DEBRIS FLOWS: Disasters, Risk, Forecast, Protection

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泥石流：
灾害、风险、预测、防治

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При создании логотипа конференции использован рисунок из книги С.М. Флейшмана «Селевые потоки» (Москва: Географгиз, 1951, с. 51).

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

Infrastructure safety in Russian mountains: From debris flow assessment to technical mitigation

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Abstract. Debris flows pose significant natural hazards globally, causing widespread destruction and loss of life. Despite annual efforts to mitigate their impacts, regions such as the Russia's Far East and Southern European regions are continuously impacted by debris flow events. These hazards not only threaten mountain settlements but also endanger linear infrastructures like power lines and roads, leading to severe disruptions and emergencies.

To address these challenges and to mitigate underlying hazards, quantitative risk information is crucial. However, in many mountainous regions, essential data is either lacking or inaccessible. In response, this study proposes a comprehensive approach that integrates traditional engineering field methods with modern modelling and remote sensing techniques. By combining ground-truth data with numerical simulations and satellite imagery, we aim to develop reproducible workflows for reliable and cost-efficient debris flow mitigation.

Traditional methods such as topographical surveys and geomorphological mapping provide foundational insights into hazard dynamics, albeit with limitations in remote areas. Meanwhile, remote sensing technologies, including UAVs, enable high-resolution data acquisition, facilitating detailed terrain analysis and hazard monitoring. By integrating these methodologies, we develop comprehensive hazard maps and risk management strategies tailored to the specific needs of linear infrastructure such as railway lines. This holistic approach not only enhances the accuracy of hazard assessments but also improves the efficiency of mitigation measures, ultimately reducing the socio-economic impacts of debris flow events and enhancing community resilience to natural disasters.

Key words: *debris flow, technical mitigation, remote sensing, hazard maps*

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Безопасность инфраструктуры в горах России – от оценки селевой опасности до защиты от селей

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Аннотация. Селевые потоки представляют собой серьезную стихийную опасность во всем мире, вызывая масштабные разрушения и гибель людей. Несмотря на ежегодные усилия по их сокращению, такие регионы, как Дальний Восток России и Южная Европа, постоянно подвергаются воздействию селей. Эти опасные процессы угрожают не только горным поселениям, но и линейной инфраструктуре, например ЛЭП и дорогам, что приводит к серьезным разрушениям и чрезвычайным ситуациям.

Для решения этих проблем и смягчения последствий решающее значение имеет количественная информация о рисках. Однако во многих горных регионах необходимые данные либо отсутствуют, либо недоступны. Это исследование предлагает комплексный подход, который объединяет традиционные инженерные полевые методы с современными методами моделирования и дистанционного зондирования. Объединив наземные данные с численным моделированием и спутниковыми снимками, мы разрабатываем воспроизводимые процессы для надежной и экономически эффективной защиты от селей.

Традиционные методы, такие как топографические исследования и геоморфологическое картографирование, дают фундаментальное, хотя и ограниченное представление о селевых процессах для отдаленных районов. Между тем, технологии дистанционного зондирования (в том числе БПЛА) позволяют собирать данные с высоким разрешением и облегчают детальный анализ местности и мониторинг опасностей. Интегрируя эти методологии, мы разрабатываем комплексные карты опасностей и стратегии управления рисками, адаптированные к потребностям линейной инфраструктуры, такой как железнодорожные пути. Комплексный подход не только повышает точность оценки опасных процессов, но и увеличивает эффективность мер по защите от селей, в конечном итоге снижая социально-экономические последствия их схода и повышая устойчивость населения к стихийным бедствиям.

Ключевые слова: *селевой поток, меры защиты, дистанционное зондирование, карты опасности*

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Introduction

Debris flows are natural hazards that lead to destruction and loss of life all across the world. Situated amongst landslides, rockfall, and floods [*Rickenmann, 2002*], debris flows are mixtures of water and sediment, ranging from clay-sized particles to boulders of several meters in diameter. The destructive nature of debris flows is mainly due to potentially high values of density, velocity, and discharge. Front velocities exceeding 20 m/s have been observed [*e.g., Costa, 1982*], and peak discharges one or two orders of magnitude larger than normal floods in the same catchment have been estimated. About 10% of the territory of Russia is prone to debris flow hazards [*Perov et al., 2017*]. Despite the efforts taken annually to reduce their adverse effects, they continue to cause damage, with the territories of the Far Eastern region and the south of European Russia suffering the most [*Gavrilova et al., 2011*]. Debris flow processes are not only especially harmful for mountain settlements but also for linear infrastructures such as power and communication lines, railways, and roads. Linear infrastructure is not only directly exposed, but any interruption also results in secondary effects such as reduced accessibility or an interruption of supply chains, creating an emergency situation [*Petrova, 2020*].

In order to mitigate these hazards and to adapt to the adverse consequences, quantitative information on risk is needed. However, similar to snow avalanche hazards, in many mountain regions necessary data is missing [*Shnyparkov et al., 2012*] or not available due to institutional circumstances [*Papathoma-Köhle et al., 2021*], and considerable efforts have to be undertaken systematically to acquire necessary information. In this contribution, we present an approach to close this gap by combining traditional engineering field methods with modelling approaches and modern remote sensing methods such as the use of uncrewed[2] aerial vehicles (UAVs) or satellite data. This allows us to achieve a reproducible workflow targeted at reliable and cost-efficient technical mitigation to protect exposed infrastructure from the impact of debris flow hazards.

The integration of traditional and modern techniques offers several advantages in assessing and mitigating debris flow hazards. Traditional engineering field methods provide valuable ground-truth data, including topographical surveys, lithological analysis, and geomorphological mapping, which form the basis for understanding local terrain characteristics and hazard dynamics. However, these methods are often time-consuming and labour-intensive, particularly in rugged or inaccessible terrain.

In contrast, modelling approaches, such as numerical simulations and statistical analyses, enable the extrapolation of field data to larger spatial scales and the quantification of hazard probabilities and magnitudes. These models allow for scenario-based risk assessments, considering various factors such as rainfall intensity, slope gradient, and land cover, to identify high-risk areas and prioritize mitigation efforts.

Additionally, modern remote sensing techniques, including UAVs and satellite imagery, offer a non-invasive and cost-effective means of acquiring high-resolution spatial data over large areas. UAVs, equipped with cameras, LiDAR sensors, and other remote sensing instruments, can capture detailed terrain information with centimetre-level accuracy, allowing for the generation of digital elevation models (DEMs), orthophotos, and 3D reconstructions of the landscape. Similarly, satellite imagery provides synoptic views of terrain features and environmental conditions, enabling the monitoring of changes over time and the detection of potential hazard triggers.

By integrating these diverse datasets and methodologies, researchers and practitioners can develop comprehensive hazard maps, vulnerability assessments, and risk management strategies tailored to specific regions and infrastructure networks. This holistic approach not only improves the accuracy and reliability of hazard assessments but also enhances the efficiency and effectiveness of mitigation measures, ultimately reducing the socio-economic impacts of debris flow events and enhancing community resilience to natural disasters.

Methods

In order to assess debris flow hazards and to design and implement engineering protection, it is necessary to determine the severity affecting the element at risk, including characteristic features of the hazard-prone area. First and foremost, the hazard inventory process entails gathering and analysing essential information pertaining to debris flow events. This includes compiling data on historical occurrences, assessing the geomorphological characteristics of the terrain, and identifying factors contributing to debris flow initiation and propagation. By examining past events and understanding the underlying geological, hydrological, and topographical factors, it becomes possible to delineate areas susceptible to debris flow hazards and anticipate future risks. Consequently, the hazard inventory includes information on assumed probabilities of occurrence (frequencies) and magnitudes (volumes), as well as an impact analysis. Engineering surveys (geology, geomorphology) are a standard procedure to achieve this type of information, and this procedure is well-justified and widely applied also in remote mountain areas [*Kharichkin et al., 2021*]. The overall workflow includes three stages: 1) preliminary desktop mapping, 2) field survey and 3) processing of the collected data including process modelling where appropriate.

(1) As part of the first stage, visual analysis of the traces of debris flow processes is performed, leveraging accessible datasets like Google Earth and high-resolution satellite

[2] The terms ‘unmanned aircraft systems’ (UAS), ‘remotely piloted aircraft systems’ (RPAS) or ‘unmanned aerial vehicle’ (UAV) are used synonymously to emphasise the lack of people in piloting and crewing roles on board. Following recent discussions in the scientific literature, we prefer to use the word ‘uncrewed’ here [*Joyce et al. 2021*].

imagery, etc. The analysis incorporates morphological, geological and landscape criteria, and is performed in accordance with existing recommendations [*Perov, 2012*]. As a result, a preliminary map of debris flow hazards is created showing the general susceptibility of the infrastructure at risk, and informing subsequent stages of hazard evaluation and risk mitigation strategies.

(2) The second stage includes a detailed geomorphological mapping aiming at a spatially explicit delineation of release, transit and deposition areas focusing on debris flows, an overall assessment of slope movement and other indicators for mass wasting. The main objectives are to describe the conditions for the formation of debris flows and to obtain quantitative characteristics. The preliminary scheme of debris flows obtained in stage 1 is updated, the forms of debris flow relief and deposits are described. The results of these studies allow us to draw conclusions about the nature of debris flows in the basin; the sources of solid and liquid supply of flows; possible mechanism of their origin; genesis; their discharge volume and frequency [*Perov, 2012*]. The mapping is a prerequisite to obtain a deeper understanding of the potential geohazard situation within the project area.

Another step of the second stage is to gather remote sensing data from UAVs, which due to technological advances became increasingly prominent in recent years [*Rossini et al., 2023*]. In the last few years, research with drones has been widely used in mountainous areas. UAVs provide the opportunity to conduct research with high spatial resolution, expanding our capabilities to monitor the changing environment and landscape features. The use of modern methods has allowed accelerating the acquisition of information about the research site, with the accuracy matching that of the classical survey methods. By combining drone surveys with traditional methods, it is possible to promptly obtain precise data for assessment and modelling of debris flow hazards, which therefore becomes a base for a further mitigation concept. With the development of survey technologies, it has become easier to obtain detailed data in remote mountainous areas, such as an orthophotoplan, a 3D model or a heightmap of the territory. We conduct drone flights using a DJI Matrice 300 RTK UAV with a DJI Zenmuse P1 photogrammetric camera and a DJI Zenmuse L1 lidar (airborne laser scanner) as payload.

(3) The third stage the boundaries of basins, the system of debris flow-prone watercourses, the directions and slopes of the talweg channels are clarified. Information on the granulometric composition is summarized. Based on the results of the field survey, a final map of debris flow characteristics is being created in a GIS environment, and a written report describes in detail the information on magnitudes and frequencies of every identified hazard phenomenon using a scheme based on the Austrian Standard ONR 24810 (Fig. 1).

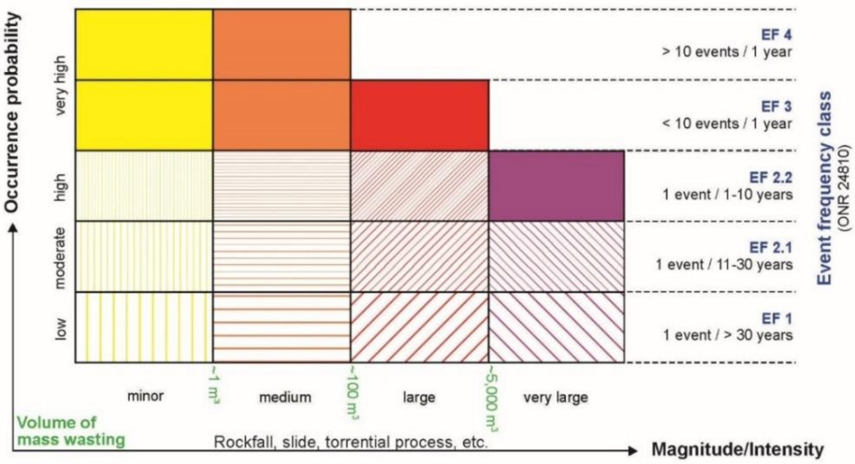

Fig. 1. Geohazard matrix for mass wasting processes differentiating volume (intensity) and frequency of rockfall, sliding processes and torrential processes. Classification based on the Austrian Standard ONR 24810:2020 01 with minor adjustments [*Austrian Standards Institute, 2017*]

The result of the UAV flights and the desktop processing of the data is an orthophotoplan, a digital elevation model and a topographic plan at a scale of 1:500. An orthophotoplan is a digitally transformed image of an area (object) created from overlapping photos. A digital elevation model (DEM) is based on a point cloud classification after airborne laser scanning, which contains information about the height of the true terrain, excluding vegetation and buildings. The topographic plan is the basis for the design of engineering protection. Planned features such as roads, forest, rock outcrops and utility infrastructure are plotted on the topographic plan from an orthophoto.

Results

In the following, results of individual stages (1) to (3) are presented using the example of a project in the Baikal Ridge, Irkutsk region, Russia.

(1) A debris flow hazard assessment was carried out on the section of the Baikal-Amur railway, which runs through the Baikal Ridge. At the preliminary stage nine catchment basins were highlighted using available 2010 satellite images in Google Earth, and a preliminary desktop mapping was undertaken to identify process types and activities. The position of the identified catchment areas, where occurrence of the hazards is possible, is shown in Fig. 2.

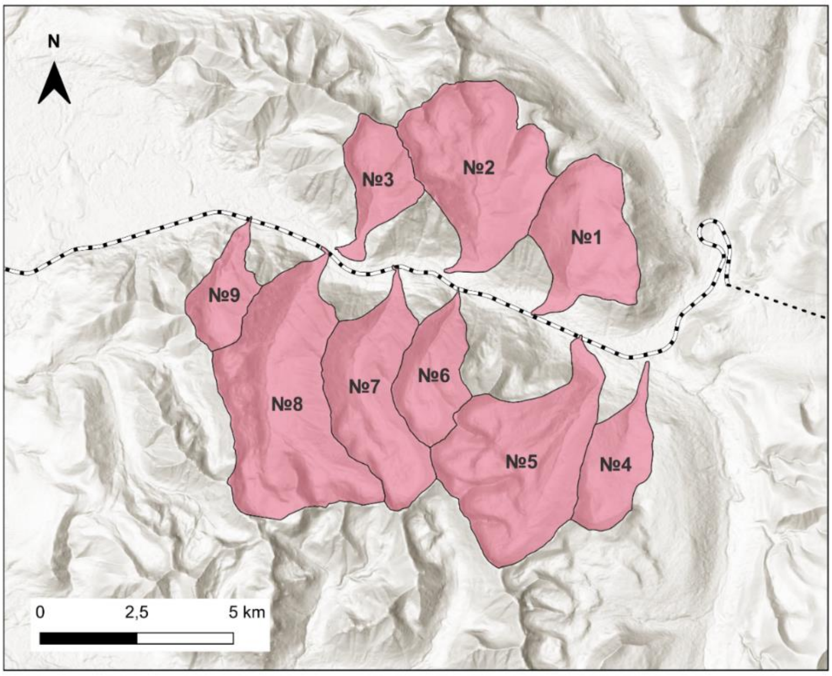

Fig. 2. Preliminary stage, scheme of debris flow basins, the Baikal Ridge. Image source: ESRI World Hillshade

(2) These nine basins were studied during the second stage during a field campaign in 2023. Detailed geomorphological mapping was conducted along the studied section of the railway and in the debris basins. Debris flow landforms and deposits were depicted, and, as such, the results of stage (1) were updated and assessed in more detail. The main attention was paid to creeks with indicators of debris flow activity. The traces of high-water levels, debris flow splashes on trees and the maximum size of boulders carried by debris flows were identified. As a result of the field study, an assessment of debris flow activity was estimated. The coefficient of debris flow activity characterising the intensity of the development of the debris flow processes [*Perov, 1996*] was assigned to the channels of nine brooks. The coefficient values were determined on the basis of visual analysis of satellite images and a field survey of the area. The most intense debris flows occurred in the Vredny brook basin (Fig. 3).

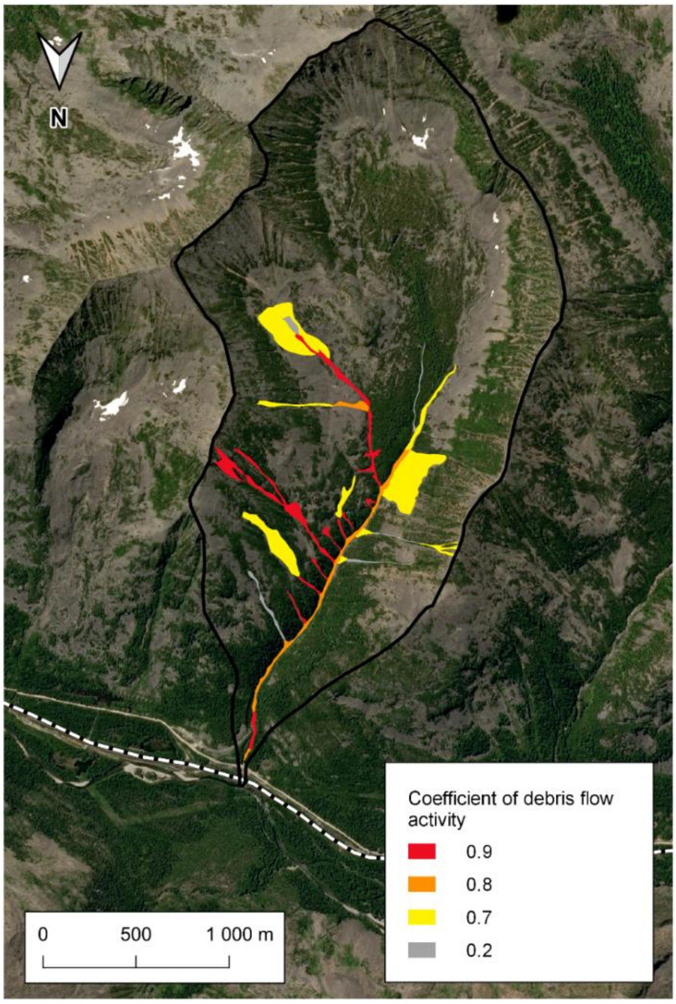

Fig. 3. Coefficient of debris flow activity assigned to the Vredny creek, the Baikal Ridge. Image source: Google Earth

(3) In total UAV flights with camera and lidar covered an area of 45 km^2. The result of the postprocessing of data from the Baikal Ridge was a digital elevation model with a resolution of 5 cm/pixel (Fig. 4). Combined with the terrain analysis modules in QGIS, the morphological characteristics of debris flow valleys were obtained, and the data was used to refine mapping and risk assessment results in order to obtain a design concept for technical mitigation.

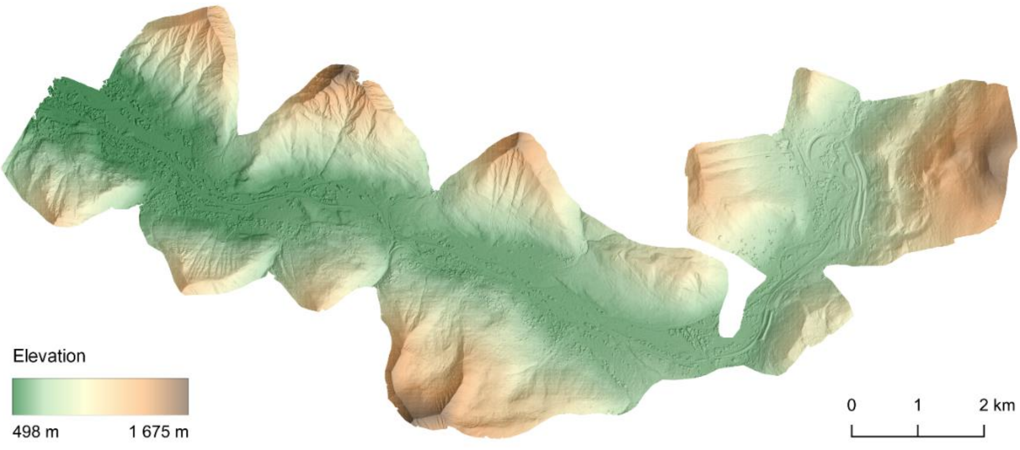

Fig. 4. Digital elevation model of the studied section of the Baikal Ridge

Design concept

Based on these results, the design concept for hazard mitigation was created. When developing engineering protection systems in mountainous areas, the key point in the design of protective structures is the choice of their installation locations. Most often a combination of structures is used to help control the destructive power of the event by restricting velocity and erosive potential and based on principles of economic efficiency of risk reduction investments [*see e.g., Fuchs and McAlpin 2005*]. Mathematical modelling is mainly used to calculate debris flows and obtain basic quantitative characteristics.

Engineered protective measures for controlling debris flows are often located on the debris fan and can be divided into two categories: open and closed control structures. Open structures generally provide controlled passage of debris into the deposition zone. This strategy differs from closed structures, which attempt to stop further progression of debris within the fan or along the channel. These systems are designed to absorb initial dynamic pressure created by fronts of debris. At the same time, they provide a mechanism for inducing coarse-grained deposition by dewatering combined with a reduction of debris velocity [*Bichler et al., 2012*]. Within the study area, we suggested to use Trumer flexible systems (the so-called Debris Catcher), as they are very cost-efficient and can be adapted to a multitude of terrain features. Typical barriers are installed in run-out or deposition zones, close to the elements at risk that they protect. The Debris Catcher has a unique design without retaining ropes and therefore no components in the upstream path of the flow that can fail or compromise the functionality of the system (Fig. 5). When the volume of debris material is relatively small, the barrier retains it completely and stops the debris flow. In case of large volumes of sediments, a barrier only reduces the energy of the debris flow, but does not stop it. For large debris flows a cascade of barriers is recommended [*Trumer Schutzbauten, 2014*].

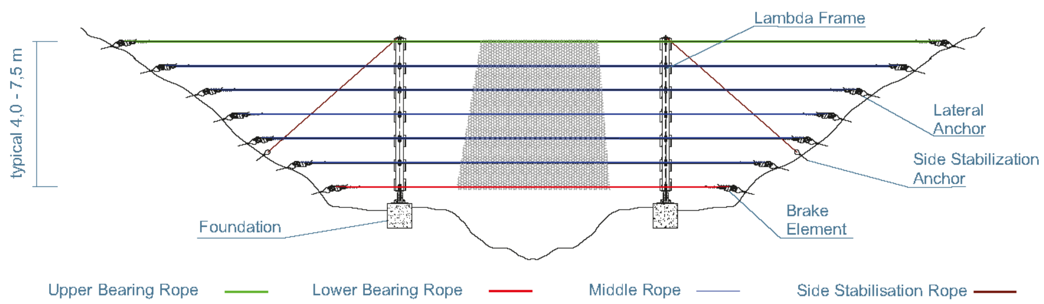

Fig. 5. Typical layout of the Trumer Schutzbauten Debris Catcher (front view). Please note that every debris flow structure is custom designed for a specific site and loading conditions and so the exact details of the system will vary from site to site. Source: Trumer Schutzbauten 2014

For the studied section of the Baikal-Amur railway, a cascade of two Trumer Debris Catchers was suggested to be installed in the channel, 150 and 250 m upstream of the rail track (Figs. 6 and 7). The main purpose of the cascading system is to retain individual large events. The Debris Catchers were designed considering judgment from post debris event field observations and calculations according to Russia's standard VSN 03-76 [*VSN 03-76, 1976*]. During the field stage normal discharge of the creek as well as block geometry were measured. Loading design input was based primary on the accepted in Russia methodology of parameter calculation of debris flows of certain probabilities. According to calculations, the maximum discharge of a 1-in-100-year debris flow event in Vredny basin is 37 m^3/s, with static pressure of 5 kPa, and dynamic pressure of 138 kPa. In this scenario the Trumer Debris Catcher was found to be the most suitable solution, as the structure can withstand impact pressure up to 150 kPa. With two barriers in a row, the retention capacity increases. The installation place was chosen to maximize the debris storage volume behind the structure and to have relatively easy access to the systems for maintenance.

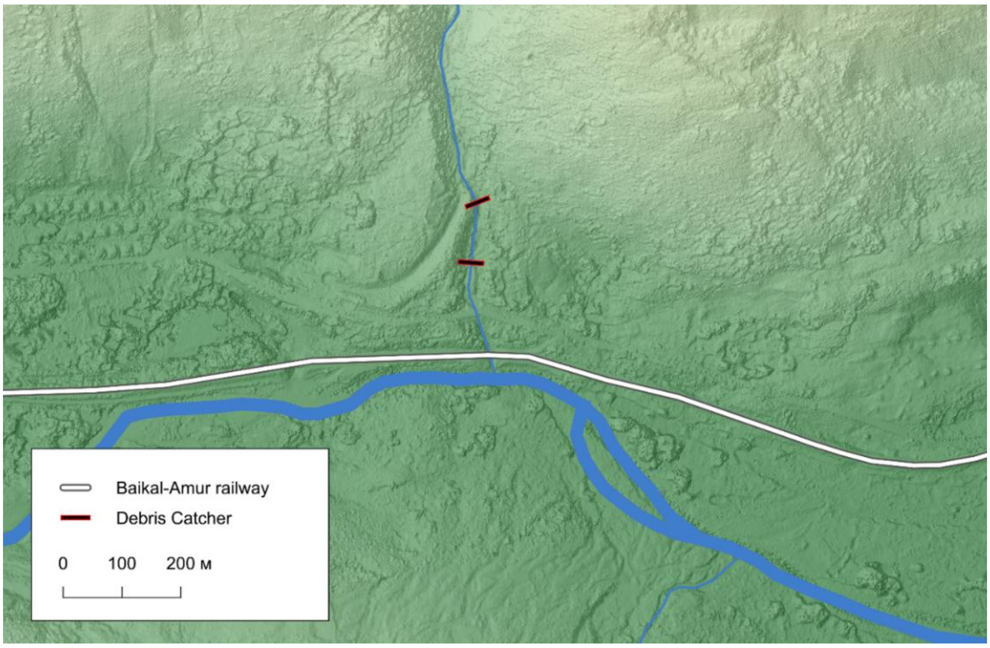

Fig. 6. Proposed cascade of Trumer Debris Catcher barriers, the Baikal Ridge. Image source: own digital elevation model

Fig. 7. Debris Catcher system from Trumer Schutzbauten (TS-DC-LAMBDA). Source: Trumer Schutzbauten

Discussion

The central aspect within debris flow risk assessment is to ensure an acceptable safety level and sustainable use for the exposed mountain areas with regards to economic and social conditions. This becomes of vital importance when tailoring the hazard and risk assessment along traffic infrastructure with high significance, limited number of applicable structural measures, and a dynamic environment of elements at risk. We propose a framework for working in a debris flow prone area from scratch, from hazard assessment to the development of an effective engineering protection concept. Concerning the mitigation strategy, it is crucially important to assess both the magnitude and frequency of the hazard and develop an individual protection concept in order to secure infrastructure and reduce the existing risk to an acceptable level.

Detailed geomorphological mapping is one of the most important tools for the assessment of natural hazards. It serves to recognize and interpret the 'silent witnesses' [*Aulitzky, 1992*] as a backward-looking indication of earlier hazardous processes. At the same time, critical constellations and key positions of the process dynamics in the terrain are recognized and assessed (forward-looking indication) [*Keiler et al., 2000*]. According to generally accepted methods [*e.g., Heinimann et al., 1998*], the terrain analysis requires as preliminary work a desktop evaluation of all relevant data on spatial features (search for topographical, geological, lithological, hydrological and other documents and maps, evaluation of existing event registers) as well as a precise interpretation of aerial photographs and satellite-based imagery of the area under investigation (stage 1).

The subsequent site inspection serves to check, possibly correct and supplement the preliminary mapping derived from the basic data. While geomorphological mapping already has a long history in the assessment of natural hazards such as debris flows, the combination with new technology such as the use of drones to create high-resolution terrain models is innovative in particular in data-scarce regions (stage 2). As it can be seen from the experience of Trumer, application of UAVs makes it possible to actively use the results of drone survey to apply terrain analysis in GIS and design measures for the engineering protection of the investigated territory (stage 3).

This integration of modern technology not only enhances the accuracy and efficiency of the hazard assessment process but also opens up new possibilities for proactive risk management. By utilizing UAVs, which can access remote or hazardous areas with greater ease and safety than traditional methods, researchers and engineers can gather data in a more comprehensive and timely manner. Additionally, the high-resolution terrain models generated by UAVs allow for detailed analysis and visualization of terrain features, facilitating better-informed decision-making in the design and implementation of protective measures.

Furthermore, the use of Geographic Information Systems (GIS) alongside drone technology enables the integration of various spatial data layers, such as land use, vegetation cover, and hydrological characteristics, into a unified platform for comprehensive risk assessment and consecutive design of mitigation solutions. This spatial analysis approach provides valuable insights into the spatial distribution and interaction of factors contributing to debris flow hazards, helping to prioritize areas for intervention and optimize resource allocation. Additionally, GIS facilitates the communication of risk information to stakeholders through interactive maps and visualisations, enhancing their understanding of potential hazards and the effectiveness of proposed mitigation measures.

In addition to its application in hazard assessment and risk management, geomorphological mapping with drones holds promise for supporting post-disaster recovery and resilience-building efforts. By rapidly assessing changes in terrain morphology following a debris flow event, researchers can identify areas of heightened vulnerability and prioritise restoration efforts. Moreover, the availability of up-to-date and accurate terrain data can inform the design of resilient infrastructure and land-use planning strategies aimed at reducing future disaster risks.

Overall, the integration of drones and GIS technology into geomorphological mapping represents a significant advancement in the field of natural hazard assessment and risk management. By combining the strengths of remote sensing, spatial analysis, and geospatial visualization, this approach offers a powerful toolkit for understanding, predicting, and mitigating debris flow hazards in mountain regions. However, it is essential to continue refining methodologies and leveraging technological innovations to further enhance the accuracy, efficiency, and accessibility of hazard assessment and risk management practices, ultimately contributing to the safety and sustainability of mountain communities worldwide.

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