influence debris flow initiation.

The use of digital tools such as Geographic Information Systems (GIS), digital image processing, photogrammetry, and Global Positioning Systems (GPS) enables detailed investigation and monitoring of debris flows. Satellite imagery from Landsat and Sentinel-2 provides high-resolution data suitable for detecting vegetation changes and soil moisture variations that are early indicators of potential debris flow activity. Multi-temporal high-resolution data facilitates tracking of temporal changes, such as variations in vegetation, and detect early signs of potential debris flow activity, dynamics of moraine lakes, and transformations in debris flow sources. Remote sensing data can be combined with Digital Elevation Models (DEMs), meteorological and geophysical datasets to enhance understanding and prediction of debris flow mechanisms.

Satellite imagery allows for detailed delineation of debris flow pathways and identification of the key factors of their formation. For example, Landsat imagery can be employed to monitor mountain slope degradation and potential debris flow hazard zones. In recent years, the application of multispectral satellite data analysis has improved the accuracy of debris flow sites classification (Guzzetti *et al*., 2012).

Debris flow interpretation is a complex process involving comprehensive analysis of natural factors contributing to debris flow formation, based on aerial and satellite data (Medeu *et al*., 2018). Methods of debris flow interpretation using multitemporal and multi-scale remote sensing data have been described in studies by R. Khonin (1976), Sadov (1972), and Golubev and Labutina (1966). Interpretation of debris flow processes based on Earth observation data is a fundamental method for their mapping, enabling the identification, delineation, and characterisation of debris-related landforms and deposits, considering the landscape context (Stupin, Plastinin and Olzoev, 2020). As a result, the main components of the debris flow system can be identified, including initiation zones, transit zones, and deposition areas.

The primary goal of this study is to apply satellite-based interpretation methods for analysing debris flow sites. In recent years, satellite imagery has been widely used for monitoring hazardous natural processes, enabling the identification of initiation zones and potential flow paths of debris flows.

MATERIALS AND METHODS

MATERIALS

The research was conducted in the basin of the Ulken Almaty River, located on the northern slope of the Ile Alatau Ridge, a part of the Northern Tien Shan. The Ile Alatau Range is located in the southeast of the Republic of Kazakhstan. It stretches along 43°N for 140 km from 76 to 78°E. The foot of the range is located at an altitude of 900–1,000 m a.s.l, and the main watershed is at an altitude of 4,000–4,300 m a.s.l. This area is characterised by mid- and high-mountain terrain, featuring glaciers, moraine deposits, and steep mountain slopes subject to intensive erosion. The hydrological regime of the river is governed by seasonal snow and glacier melt, as well as by intense precipitation, creating a high debris flow hazard. The climate is sharply continental, with cold winters and hot summers, accompanied by significant daily and seasonal temperature fluctuations. The geological structure of the basin is mainly composed of metamorphic and sedimentary rocks prone to weathering and the formation of debris flows. Due to active tectonics and high seismicity, the Ulken Almaty River basin is vulnerable to natural disasters, including earthquakes and glacial lake outburst floods, both of which are major triggers of debris flows. The study area is characterised by a high concentration of debris flow sites and glacial lakes, which serve as key contributors to debris flow initiation.

Debris flow activity in the Ulken Almaty River basin has a long history (Mussina *et al*., 2024). The earliest documented

© 2025. The Authors. Published by Polish Academy of Sciences (PAN) and Institute of Technology and Life Sciences – National Research Institute (ITP – PIB).
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/)

event dates back to 1841, when a powerful mud and debris flow swept through the valleys of the Kishi and Ulken Almaty Rivers, destroying everything while moving (Gorbunov and Severskiy, 2001). In 1887, a major earthquake (with 9–10 points intensity) triggered extensive debris flows in the Ile Alatau (Mushketov, 1890). One of the most catastrophic events occurred on 8–9 July 1921, when debris flows affected almost all rivers in the Ile Alatau, transporting an estimated 7–10 mln m^3 of material (Gorodetskiy, 1936). The mud and debris flow devastated much of Almaty, taking the lives of over 500 people.

Later, on 8 July 1950, another debris flow was triggered by heavy rainfall, with 60 mm of precipitation recorded (Duisenov, 1971). In August 1977, a major debris flow was caused by a glacial lake outburst (Laptev, 1990). Over the course of a month, nearly 400 debris surges occurred along the Ulken Almaty River, with some individual surges reaching heights of 10–12 m and transporting boulders 5–6 m in diameter. In 2006, a rain-induced debris flow in the same basin destroyed two bridges and damaged a road (Yafyazova, 2007). In 2023, both pluvial and glacial debris flows were recorded. In 2024, debris flows were solely caused by intense rainfall events.

METHODS

The study used satellite imagery from Google Earth as well as data from the Shuttle Radar Topography Mission (SRTM) digital elevation model. Debris flow sites were interpreted using a combination of textural and spectral image characteristics. Morphometric parameters were assessed in ArcGIS software, enabling detailed analysis of the region's geomorphological features. The following types of debris flow sites were identified: debris gullies, incision zones, and dispersed debris-forming sites. Debris flow sites were classified by low-, mid-, and high-mountain altitudinal zones.

The interpretation methodology relied on the comparison of multi-temporal satellite images, which allowed for the assessment of dynamic changes in debris flow sites. The integration of satellite imagery, digital elevation models, and image analysis algorithms improved the accuracy of debris flow sites mapping.

Debris flow sites were identified on satellite images based on distinctive interpretation signatures across various spectral bands. Google Earth and Landsat imagery were used in this study. Google Earth provides access to Landsat images (30 m or 15 m resolution in panchromatic mode), orthophotos (0.5–2.0 m resolution), and other high-resolution commercial satellite data. The work used images from October 16, 2023 to June 6, 2024 with a resolution of 5–30 m·pix^{-1}.

During the interpretation process, the geographic coordinates and elevations of topographic features were determined to define the spatial location and boundaries of debris flow sites and their geomorphological structure. Relief information in Google Earth is based on digital elevation models from the Shuttle Radar Topographic Mission (SRTM) (30 or 90 m resolution) or NOAA's Global Land One-km Base Elevation Project (GLOBE) (Wang, 2017).

To determine the morphometric characteristics of debris flow sites, SRTM elevation data with 24 m resolution (http://dwtkns.com/srtm) were processed in ArcGIS software to extract thalweg lines of debris flow channels.

The area of each debris flow site was calculated using the "Create Polygon" tool, where each site was digitised individually as a polygon layer.

Based on the DEM, longitudinal slope profiles, maximum site altitude, site length, site mouth altitude, mean site slope, and thalweg lines were derived and digitised.

Field methods are based on determining the boundaries of mudflow sites, mudflow channels, and mudflow deposits. To implement field methods, scale rulers, measuring tapes, clinometers, laser rangefinders, and global positioning systems were used. Field work was carried out in 2023–2024.

RESULTS AND DISCUSSION

The identification of debris-prone areas using satellite imagery primarily relies on recognising traces of past debris flows. Debris deposits that fill widened sections of river valleys or form alluvial fans at the foot of mountain gorges are most readily interpreted. Fresh deposits lacking vegetation appear bright or nearly white on imagery, whereas older deposits, covered with soil and vegetation, exhibit darker tones. Ancient debris deposits are often partially eroded and overgrown. In vegetated terrain, debris flow sites are distinguishable by contrasting colours ranging from light yellow to white (Fig. 1).

Debris flow sites, channels, incised areas, and flow paths were identified and mapped using Google Earth and ArcGIS resources (Figs. 2, 3). Zoom tools were used to adjust the view when the observer's height was insufficient to detect debris flow sites.

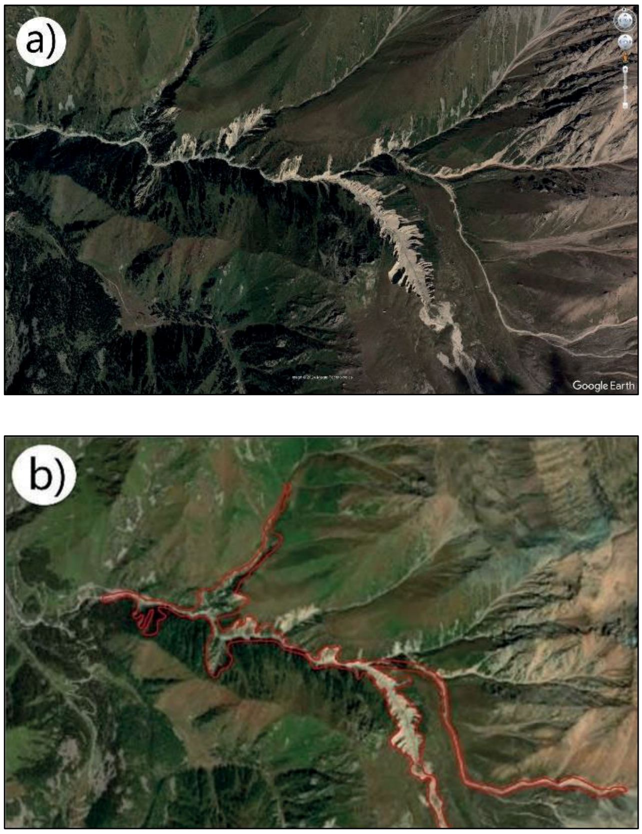

Fig. 1. A debris flow source in the Kumbelsu Gorge: a) the satellite imagery (source: Google Earth Pro), b) mudflow source borders (source: own elaboration based on ArcGIS Online)

© 2025. The Authors. Published by Polish Academy of Sciences (PAN) and Institute of Technology and Life Sciences – National Research Institute (ITP – PIB).
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/)

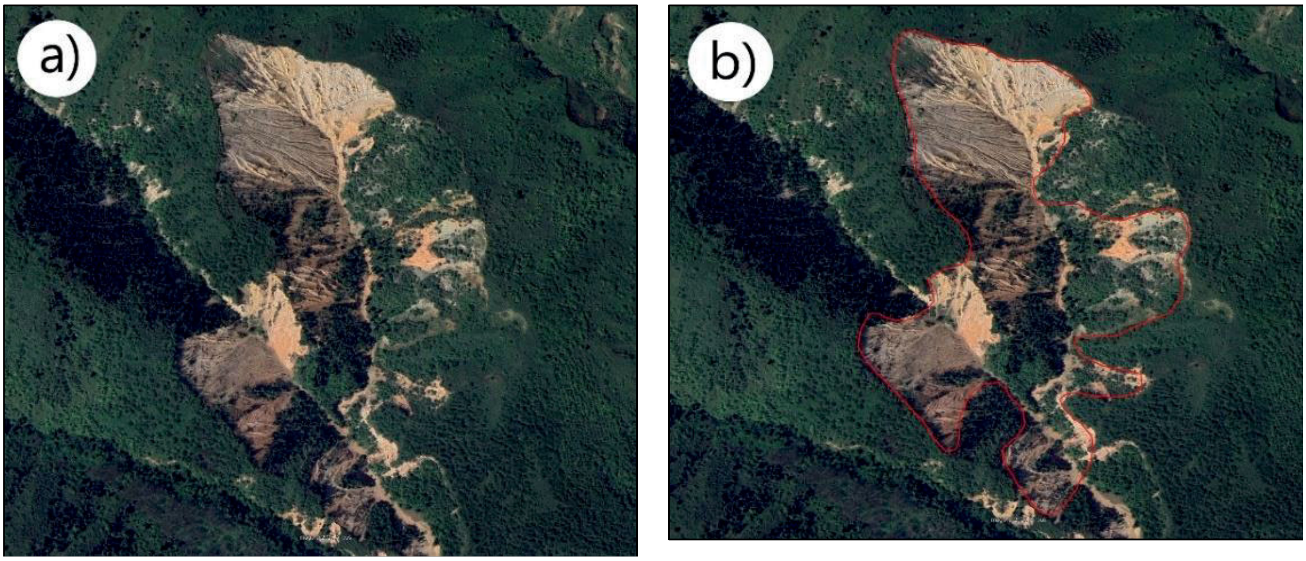

Fig. 2 . Dispersed debris-forming sources in Kokshukyr Gorge: a) the satellite imagery (source: Google Earth Pro), b) mudflow source borders (source: own elaboration based on ArcGIS Online)

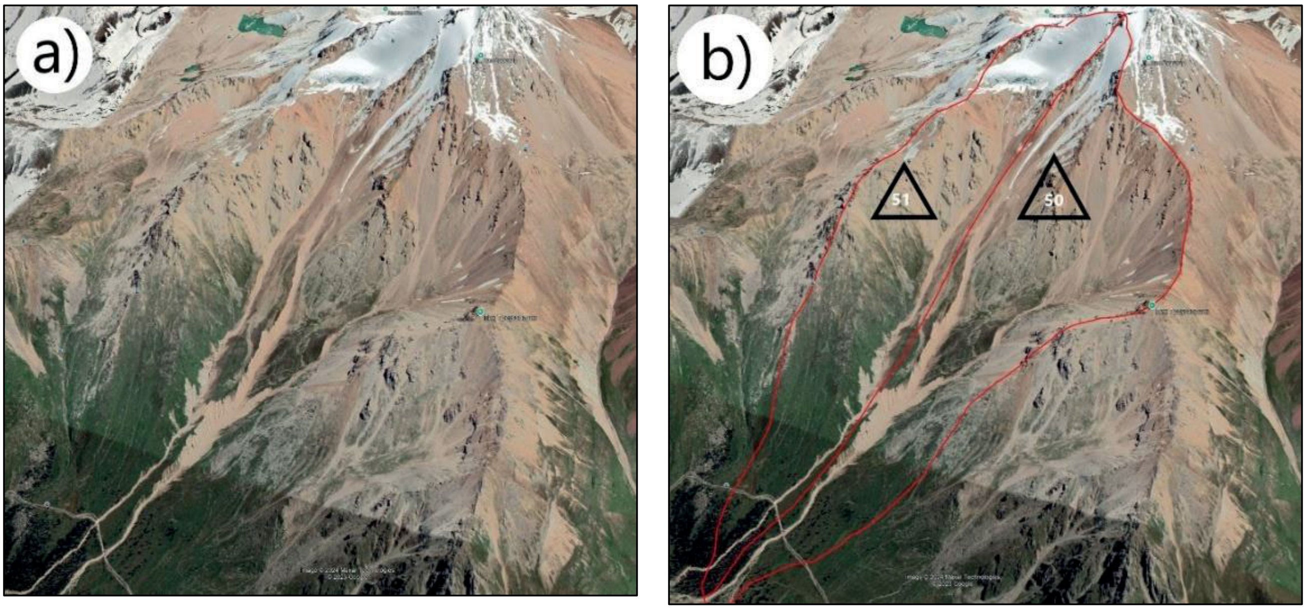

Fig. 3 . Debris flow sources and channels in the Ozernaya River basin: a) the satellite imagery (source: Google Earth Pro), b) mudflow source borders and numbers (source: own elaboration based on ArcGIS Online)

Dispersed debris-forming sources are steep, eroded slopes composed of unconsolidated deposits, from which surface runoff concentrates into linear flow channels (Yafyazova, 2007). On satellite imagery, these sources appear as bright-coloured polygons against a dark background of vegetated surroundings (Fig. 2). Erosional grooves extending from ridge crests to the base of the slopes are clearly visible.

Debris gullies represent negative landforms carved into slope deposits (Yafyazova, 2007). They exhibit a linear morphology, ranging in length from 500 to 800 m, with depths up to 10 m and slope gradients between 15° and 35°.

A characteristic feature of debris flow channels (Fig. 3) includes accumulations of debris deposits in the form of ridges and terraces, as well as sections of deep and lateral erosion (Perov, 1996).

The resulting polygonal and linear layers were converted into a file suitable for further processing in ArcGIS software. The integration of Google Earth data into ArcGIS made it possible to obtain the morphometric characteristics of 86 debris flow sites (Tab. S1) and to develop a debris flow site map for the Ulken Almaty River basin (Fig. 4). Parts of complex mudflow sources, consisting of several simple sources, are marked on the map with a number with letter or digital indices.

Debris flow sites were divided by size into 6 classes depending on their area (F) and length (L): very large (area $F > 2.0$ km^2, length $L > 2.0$ km), large ($F = 1.0$–2.0 km^2, $L = 1.5$–2.0 km), big ($F = 1.0$–1.5 km^2, $L = 1.0$–1.5 km), medium ($F = 0.5$–

© 2025. The Authors. Published by Polish Academy of Sciences (PAN) and Institute of Technology and Life Sciences – National Research Institute (ITP – PIB).
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/)

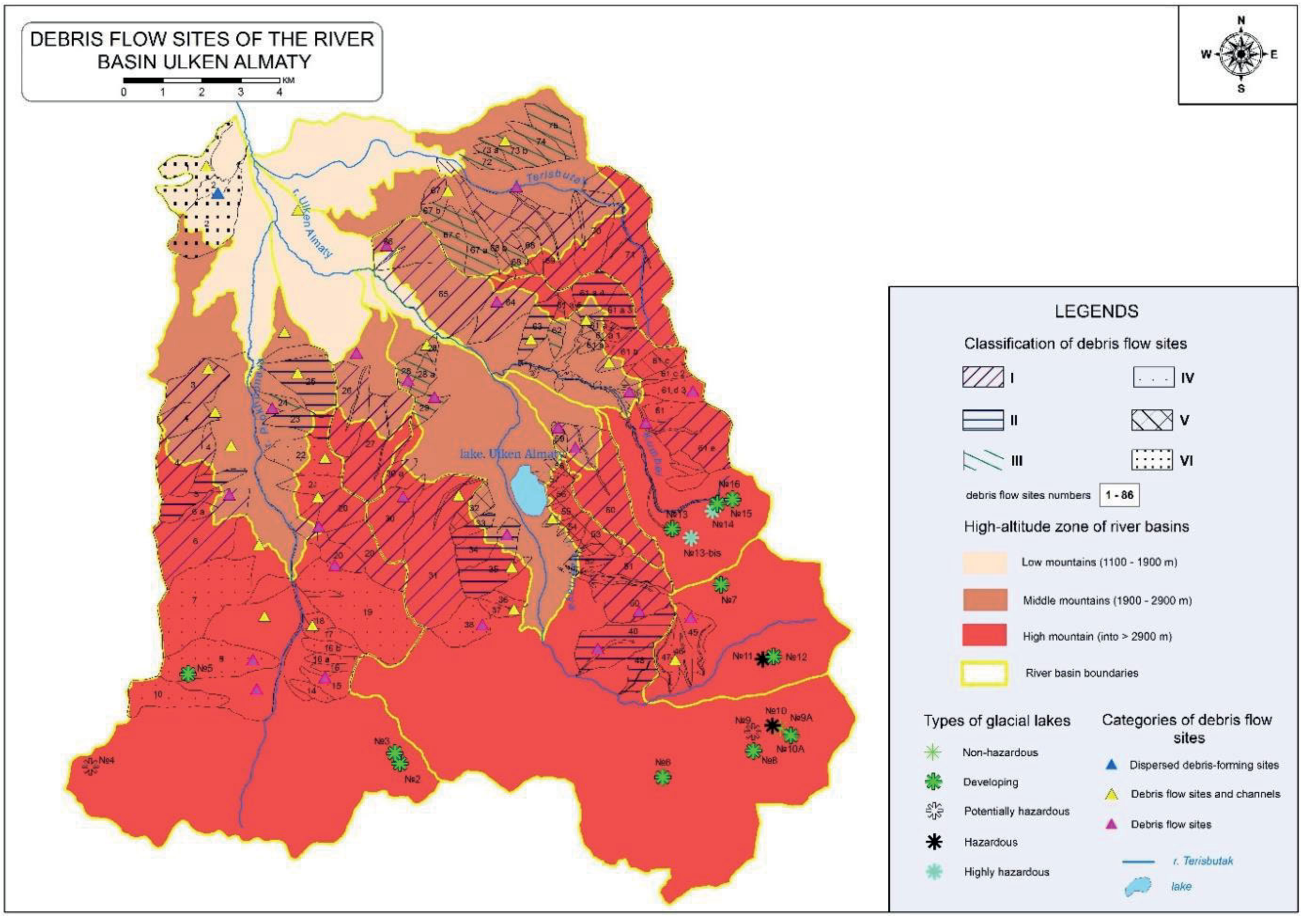

Fig. 4. Debris flow sources map of the Ulken Almaty River basin; I = very large, II = large, III = big, IV = medium, V = small, VI = very small; source: own elaboration based on ArcGIS Online

1.0 km^2, L = 0.5–1.0 km), small (F = 0.2–0.5 km^2, L = 0.5–1.0 km), very small (F < 0.2 km^2, L < 0.5 km).

All debris flow sites were classified into three categories based on altitude: low-mountain, sites (below 1,900 m a.s.l.), mid-mountain sites (1,900–2,500 m a.s.l.), and high-mountain sites (>2,500 m a.s.l.).

Debris flow power, expressed as volume (V) and maximum discharge (Q), is shown on the map by coloured triangles. According to these indicators, debris flows are divided into three categories, according to Medeu, Baymoldayev and Kirenskaya (2016): small (V < 10 thous. m^3, Q < 50 m^3·s^{-1}), medium (V = 10–100 thous. m^3, Q = 50–200 m^3·s^{-1}), and large (V > 100 thous. m^3, Q > 200 m^3·s^{-1}). Debris flow volumes and discharges were determined based on historical data, field research materials, or calculations using the methodology described in Musina *et al.* (2023).

Glacial lakes were mapped as a point layer and categorised into five classes: non-hazardous, developing, potentially hazardous, hazardous, and highly hazardous. When determining the category of the lake, the criteria proposed in the work (Zapparov *et al.*, 2023) were used. The size of the lake and the condition of the dam were taken into account.

The image interpretation resulted in the identification of 86 debris flow sources in the Ulken Almaty River basin, and their key morphometric characteristics were determined. Histograms of the distributions of these characteristics are presented in Figure 5.

The debris flow site areas vary from 0.2 to 4.7 km^2. The distribution of this parameter has a pronounced positive skew. The most common sites are 0.2–0.4 km^2. The distribution of the debris flow site lengths also has a strong positive skewness. It varies from 640 to 7,500 m. The most common sites are 800–1,000 m long. The mean slope of the debris flow sites varies from 6° to 33°. The distribution of this parameter is bimodal and has a negative skew. The most common sites are slopes of 17–18°. The distribution of the maximum altitude of debris flow site also has a negative skewness. The majority of the sites are located between 2,500 and 3,900 m a.s.l.

The distribution of debris morphometric parameters have a great impact on the debris flow hazard of the area. The maximum volumes and discharges of rain debris flows depend on the area of the site and maximum daily precipitation (Mussina *et al.*, 2023). Therefore, the distribution of debris flow parameters should also have a positive skewness, which is confirmed by historical data (Medeu *et al.*, 2019).

Since the amount and intensity of precipitation in Ile Alatau increase with altitude, the maximum sizes and frequency of rain debris flows are observed in the altitude zone of 2,500–3,500. Above 3,500, the activity of rain debris flows decreases due to a decrease in the proportion of liquid precipitation, but the activity of glacial debris flows increases due to the appearance of glacial lakes (Medeu *et al.*, 2019). These features should be taken into account when mapping mudflow hazard.

© 2025. The Authors. Published by Polish Academy of Sciences (PAN) and Institute of Technology and Life Sciences – National Research Institute (ITP – PIB).
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/)

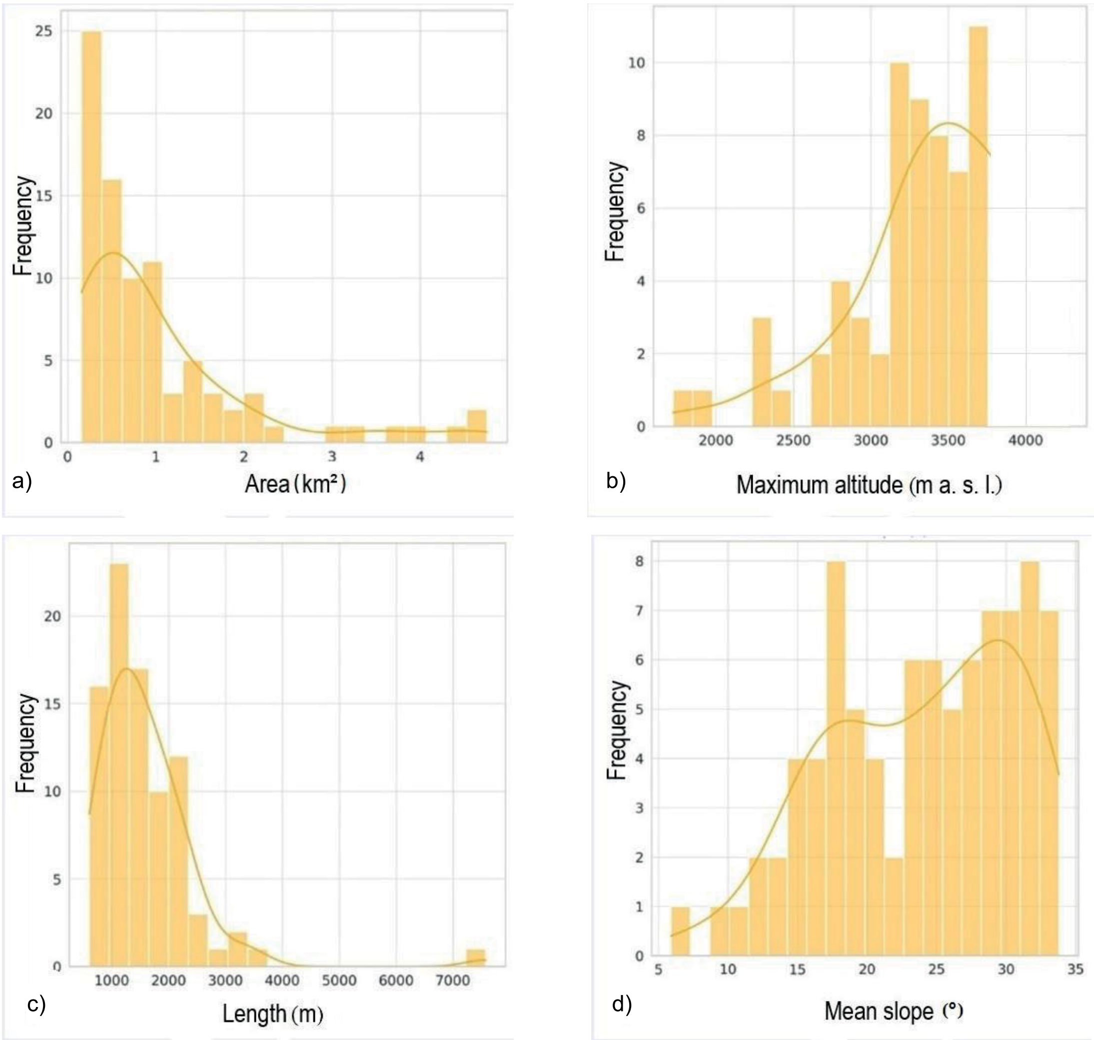

Fig. 5. Histograms of key morphometric characteristics of debris flow sources: a) area, b) maximum altitude, c) length, d) mean slope; source: own study

CONCLUSIONS

Satellite image interpretation is an effective tool for the inventory, mapping, and determination of morphometric parameters of debris flow sites. The main interpretation features of debris flow sites are colour, saturation, and image texture on satellite images. To study the dynamics of debris flow processes, multi-temporal imagery can be used. High-quality results can be obtained from Google Earth imagery using the SRTM digital elevation model and ArcGIS software.

In the mountainous regions of the Northern Tien Shan (Zhetysu Alatau, Ile Alatau, and Kungey Alatau), the distributions of the area and length of debris flow sites are characterised by strong positive skewness, while the distributions of slope and altitude show moderate negative skewness. These features are important for assessing debris flow hazards in the region, including estimating flow volumes, discharges, and recurrence intervals.

For calculating peak discharges of rainfall-induced debris flows, data on the area and altitudinal position of debris flow sites, along with regional relationships between maximum daily precipitation and altitude, can be used. The reliability of precipitation data is the main limiting factor for the use of satellite imagery in debris flow hazard assessment in climatically understudied mountainous regions.

Given that the area distribution of debris flow sites has a positive skew, and considering the increase in site area and precipitation with altitude, a positively skewed distribution of maximum volumes and discharges of debris flows and their increase with elevation should be expected. This is confirmed by long-term debris flow monitoring data in the Ile Alatau. Positive skewness in size distributions is generally characteristic of many hazardous natural phenomena.

FUNDING

This research has been funded by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. BR21881982).

SUPPLEMENTARY MATERIAL

Supplementary material to this article can be found online at: https://www.jwld.pl/files/Supplementary_material_67_Lyy.pdf.

© 2025. The Authors. Published by Polish Academy of Sciences (PAN) and Institute of Technology and Life Sciences – National Research Institute (ITP – PIB).
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/)

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

REFERENCES

Adhikari, D.P. and Koshimizu, S. (2005) "Debris flow disaster at Larcha, upper Bhotekoshi Valley, central Nepal," *The Island Arc*, 14(4), pp. 410–423. Available at: https://doi.org/10.1111/j.1440-1738.2005.00495.x.

Cui, P. *et al.* (2013) "Debris flows resulting from glacial-lake outburst floods in Tibet, China," *Physical Geography*, 31(6), pp. 508–527. Available at: https://doi.org/10.2747/0272-3646.31.6.508.

Duisenov, E.D. (1971) *Debris flows in the Zailiyskiy Alatau*. Alma-Ata: Izd. Kazakhstan.

Golubev, G.N. and Labutina, I.A. (1966) "Deshifrirovaniye seley v gornykh rayonakh s ispol'zovaniyem aerofotosnimkov [Interpretation of debris flows in high mountain regions using aerial photographs]," *Vestnik Moskovskogo Universiteta*, 1, pp. 48–53.

Gorbunov, A.P. and Severskiy, E.V. (2001) *Seli okrestnostey Almaty: Vzglyad v proshloye [Debris flows in the vicinity of Almaty: A look into the past]*. Almaty: Izdatel'skiy tsentr "Interlig".

Gorodetskiy, V.L. (1936) *Prichiny Almaatinskoy katastrofy 8 iyulya 1921 goda [Causes of the Almaty catastrophe of July 8, 1921]*. Alma-Ata: Knigo-zhurnal'naya tipografiya NKMP.

Guzzetti, F. *et al.* (2012) "Landslide inventory maps: New tools for an old problem," *Earth-Science Reviews*, 112(1–2), pp. 42–66. Available at: https://doi.org/10.1016/j.earscirev.2012.02.001.

Hungr, O., McDougall, S. and Bovis, M.J. (2001) "Entrainment of material by debris flows," in *Debris-flow hazards and related phenomena*. Berlin, Heidelberg: Springer, pp. 135–158. Available at: https://doi.org/10.1007/3-540-27129-5_7.

Hürlimann, M., Rickenmann, D. and Graf, C. (2003) "Field and monitoring data of debris-flow events in the Swiss Alps," *Canadian Geotechnical Journal*, 40(1), pp. 161–175. Available at: https://doi.org/10.1139/t02-087.

Iverson, R.M. (1997) "The physics of debris flows," *Reviews of Geophysics*, 35(3), pp. 245–296. Available at: https://doi.org/10.1029/97RG00426.

Khonin, R.I. (1976) *Rukovodstvo po izucheniyu selevykh potokov [Manual on the study of debris flows]*. Leningrad: Gidrometeoizdat.

Kozlovsky, E.A. (1984) "*Opolzni i seli [Landslides and debris flows]*," Vol. 1. Moskva: Tsentr mezhdunarodnykh proyektov Gosudarstvennogo komiteta po nauke i tekhnike.

Laptev, V.I. (1990) "Opisaniye selevogo potoka 3–4 avgusta 1977 g. v basseynakh rek Kumbelsu i Bolshoy Almatinki [Description of the debris flow of August 3–4, 1977 in the Kumbelsu and Bolshaya Almatinka River Basins]," *Selevye potoki*, 5, pp. 55–59.

Medeu, A.R., Baymoldayev, T.A. and Kirenskaya, T.L. (2016) *Seli v yugo-vostochnom Kazakhstane. Antologiya seley i ikh izucheniye [Mudflows in South-East Kazakhstan: Anthology of mudflows and their research]*. Almaty, Kazakhstan: Nauka.

Medeu, A.R. *et al.* (2018) *Selevye yavleniya yugo-vostochnogo Kazakhstana. Vol. 2, p. 2.* Osnovy monitoringa v Ile Alatau [*Debris flow phenomena in southeastern Kazakhstan: Monitoring principles in the Ile Alatau*. Almaty: Institut geografii. Available at: https://www.debrisflow.ru/wp-content/uploads/2020/02/V.2_Part_2_Medeu_Blagovechshenskiy_Baimoldayev_Kirenskaya_Stepanov_2018.pdf (Accessed: March 13, 2018).

Medeu, A.R. *et al.* (2019) "Debris flow activity in Trans-Ili Alatau in the 20th–early 21st centuries," *Geography and Natural Resources*, 40, pp. 292–298. Available at: https://doi.org/10.1134/S1875372819030120.

Mushketov, I.V. (1890) "Vernenskoye zemletryaseniye 28 maya (9 iyunya) 1887 g. [The Verny Earthquake of May 28 (June 9), 1887]," *Trudy geolokogicheskogo komiteta*, 10(1). Sankt Peterburg: Geologicheskiy komitet.

Mussina, A. *et al.* (2024) "Assessment of the current state and temporal changes of glacial-moraine lakes in the Central and Eastern part of the northern slope of the Ile Alatau, Kazakhstan," *Journal of Water and Land Development*, 63, pp. 19–24. Available at: https://doi.org/10.24425/jwld.2024.151786.

Mussina, A.K. *et al.* (2023) "Mountain resilience: A tool for mudflow risk management in the Ile Alatau mountains, Kazakhstan," *Mountain Research and Development*, 43(1), pp. D1–D10. Available at: https://doi.org/10.1659/MRD-JOURNAL-D-22-00004.

Mussina, A.K. and Zhanabayeva, Z.A. (2016) "GIS-technology in the management of mudflow risk," *KazNU Bulletin Geography Series*, 1(42), pp. 140–146. Available at: https://bulletin-geography.kaznu.kz/index.php/1-geo/article/view/293 (Accessed: March 10, 2025).

Perov V.F. (1996) *Selevye yavleniya: terminologicheskiy slovar' [Mudflow phenomena: A glossary of terms]*. Moscow: MGU.

Sadov, A.V. (1972) *Aerometody v izuchenii seley [Aerial methods in debris flow research]*. Moscow: Nedra.

Sepúlveda, S.A. *et al.* (2015) "Debris flows in the Andean ranges of central Chile and Argentina triggered by 2013 summer storms: characteristics and consequences," *Landslides*, 12, pp. 115–133. Available at: https://doi.org/10.1007/s10346-014-0539-0.

Sergeyeva, G.A., Volobuyeva, L.L. and Krivosheyeva, E.A. (2012) "Chrezvychaynye situatsii, svyazannye s selyami na severnom Kavkaze [Emergency situations associated with debris flows in the North Caucasus]," *Inzhenernyy vestnik Dona*, 4-1(22), p. 161. Available at: http://www.ivdon.ru/magazine/archive/n4t1y2012/1154 (Available at: March 10, 2025).

Stupin, V.P., Plastinin, L.A. and Olzoev, B.N. (2020) "Ispol'zovanie dannykh distantsionnogo zondirovaniya Zemli pri srednemasshtabnom geoinformatsionnom kartografirovanii selevoy opasnosti Baykal'skoy gornoy strany [Remote sensing data for debris flow hazard mapping of the Baikal-Amur Mainline station section]," in S.S. Chernomorets and K.S. Viskhadzhieva (eds.) *Selevye potoki: katastrofy, risk, prognoz, zashchita [Mudflows: disasters, risk, forecast, and protection]*. Trudy 6-i Mezhdunarodnoy konferentsii (Dushanbe–Khorog, Tadzhikistan). T. 1. Dushanbe: OOO «Promoushn», pp. 541–552. Available at: https://www.debrisflow.ru/wp-content/uploads/2020/12/Stupin_DF20.pdf (Accessed: March 10, 2025).

Wang, Y. *et al.* (2017) "Google Earth elevation data extraction and accuracy assessment for transportation application," *PLoS ONE*, 12(14), e0175757. Available at: https://doi.org/10.1371/journal.pone.0175756.

Xu, Q. *et al.* (2012) "The 13 August 2010 catastrophic debris flow after 2006 Wenchuan earthquake, China," *Natural Hazards and Earth System Sciences*, 12, pp. 201–216. Available at: https://doi.org/10.5194/nhess-12-201-2012.

Yafyazova, R.K. (2007) "Priroda seley [Nature of debris flows]," in *Priroda seley Zailiyskogo Alatau*. Nature of debris flows in the Ile Alatau: Adaptation problems. Almaty: Ministerstvo okhrany okruzhayushchey sredy Respubliki Kazakhstan, Respublikanskoe gosudarstvennoe predpriyatie «Kazgidromet».

Zapparov, M.R. *et al.* (2023) *Kriterii proryvoopasnosti lednikovo-morennykh ozer [Criteria for glacial-moraine lake outburst hazard]*. Almaty: Mektep.

© 2025. The Authors. Published by Polish Academy of Sciences (PAN) and Institute of Technology and Life Sciences – National Research Institute (ITP – PIB).
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/)