DEBRIS FLOWS: Disasters, Risk, Forecast, Protection

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灾害、风险、预测、防治

會議記錄

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Conference logo is based on a figure from S.M. Fleishman’s book on Debris Flows (Moscow: Geografgiz, 1951, p. 51).

Mapping the territories of the mountain-foothill zone of Tajikistan exposed to natural hazards

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Abstract. In recent years, debris flows have emerged as a significant threat to infrastructure and lives in Tajikistan, with their frequency and severity on the rise. This study focused on analyzing hazardous natural phenomena, specifically debris flows, in the mountain-foothill zone of Tajikistan between 2020 and 2023. Monitoring and research were conducted using a QC-2 Micro UAV and a DJI Phantom 4 quadcopter. Aerial photographic techniques were employed in various districts, revealing the destructive impact of debris flows. Furthermore, changes in the study area were observed through pre- and post-event Sentinel-2 images using the Normalized Difference Water Index (NDWI) and Normalized Difference Vegetation Index (NDVI) techniques to assess the effectiveness of automatic detection of debris flow-prone areas. The study identified 49 districts and cities in Tajikistan affected by debris flows during the study period, with an estimated 30.2 million US dollars in damages. Notable changes were observed in Khuroson, Tojikobod, and Lakhsh districts, where significant alterations were detected using both NDWI and NDVI. The study also revealed that the foothills zones primarily experience rain-induced debris flows, while the mountain zones are characterized by rain-snow-induced and glacial-induced mudslides triggered by outbursts of glacial lakes. The composition of the debris flows in the six studied areas was mostly clay, with some areas covered by mud-stone, and a few places with a mixture of clay and mud-stone. Integrating UAV and remotely sensed technologies provides crucial data for analyzing damage, identifying vulnerable areas, informing emergency response efforts, and is also imperative for disaster risk management in Tajikistan.

Key words: *disaster, debris flows, remote sensing, unmanned aerial vehicles, Tajikistan*

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Картографирование территорий горно-предгорной зоны Таджикистана, подверженных опасным природным явлениям

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Аннотация. В последние годы сели превратились в серьезную угрозу инфраструктуре и жизни людей в Таджикистане, причем их частота и серьезность растут. Данное исследование было посвящено анализу опасных природных явлений, в частности селевых потоков, в горно-предгорной зоне Таджикистана в период с 2020 по 2023 г. Мониторинг и исследования проводились с использованием беспилотного летательного аппарата QC-2 Micro и квадрокоптера DJI Phantom 4. В различных районах были применены методы аэрофотосъемки, позволяющие выявить разрушительное воздействие селей. Кроме того, изменения в исследуемой зоне наблюдались с помощью изображений Sentinel-2 до и после события с использованием методов нормализованного разностного индекса воды (NDWI) и нормализованного разностного индекса растительности (NDVI) для оценки эффективности автоматического обнаружения районов, подверженных селевым потокам. В ходе исследования были выявлены 49 районов и городов Таджикистана, пострадавших от селей за исследуемый период, ущерб от которых оценивается в 30,2 млн долларов США. Заметные изменения наблюдались в Хуросонском, Тоджикободском и Лахшском районах, где значительные изменения были обнаружены как с помощью NDWI, так и с помощью NDVI. Исследование также показало, что в предгорных зонах в основном наблюдаются селевые потоки, вызванные дождем, в то время как для горных зон характерны дождевые, снежные и ледниковые оползни, вызванные прорывами ледниковых озер. Состав селевых потоков в шести исследованных районах был в основном глинистым, причем некоторые участки были покрыты глинобитом, а в нескольких местах – смесью глины и глинобитного грунта. Интеграция технологий беспилотных летательных аппаратов и дистанционного зондирования позволяет получать важные данные для анализа ущерба, выявления уязвимых зон, информирования об усилиях по реагированию на чрезвычайные ситуации, а также является необходимым условием для управления рисками стихийных бедствий в Таджикистане.

Ключевые слова: *катастрофа, селевые потоки, дистанционное зондирование, беспилотные летательные аппараты, Таджикистан*

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Introduction

Natural hazards, such as debris flows, earthquakes, and avalanches, collectively pose a significant threat to Tajikistan, leading to devastating consequences for both infrastructure and the regional population [*Scaini et al., 2024*]. The frequency and intensity of these disasters have been steadily increasing in recent years [*Fazylov et al., 2017a*], emphasizing the urgent need for robust monitoring and mitigation strategies [*IPCC, 2014*]. Tajikistan in particular, vulnerable to natural disasters, whereas debris flows accounting for a significant portion of the risk. Roughly 85% of the country's territory is exposed to debris flow dangers, with 32% falls within high-risk zones [*Fazylov et al., 2017b*].

In response to these challenges, researchers and specialists in Tajikistan have started harnessing cutting-edge technologies to map and assess natural hazards. Unmanned aerial vehicles (UAVs) and satellite imagery from platforms like Sentinel-2 have emerged as invaluable tools for monitoring and analyzing debris flow events, providing critical data for effective disaster management and emergency response. Sentinel-2, part of the European Space Agency's Copernicus program, offers multispectral, high-resolution imagery that enables detailed monitoring and analysis of environmental changes. Moreover, Sentinel-2 allows to obtain the Normalized Difference Water Index (NDWI) and Normalized Difference Vegetation Index (NDVI) techniques to observe changes through pre- and post-event scenarios. These indices, widely used in remote sensing applications, facilitate the evaluation of water bodies and vegetation cover, respectively, aiding in the automatic detection of debris flow-prone areas. Integrating high-resolution Sentinel-2 imagery with UAV data enhances the understanding of terrain dynamics and vulnerability assessments [*Medeu et al., 2018*] and allow to some extent minimize the damage, help organize the evacuation of the population from vulnerable areas and assess the extent of damage after debris flow events [*Musaeva et al., 2018*].

Understanding the role of climate factors such as increased rainfall and ice melting in high elevations is essential in comprehending the origins of debris flows in Tajikistan. Factors such as heavy rainfall, steep terrain, and loose soil or rock materials contribute to the occurrence of debris flows [*Xu et al., 2014; Bai et al., 2022*]. In mountainous regions like Tajikistan, the combination of high elevations and prevalent glaciers, along with intensified rainfall and accelerated ice melting due to climate change significantly heightens the risk of debris flows [*Mergili et al., 2012; Mustaeva et al., 2015*]. However, due to inaccessible surface topography and inhospitable climate condition, relying on high-resolution remotely sensed applications are the best available option to quantify such alarming environmental issues.

Enhancing management practices for high-risk natural disasters and advancing monitoring and assessment technologies are urgent priorities in the current landscape [*Stupin et al., 2020*]. Remote sensing technologies, including UAVs and platforms like Sentinel-2, play pivotal roles in emergency management, particularly during geological and hydrological disasters [*Tatham, 2009; Shvarev et al., 2020*].

Given the increasing risks posed by natural disasters, particularly debris flows, the primary objective of this research is to analyze natural disasters in Tajikistan from 2020 to 2023. Emphasis was placed on the vital role of modern technologies, such as UAVs and Sentinel-2 imagery, as well as utilizing available reports, conducting own fieldwork, and tapping into other resources. By utilizing high-resolution UAV images and techniques like NDWI and NDVI, the aim is to map and detect changes in debris flow-prone areas. The research seeks to examine the current state of debris flows in Tajikistan, evaluate their impact on the population and economy, and identify vulnerable areas at risk of natural disasters. It underscores the importance of technological innovation in enhancing resilience and response capabilities in Tajikistan.

Materials and methods

Analysis of natural disasters in Tajikistan (2020–2023)

To analyze natural disasters in Tajikistan from 2020 to 2023, primary data from reports of the Committee for Emergency Situations and Civil Defense under the Government of the Republic of Tajikistan (hereafter referred to as Emergency Committee), as well as other resources, were studied. Additionally, several intensive field visits were conducted in areas prone to natural disasters, and an annual analysis of statistical data on the frequency and types of natural disasters such as avalanches, debris flows, earthquakes, strong winds, heavy rains, rockfalls, landslides, increased water levels in reservoirs, thunderstorms were taken into consideration. The research methodology included the collection and analysis of data on the frequency and impact of natural disasters on various sectors of the economy and the population of Tajikistan, along with estimating financial damages.

UAV technology for disaster mapping and monitoring

Since the beginning of 2017, the Research Center for the Environment of Central Asia (based in Dushanbe), in collaboration with scientific institutions of the National Academy of Sciences of Tajikistan (NAST) and with support from the Emergency Committee, have utilized UAVs for monitoring natural hazards. Specifically, from 2020 to 2023, numerous UAV surveys were deployed to investigate debris flow sites in various regions, including the Khuroson district of the Khatlon region (May 2020), the Tojikobod region (August 2020), the Vakhsh district of the Khatlon region (May 2021), the city of Panjakent in the Sughd region (July 2021), Lakhsh district (August 2022), and Varzob district (August 2023) as illustrated in Fig. 1 and Table 1.

Monitoring activities focused on areas prone to debris flows and were conducted at different altitudes. For instance, the maximum flight altitude during the assessment of debris flow impacts in the Vakhsh district reached 684 meters above sea level, while for the Archakapa section in the Lakhsh district (the basin of the Baralmos glacier, currently called the Said Nafisi; Resolution of the Government of the Republic of Tajikistan, No.269, 2021), it was 6209 meters above from the mean sea level. Aerial photography requirements included transverse and longitudinal image overlap, as well as adjusting flight altitude based on the terrain characteristics of the area.

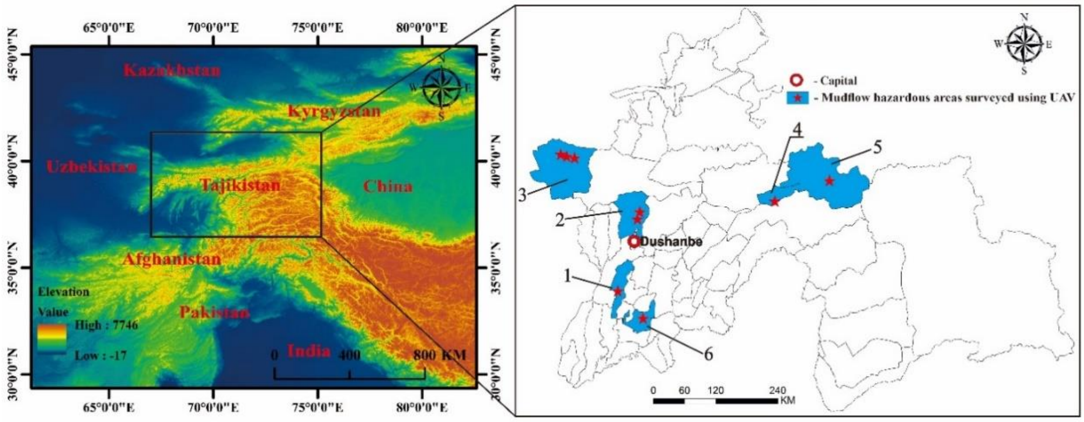


Fig. 1. Monitoring of debris flows in Tajikistan using UAVs in the period 2020–2023. Numbers are highlighting the place names accordingly (1 – Khuroson district, 2 – Varzob district, 3 – Panjakent city, 4 – Tojikobod district, 5 – Lakhsh district and 6 – Vakhsh district)

A DJI Phantom 4 quadcopter and a QC-2 Micro UAV with dimensions of 1.8m width and 1.1m length, equipped with a Sony RX1R camera and a flight time exceeding 1 h, were employed for aerial photography. The UAV field monitoring approach encompassed selecting optimal takeoff and landing sites, inspecting the study area for obstacles, completing pre-flight tasks, conducting aerial photography, monitoring UAV technical parameters, manually landing the UAV, and uploading images and POS data for processing. Flight altitude and image resolution were adjusted based on research objectives and natural conditions, with higher resolutions facilitating detailed investigation of debris flow elements and processes [*Safarov et al., 2021*]. To generate high-resolution orthophotos and digital elevation models, aerial photographs and POS data were processed using MS Excel and Pix4Dmapper [*Karamuz et al., 2020; Safarov et al, 2022*], and subsequently integrated into ArcGIS software for further analysis. Furthermore, combine all UAV images into a single spatial orthomosaics layer in the ArcGIS for analysis post-scenario of debris flow events, whereas high-resolution Google Earth images and Sentinel-2 datasets were utilized to check the pre-disaster condition [*Dokukin et al., 2021*].

Table 1. Debris flow-hazardous areas were investigated using UAVs in the period 2020–2023 and aerial photography parameters

Site name	District/city	Region/ districts of repub-lican subor-dination (DRS)	River basin	UAV type	Max. high flight, m a.s.l.	Ortho-mosaic resolu-tion, cm	Year
Ayni	Khuroson	Khatlon	Vakhsh	DJI Phantom, QC-2 Micro	1050	5.62	2020
Margh	Tojikobod	DRS	Vakhsh	QC-2 Micro	3300	9.33	2020
Ittifok	Vakhsh	Khatlon	Vakhsh		684	4.69	2021
Kishtudak	Panjakent	Sughd	Zeravshan		3513	18.6	2021
Vishist	Panjakent т	Sughd	Zeravshan		3308	17	2021
Archakapa	Lakhsh	DRS	Vakhsh	DJI Phantom, QC-2 Micro	6209	43	2022
Gusgarf	Varzob	DRS	Kafirnigan	DJI Phantom	1399	12.2	2023
50 km of the Dushan-be – Khujand highway	Varzob	DRS	Kafirnigan		1922	9.8	2023

Quantifying debris flow-prone areas using satellite image

Satellite datasets are indispensable tools for monitoring natural hazards like debris flows [*Atefi et al., 2022*]. In this study, the Sentinel-2 satellite imagery was utilized to analyze selected sites using the NDWI and NDVI to obtain vegetation health, density, and water body presence, which can influence debris flow risks within the study area. For instance, a decrease in NDVI values may signal vegetation stress or land cover changes, potentially heightening the debris flow risk.

The satellite data underwent preprocessing steps, including geometric corrections, and was further cross-validated with Google Earth images to ensure accurate analysis. For Sentinel-2 NDWI and NDVI values were calculated in ArcGIS using these following formulas:

$$\mathrm{NDWI} = \frac{(\mathrm{Green} - \mathrm{Near\ Infrared})}{(\mathrm{Green} - \mathrm{Near\ Infrared})}, \quad (1)$$

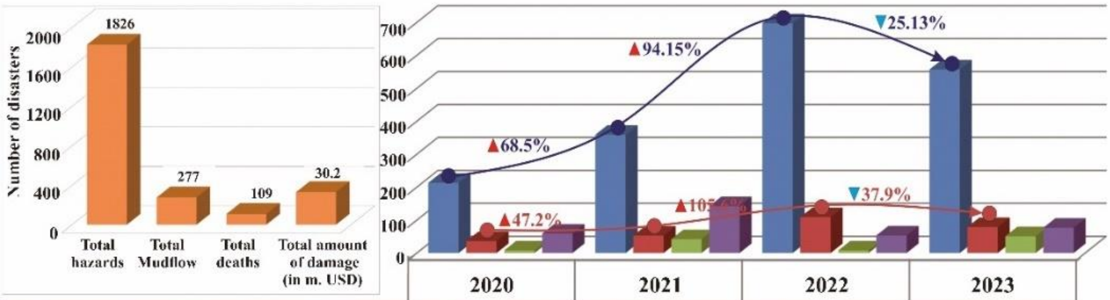
$$\mathrm{NDWI} = \frac{(\mathrm{NIR} - \mathrm{RED})}{(\mathrm{NIR} - \mathrm{RED})}. \quad (2)$$

Moreover, the study integrated Advanced Land Observing Satellite (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR) Digital Elevation Model (DEM) data with a resolution of 12.5 meters sourced from the Alaska Satellite Facility (ASF) Distributed Active Archive Center (DAAC) (ASF, 2023). This dataset was used to generate slope, aspect, and contour maps of the debris flow basins across the selected sites. Validation methods were employed to assess the accuracy of the derived indices and comparison with existing datasets. By incorporating these detailed methodologies, the study ensured a robust and comprehensive analysis of debris flow-prone areas using satellite and UAVs imagery.

Results and discussion

Natural disasters in Tajikistan for 2020–2023 using UAVs

The study reveals that natural disasters occur in Tajikistan almost in every year. Fig. 2 provides information on natural disasters in Tajikistan for the period from 2020 to 2023, observed nearly 1826 disasters were accompanied by casualties resulting in the death of 109 people. The maximum number of disasters in Tajikistan was noted in 2022, where it was gradually declined by 25.1% along with significant reduction of debris flow events up to 37.9% in 2023.



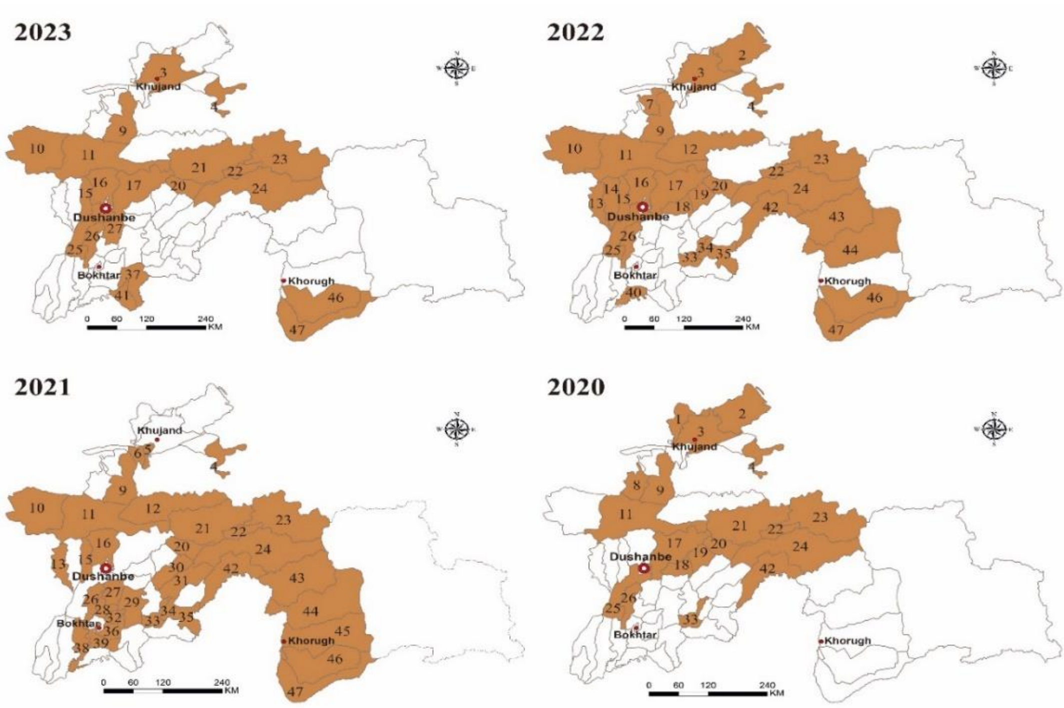
	2020	2021	2022	2023
Total disasters	213	359	697	557
Mudflows	36	53	109	79
Total deaths	8	42	8	79
Total amount of damage (in m. USD)	5.4	12.59	5.2	7.01

Fig. 2. Natural disasters in Tajikistan for the period 2020–2023

In 2020, 213 natural emergencies were registered, including 95 cases of avalanches, 36 cases of debris flows, 30 earthquakes, 21 strong winds, 9 heavy rains, 9 rockfalls, 6 landslides, 4 cases of rising water levels in reservoirs, and 2 cases of thunderstorms. Analysis of emergency situations in 2021 showed that 359 natural disasters were registered in Tajikistan, including 153 avalanches, 53 floods, 42 rockfalls, 40 strong winds, 33 earthquakes, 19 rises in water levels in reservoirs, 8 torrential rains, 7 landslides, 1 soil erosion with collapse, 1 severe cold, and 1 thunderstorm with lightning.

Regarding the situation in 2022, the number of natural disasters amounted to 697, a 94.2% increase from 2021, and the number of debris flows over the same period increased 2.1 times. In 2023, 48 out of 557 recorded natural emergencies in Tajikistan caused damage to the population and economy of the country amounting to around 7 million USD (Fig. 2). In 2020, the damage due to natural disasters and catastrophic events amounted to 5.4 million USD, of which debris flows individually accounted around 1,85 million USD. Over the past four years, the total amount of damage from natural phenomena reached 30.2 million USD.

Intensive and integrated evaluation of debris flow activity from 2020 to 2023 in Tajikistan is illustrated in Fig. 3. Considering the current situation, the implementation of modern monitoring technologies, including UAVs, in areas with risks of natural disasters, as well as methods for processing it, has allowed a comprehensive state-of-art of debris flow-prone areas and assessment of regional damage along with their consequences in various regions of Tajikistan for the period 2020–2023 (Fig. 4).



Sughd Region	Districts of Republican Subordination	Katlon region	Badakhshan Mountainous Autonomous Region
1- Mastchoh	13- Tursunzoda	26- Khuroson	42- Darvoz
2- Asht	14- Shahrinav	27- Yovon	43- Vanj
3- B. Gafurov	15- Hisor	28- A. Jomi	44- Rushon
4- Isfara	16- Varzob	29- Danghara	45- Shughnon
5- Rasulov	17- Vahdat	30- Baljuvon	46- Roshtqal'a
6- Spitamen	18- Faizobod	31- Hovaling	49- Ishkoshim
7- Istaravshan	19- Rogun	32- Levakand	
8- Shahristan	20- Nurobod	33- Vose'	
9- Gonchi	21- Rasht	34- Kulob	
10- Panjakent	22- Tojikobod	35- M.A. Hamadoni	
11- Aini	23- Lakhsh	36- Kushoniyon	
12- Maschohi kuhi	24- Sangvor	37- Farkhor	
	25- Rudaki	38- Dusti	
		39- J. Rumi	
		40- Jaihun	
		41- Panj	

- Capital
- Regional centers
- Districts and cities where mudflows were recorded

Fig. 3. Distribution of debris flows in Tajikistan for 2020–2023

Fieldwork included aerial photography of the consequences of debris flows in certain areas of the Khuroson district, Khatlon region, revealing flooded residential buildings and personal plots of local residents (Fig. 4*a*). In total, 338 residential buildings were damaged by debris flows and landslides, with 14 houses completely destroyed, a few houses are partially destroyed, and 12 houses dismantled by locals.

In the Shurak River basin in the Tojikobod district (Fig. 4*b*), rainfall and lake outburst-induced debris flows have been observed periodically, causing significant damage to the regional economy and, in some cases, to residential buildings. The debris flow prone area in this region has been gradually expanded, with changing the river course, and agricultural lands.

Investigation of the debris flow situation in the Vakhsh district (Fig. 4*c*) determined that 4 villages were damaged by the disaster. Operational data from the disaster response headquarters as of May 16, 2021, reported that 46 houses were completely destroyed, 43 houses were partially damaged, and 2.5 thousand hectares of land washed away along with the destruction of 5 bridges and roads due to the debris flow.

The research also covered the territory of the debris flow-prone area Veshist in Panjakent city (Fig. 4*d*). Visible changes after the debris flow, such as a destroyed bridge, debris flow deposits on a residential building's land, and the Zarafshan river bank, were observed in the Veshist village area. From 2013 to 2021, the area covered by debris flow deposits has increased, affecting the river's coastline due to the deposition of sediments stretching over 120 meters (Fig. 4*d*).

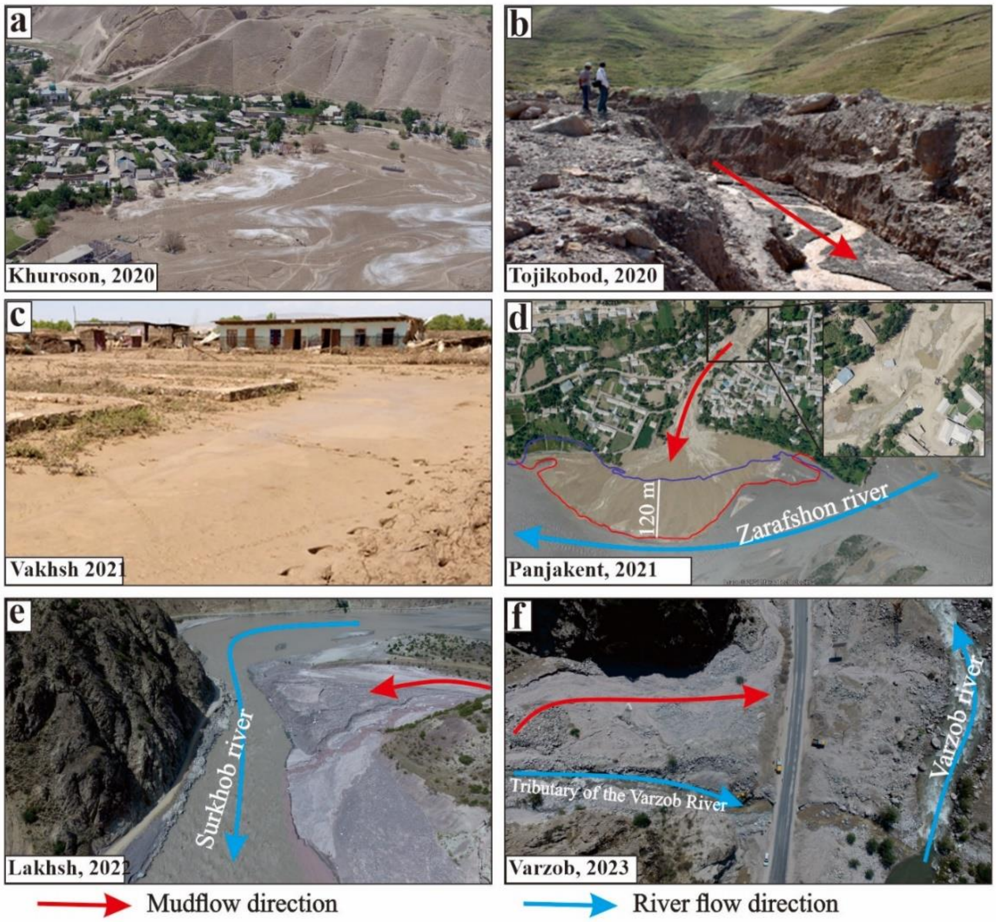


Fig. 4. Consequences of debris flow in various regions of Tajikistan for the period 2020–2023. Photo by M.S. Safarov

In the Lakhsh district (Fig. 4*e*), debris flows of various types and volumes have become more frequent on the slopes of the Peter the Great ridge in recent decades. In the lower reaches of the Baralmos glacier, debris flows form due to glacier melting and glacial lake outburst in the river basin of Archakapa. Such debris flows and outburst floods, spreading several kilometers down the valleys, have led to the destruction of the international highway and blockage of the river bed in the Surkhob (Fig. 4*e*).

Research also covered sections of the Dushanbe-Khujand highway prone to debris flows and avalanches, which mostly depend on the seasons. Aerial photography was conducted in the Gusgarf and 50 km sections in the Varzob district (Fig. 4*f*), revealing damage to houses, asserts or properties, vehicles, and the highway, with 15 cars buried under mud and debris after debris flow in August 2023.

Thus, through aerial photography, archival data study, and orography analysis confirmed that these areas are periodically susceptible to debris flows. Analyzing satellite images from Google Earth before the debris flow and comparing them with aerial photographs taken after the debris flow using UAVs revealed details of the destruction of several houses, the zone of debris flow formation, destroyed roads, and other damaged objects. Fig. 5 shows the results of mapping the study areas before and after the debris flow in the Khuroson (*a*, *b*, *c*) and Vakhsh (*d*, *e*, *f*) districts of the Khatlon region.

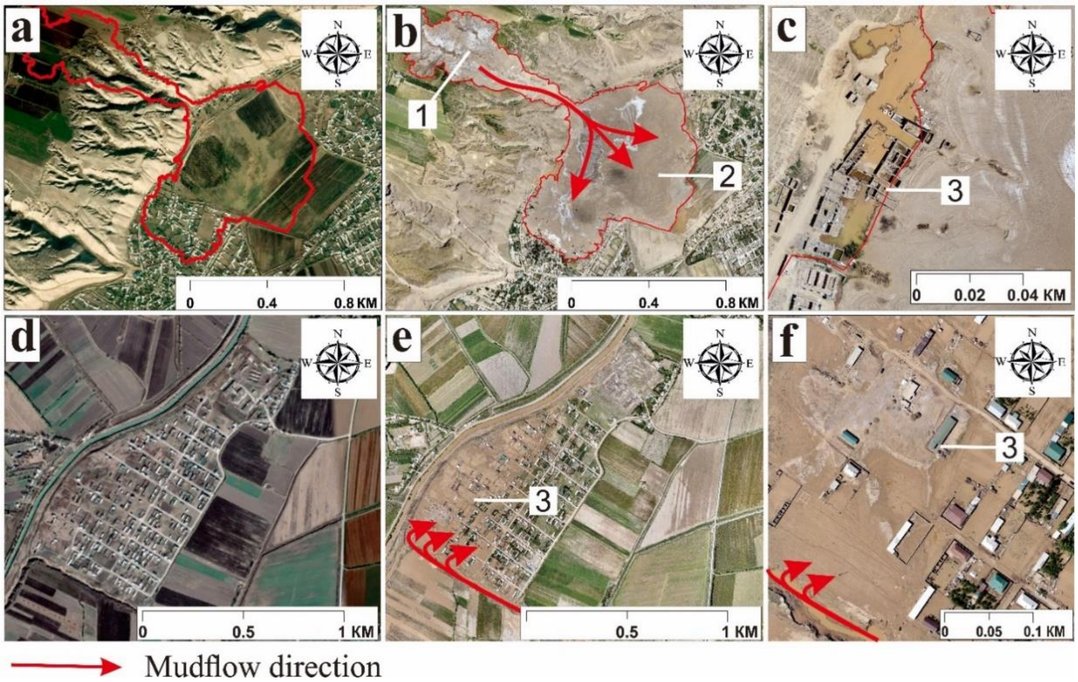


Fig. 5. Mapping of the study areas before and after the debris flow in the Khuroson (a–c) and Vakhsh (d–f) districts of the Khatlon region: a, d – © Google Earth images before the debris flow; b, c, e, f – orthomosaics of areas obtained from the results of aerial photography using a UAV after the debris flow. Designations: 1 – debris flow formation zone, 2 – debris flow deposits, 3 – residential buildings destroyed after the debris flow. Spatial resolution – 5.62 cm/pixel (Khuroson region) and 4.69 cm/pixel (Vakhsh region)

Using Sentinel-2, the most notable change was identified at the Khuroson site, where both NDWI and NDVI displayed a significant alteration following the debris flow event (Fig. 6). Moreover, discernible changes were also observed in the Tojikobod and Lakhsh regions, where large-size debris type debris flows are commonly encountered. Fig. 6 (Id-VId) visually illustrates the presence of the steepest slopes in the Tojikobod and Lakhsh areas, potentially influencing the frequency and severity of debris flows in these locations. It was determined that the Khuroson area primarily experiences rain-induced debris flows, while the Tojikobod area is characterized by rain-snow-induced debris flows. On the other hand, the Lakhsh area is prone to glacial-induced debris flows, with mudslides triggered by outbursts of glacial lakes on the Said Nafisi glacier (Baralmos). The unique nature of these debris flow events underscores the diverse environmental factors at play in each region, shaping the occurrence and impact of such natural phenomena.

Fig. 7 shows the mapping of areas prone to debris flows in various regions of Tajikistan. It has been established that in three studied areas, the debris flows are mostly characterized by clay in composition, whereas some areas were covered by mud-stone, and in few places with mixture of clay and mud-stone. Based on the identified current and previous debris flow deposits, the periodicity of debris flow events in the study areas was confirmed, which corresponds with the conclusions of previous studies [*Atutova et al., 2018; Safarov et al., 2023*], those reported that high-mountain regions are the source of mud-stone flows by long-transported river channels. In the mountainous terrain of Tajikistan, the use of remote sensing monitoring and early warning systems (EWS) could help eradicate such issues, which are currently lacking in the region [*Pecoraro et al., 2019*]. Flexible ring mesh barriers are proposed as an alternative to concrete dams and barrage systems to reduce slope and bottom erosion caused by debris flows [*Wendeler et al., 2019*]. Nonetheless, continuous monitoring and local-level EWS remain collectively significant in minimizing potential hazards like debris flows.

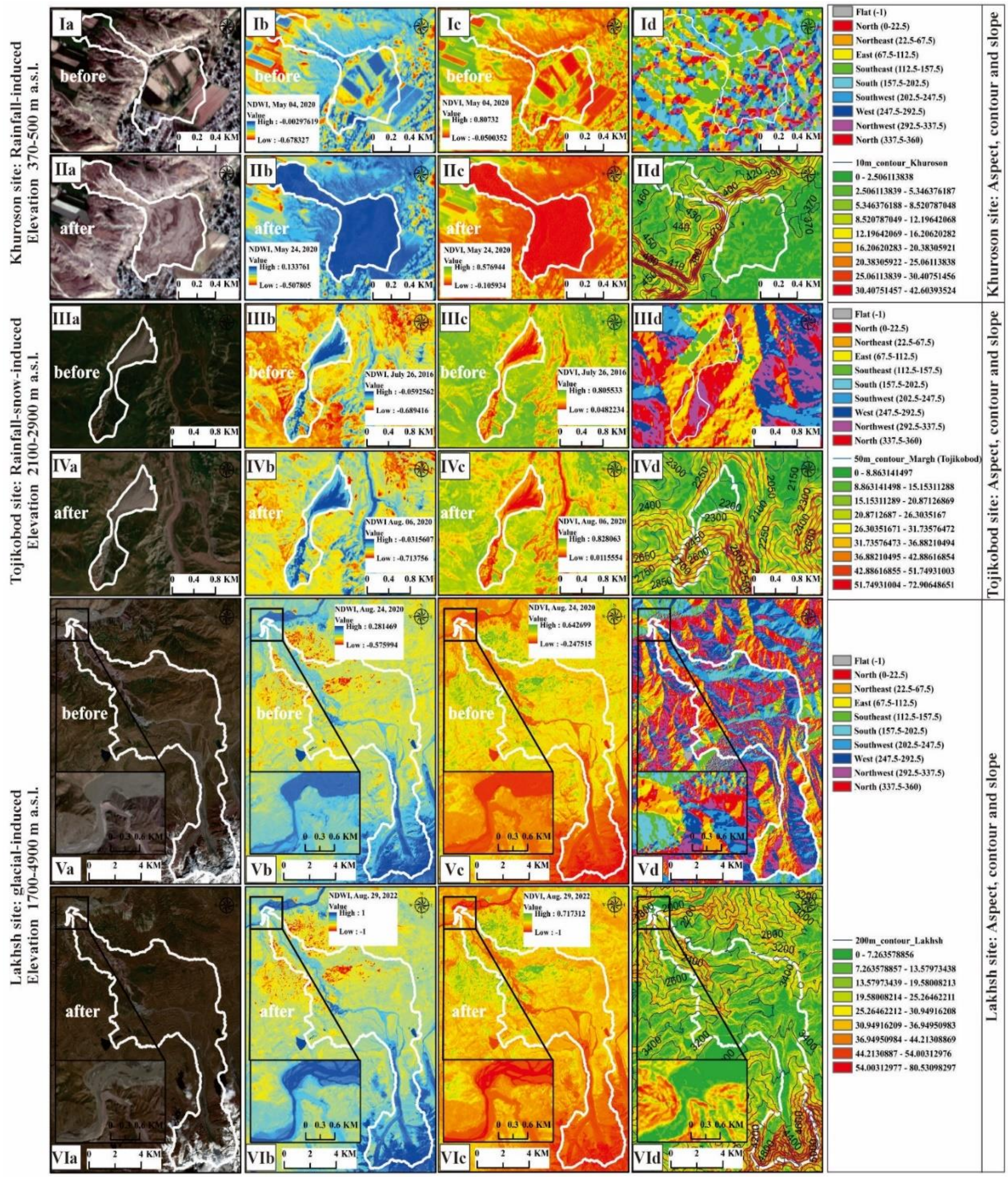


Fig. 6. Observation of changes in the study area by using pre- (Ia-c, IIIa-c, Va-c) and post-event (IIa-c, IVa-c, VIa-c) Sentinel-2 images and Slope, aspect and elevation contours (1d-6d) for selected sites

Conclusions

The research conducted from 2020 to 2023 in Tajikistan has provided valuable insights into the prevalence and impact of hazardous natural phenomena, particularly debris flows. The application of UAVs and satellite data has been instrumental in detecting changes and analyzing patterns in these regions.

Notable changes were observed in Khuroson, Tojikobod, and Lakhsh districts, where significant alterations were detected using both NDWI and NDVI. The composition of debris flows in the six studied areas was predominantly clay, with some regions also covered by mud-stone, and a few areas exhibiting a mixture of clay and mud-stone. These findings underscore the importance of incorporating remote sensing technologies, particularly UAVs and Sentinel-2, into disaster research and response efforts.

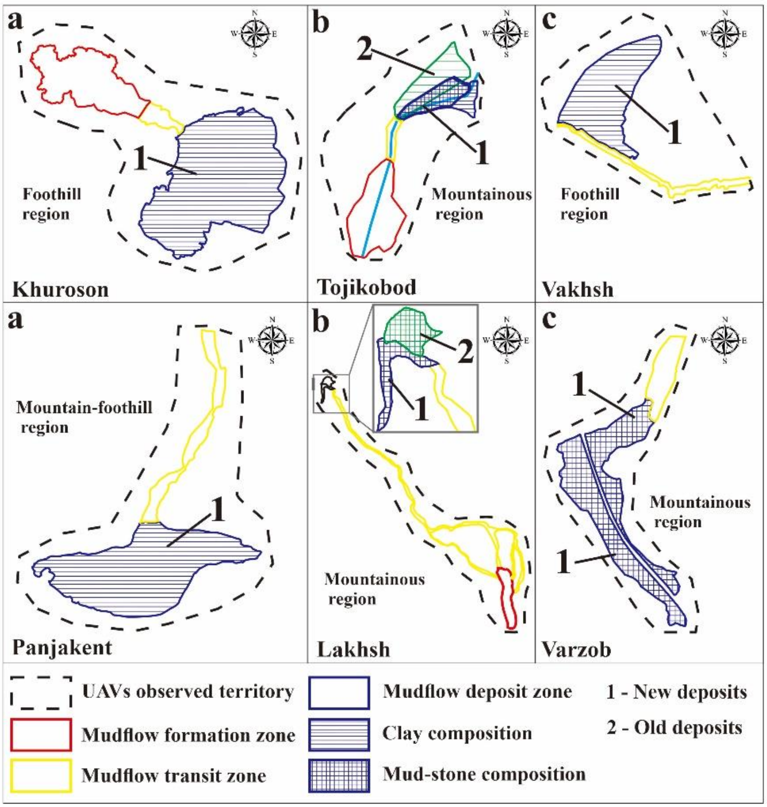


Fig. 7. Mapping of areas prone to debris flows in Tajikistan, using the example of selected areas

The research outcomes have facilitated the identification of high-risk areas prone to natural disasters, evaluating damage, and assessing the extent of debris flow impacts across various regions in Tajikistan. The study identified 49 districts and cities affected by debris flows during the study period, resulting in an estimated 30.2 million US dollars in damages.

Integrating UAV and remotely sensed technologies into monitoring and assessment frameworks is crucial for strengthening preparedness and resilience to natural disasters. By leveraging these technologies, we can minimize infrastructure damage, reduce human casualties, and improve overall disaster response coordination for upcoming events.

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