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A four-pillar strategy for natural hazard risk management in remote mountain regions: Insights from the Mestiachala HPP, Georgia

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Abstract. Effective natural hazard risk management in remote mountain regions requires a multidisciplinary approach based on four interrelated pillars: 1) data-driven hazard mapping using geomorphological analysis and process-based simulation, 2) targeted protective engineering where technically viable and cost-effective, 3) integrated monitoring and alert systems combining remote sensing with in-situ catchment data, and 4) ongoing high-resolution surveillance via local and drone-based remote surveys. Together, these pillars enable effective risk management and early warning to protect critical infrastructure from debris flows and other hazards. The foundation of this approach is field-based hazard assessment, which provides critical insight into the geomorphological, hydrological and geological factors that drive debris flow events. Process simulation, based on models that replicate and predict dynamic natural hazard processes, enables scenario testing and risk quantification. The second pillar focuses on designing engineering mitigation measures. Based on simulation results and hazard zoning, structural measures such as barriers, retention basins, and diversion channels are optimised for site-specific conditions, balancing safety, cost, and environmental impact. The third pillar introduces an approach to monitoring and early warning systems that integrate remotely sensed and ground-based information. These systems provide real-time data on precursors to hazardous events, such as weather forecasts for the catchment area. This improves the responsiveness of emergency protocols. The fourth pillar involves continuous and repeated local drone surveys to detect and document any catchment dynamics. Together, these pillars provide a scalable, adaptive methodology for managing natural hazards, such as debris flows, in remote mountain regions.

Key words: *risk assessment, technical protection, UAV monitoring, early warning, alert system*

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Четырехкомпонентная стратегия управления рисками стихийных бедствий в отдаленных горных регионах: выводы из опыта Местиачальской ГЭС, Грузия

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Аннотация. Эффективное управление рисками стихийных бедствий в отдаленных горных регионах требует междисциплинарного подхода, основанного на четырех взаимосвязанных основаниях: 1) картирование опасностей на основе данных с использованием геоморфологического анализа и моделирования на основе процессов, 2) целевая защитная инженерия, где это технически осуществимо и экономически эффективно, 3) интегрированные системы мониторинга и оповещения, объединяющие дистанционное зондирование с данными о водосборе на месте, и 4) постоянное наблюдение с высоким разрешением с помощью локальных и беспилотных дистанционных обследований. Вместе эти основания обеспечивают эффективное управление рисками и раннее предупреждение для защиты критической инфраструктуры от селевых потоков и других опасностей. Основой этого подхода является полевая оценка опасностей, которая дает критическое представление о геоморфологических, гидрологических и геологических факторах, которые вызывают селевые потоки. Моделирование процессов, основанное на моделях, которые воспроизводят и предсказывают динамические процессы стихийных бедствий, позволяет проводить тестирование сценариев и количественную оценку рисков. Второе направление фокусируется на разработке инженерных мер по смягчению последствий. На основе результатов моделирования и зонирования опасностей структурные меры, такие как барьеры, удерживающие бассейны и отводные каналы, оптимизируются для условий конкретного участка, обеспечивая баланс между безопасностью, стоимостью и воздействием на окружающую среду. Третий путь представляет подход к системам мониторинга и раннего оповещения, которые интегрируют дистанционно зондируемую и наземную информацию. Эти системы предоставляют данные в реальном времени о предвестниках опасных событий, таких как прогнозы погоды для водосборной площади. Это повышает оперативность реагирования протоколов чрезвычайных ситуаций. Четвертое направление включает в себя непрерывные и повторяющиеся локальные обследования с помощью беспилотников для обнаружения и документирования любой динамики водосбора. Вместе эти столпы обеспечивают масштабируемую, адаптивную методологию для управления природными опасностями, такими как селевые потоки, в отдаленных горных регионах.

Ключевые слова: *оценка риска, техническая защита, мониторинг БПЛА, раннее оповещение, система оповещения*

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Introduction

Georgia is a country that is frequently affected by gravitational mass movements. According to *Gaprindashvili et al.* [*2021*], large parts of the country are classified as zones of medium to high susceptibility to debris flows and similar processes. From 1995 to 2023, more than 16,200 landslides (both reactivated and newly occurring) and almost 4,100 debris flows were recorded. These resulted in 54 and 128 fatalities respectively, as well as causing damage to numerous buildings and settlements [*Todradze and Apkhaidze, 2024*]. These processes are primarily triggered by the underlying geology [*Tielidze, 2019*], but are also often initiated by intense precipitation combined with warm temperatures in the high mountain regions of the Caucasus, leading to snowmelt and glacier retreat. In addition to hydrometeorological triggers, these mass movements may also be initiated by earthquakes [*Gaprindashvili and van Westen, 2016*]. Research has focused particularly on debris flow disasters in the Greater Caucasus [*Chernomorets and Gavardashvili, 2018*], where altitudes of over 5,000 metres are reached and deglaciation and other glacial hazards significantly contribute to mass movement occurrence. Extraordinary events such as the 2019 Mestiachala event [*Fuchs et al., 2020*] and the 2023 Shovi event [*Petley, 2023*] repeatedly result in considerable loss and highlight the major challenges associated with natural hazard risk management in remote, data-scarce, high-mountain regions. In the following sections, we present a four-pillar approach to mountain hazard risk management that is specifically targeted at such extraordinary events. This approach consists of four interrelated pillars.

1. Data-driven hazard mapping using geomorphological analysis and process-based simulation.
2. Targeted protective engineering where technically viable and cost-effective.
3. Integrated monitoring and alert systems combining remote sensing with in-situ catchment data.
4. Ongoing high-resolution surveillance via local and drone-based remote surveys.

The integrated four-pillar approach enables robust natural hazard risk management and early warning, aimed at safeguarding critical infrastructure and livelihoods from debris flows and related mountain hazards. By combining hazard mapping, vulnerability analysis, and site-specific mitigation planning, the approach enhances the precision and effectiveness of risk reduction measures while minimizing socioeconomic impacts. This framework contributes to improved resilience at the local scale and supports evidence-based decision-making. The Mestiachala HPP in Georgia is presented as a case study demonstrating its practical application. The Mestiachala event in late July 2019 was a compound hazard event triggered by multiple rock avalanches in the upper part of the Murkvami valley feeding at inlet 1 of the Mestiachala Hydropower Plant (HPP) in the Mestiachala river. The rock avalanches incorporated glacier ice from the upper catchment area, travelling downstream as multiple debris flows and destroying inlet 1. The debris flows continued downstream along the Mestiachala river, damaging inlet 2 and the HPP powerhouse. This event forced both Mestiachala hydropower units – Mestiachala 1 (30 MW) and Mestiachala 2 (20 MW) – offline.

Methods

Data-driven hazard mapping using geomorphological analysis and process-based simulation

Geomorphological mapping is a long-established tool in applied geosciences and engineering geomorphology for representing landforms and their dynamics [*Smith and Pain, 2011; Griffiths, 2004; Downs and Booth, 2011*]. These maps provide essential insights into landforms, near-surface materials, and geomorphic processes, supporting hazard assessment and landscape interpretation [*Dramis et al., 2011*]. In mountainous, data-scarce regions, they are critical for visualising hazards and guiding land management [*Bollati et al., 2017; Zangana et al. 2023*]. Traditionally reliant on expert-led fieldwork [*Seijmonsbergen, 2013*], mapping is increasingly supported by digital tools such as DEMs, orthophotos, and remote sensing technologies [*Garova et al., 2025*]. While remote methods offer advantages in inaccessible terrain [*Otto and Dikau, 2004; Beckenbach et al., 2014*], hybrid approaches combining field and desktop techniques are widely recommended [*Seijmonsbergen, 2013*]. Despite advances in digital mapping [*Krichen et al., 2024*], field validation remains essential for hazard accuracy [*Kienholz et al., 2004; Cirella et al., 2014*]. UAVs and satellites now provide high-resolution, cost-effective data for generating detailed DEMs, orthophotos, and 3D models [*Schlögl et al., 2022*], enabling efficient monitoring of hazard-prone environments. Integrating multiple data sources enhances reliability, especially in transdisciplinary and data-limited contexts [*Cui et al., 2021; Sandoval et al., 2023; Malgwi et al., 2020*]. Field-based geomorphological mapping remains essential for identifying hazard initiation, transit, and deposition zones, particularly for slope movements. It leverages geomorphic indicators [*Aulitzky, 1992*] to infer process types, magnitudes, and frequencies, providing a basis for targeted hazard mapping and risk assessment [*Fuchs et al., 2017*].

Modelling approaches are widely used to simulate future geomorphological processes, providing insights into mass-wasting magnitude, run-out behaviour, and energy distribution across hazard components. Models range from physically based formulations relying on complex mathematical equations to empirical or statistical models derived from observational data and simpler mathematical relationships. Physical models may be causal, deterministic, or incorporate probabilistic elements, while statistical models address observable probabilities [*Briggs, 2016*]. For simulating complex, cascading mass movements, multi-phase models such as r.avaflow are increasingly applied. R.avaflow is an open-source, GIS-integrated tool designed to simulate up to three-phase mass flows over arbitrary topography *[Mergili and Pudasaini 2014–2024*]. It employs the NOC-TVD numerical scheme [*Wang et al., 2004*], a Voellmy-type friction model, and a simplified version of the Pudasaini multi-phase flow model [*Pudasaini and Mergili, 2019*]. For slower flows, it can alternatively apply an equilibrium-of-motion approach. Key features include the modelling of entrainment, deformation, fragmentation, dispersion, and phase transitions. Inputs can be defined via raster maps and/or hydrographs, and the tool supports multi-core processing and batch simulations for sensitivity analysis and optimisation. Outputs include maps, diagrams, and 3D or immersive visualisations [*Mergili et al., 2018; Mergili et al., 2020*]. These simulations are best interpreted in conjunction with field observations derived from geomorphological mapping, enhancing model calibration and hazard understanding.

Targeted protective engineering where technically viable and cost-effective

Engineering geological assessments and rockfall process simulations are essential components of a comprehensive geohazard analysis. In this study, rockfall trajectories were modelled using *GeoRock 2D*, a deterministic simulation tool which calculates the motion of individual blocks along two-dimensional slope profiles. The input parameters were derived from detailed field investigations and geological mapping, incorporating topographic cross-sections, lithological data and rock mass properties. These inputs were then used to construct representative slope geometries and identify potential detachment zones. The model simulates the various phases of block motion (free fall, bouncing, rolling and sliding) while incorporating key mechanical parameters, such as restitution coefficients, friction angles and surface roughness, to accurately characterise block-slope interactions.

The input data for the rockfall modelling were derived from detailed geological and geomorphological field observations. This included a statistical evaluation of the volumes and shapes of rock blocks obtained via in situ measurements and photogrammetric analyses. High-resolution digital elevation models (DEMs) were used to extract slope geometries, and detachment zones were identified through structural mapping of discontinuities and zones of weakness. Material-specific parameters, such as normal and tangential restitution coefficients and rolling friction, were estimated empirically and calibrated against observed deposition patterns using values from the literature. *GeoRock 2D* computes rockfall trajectories and associated kinematic outputs, including translational velocity, impact energy and bounce height, for a statistically representative number of simulated blocks. These outputs are essential for delineating hazard zones and assessing the risk to exposed infrastructure, such as galleries, penstocks and intake structures. The simulation results are classified by energy levels and bounce heights in accordance with the Austrian ONR 24810 guideline [*Austrian Standards Institute, 2017*] to inform the design and placement of protective measures, such as flexible rockfall barriers.

Integrated monitoring and alert systems combining remote sensing with in-situ catchment data

Developing an integrated concept for monitoring, early warning, and alerting in large, remote catchments with multiple hazards poses significant challenges. For the Mestiachala HPP, a multi-stage, prioritised approach was adopted based on the identification of high-magnitude hazard hot spots. In the first stage, critical zones – primarily compound events and debris flows ≥ 5,000 m³ identified through prior hazard assessments [*Fuchs et al. 2020*] – were evaluated weekly using the AFRY Hydro DSS, a web-based decision support system. This platform integrates freely available hydro-meteorological and earth observation data, including satellite-based precipitation (GPM), global weather forecasts (GFS), Sentinel imagery, and weather radar, to support real-time natural hazard monitoring.

In the second stage, ground-based monitoring stations were deployed to detect hazardous processes that occur independently of precipitation and temperature, enabling reliable event identification and automated alarming. These include glacier lake outburst floods (e.g., from Lekhziri and Chalaati glaciers), high-magnitude debris flows, complex events such as the 2019 Murkvami valley incident, and major rockfalls. The monitoring network comprises systems for open channel flow and discharge measurement, debris flow and rockfall detection, rock mass deformation monitoring, and LoRa®-enabled data transmission. Installation sites were selected based on criteria such as maximised lead time, safe sensor placement, LoRa® signal coverage, solar exposure, and sensor-specific optimisation to ensure high data quality and operational reliability.

Three discharge monitoring stations were installed in the Mestiachala HPP catchment at Chalaati, Lekhziri, and Murkvami valleys. Each station includes a radar sensor for flow velocity and water level, and a geophone to distinguish flood from debris flow events. Systems are powered by 120 Wp solar panels and dual 100 Ah LiPO4 batteries, with data transmitted via a LoRa® network.

To monitor rockfall activity in the upper Murkvami valley – source of the July 2019 compound hazard – two geophone stations were installed. These enable real-time detection of major events and track slope destabilisation through increased rockfall frequency. Two stations are required to differentiate local from regional events. Each system consists of two insulated aluminum enclosures (geophone, and power/data) mounted on a pole with antennas and a solar panel. Powered by a 120 Wp solar panel and two 100 Ah LiFePO4 batteries, the system can operate for up to 40 days without sunlight. Geophones are securely anchored to bedrock, large boulders, or concrete foundations to ensure accurate vibration detection.

In the third stage, satellite data, numerical weather forecasts, and ground-based monitoring outputs are integrated into an Early Warning and Alarm System (EWAS). The key distinction is that the alert system detects active hazards and initiates automatic responses, whereas the early warning system forecasts potential hazards with longer lead times, enabling proactive risk mitigation through expert assessment.

Ongoing high-resolution surveillance via local and drone-based remote surveys

The fourth pillar is an Unmanned Aerial Vehicle (UAV), which enables automated weekly visual inspections of hazard zones within its operational range. The primary UAV is a DJI Matrice 30, which is housed in a DJI DOCK and operates autonomously with environmental controls to ensure reliability in adverse weather conditions. The system has a range of 5 km, a flight time of 40 minutes, and a recharge time of 25 minutes. It is equipped with a 12 MP wide-angle camera, 200× hybrid zoom and RTK GPS, providing high-precision imaging and navigation. Deployment is feasible with stable internet (> 20 MB/s), a reliable 230 V power supply, security measures, lightning protection, compliance with Georgian airspace regulations, insurance and emergency landing protocols in place.

Results

The eastern tributary of the Mestiachala River, ranging from 1,940 to 3,838 m asl and covering ~ 1.2 ha, features steep mountainous terrain with glaciers – Murkvami (NE) and Banguriani (S) – separated by a ridge from Mount Banguriani (3,838 m asl). Current moraines resemble those from the end of the Little Ice Age in the 1850s [*Khazaradze et al., 2018*]. Since then, glaciers have been retreating at rates of tens of meters per year [*Tielidze and Wheate, 2018*]. Glacier slope influences area loss, with steeper glaciers experiencing greater retreat. Regional variability depends on factors such as orientation, altitude, mass balance, geometry, and bedrock topography. The valley floor contains glacial ground moraines and deposits resulting from gravitational processes such as rockfalls and landslides, resulting in diverse rock types and grain sizes. These materials are mobilised by glacier tongue discharge and precipitation-driven flows, including debris flows with abundant unconsolidated debris (moraines, colluvium, and sediments). Debris flows are common in mountainous regions due to steep slopes, thermal sensitivity, summer convective storms, and abundant unconsolidated debris (moraine, colluvium, and stream sediments) that facilitate initial mobilization and downstream entrainment. Non-outburst glacial debris flows typically originate in steep proglacial and periglacial zones affected by recent glacier retreat, involving material from ice-cored moraines and adjacent stream channels. These flows are often triggered by elevated summer temperatures and/or intense rainfall, which enhance thermally driven runoff; however, precipitation data for the valley were unavailable to confirm specific triggers.

Fig. 1. Overview on the eastern tributary of Mestiachala valley with the traces of the 2019 event, in the foreground the location of the former inlet 1. Photo: Sebastian Resinger, 01 Oct 2023

Initial failure volumes are often enlarged by entrainment along flow paths, producing large deposits [*Lukas, 2011*]. The 25 July 2019 event was a classic cascading mass movement in the Murkvami catchment (see Fig. 1). The release zones of the July 2019 event are situated in the northeastern Murkvami catchment, particularly along the ridge from Mt. Banguriani to the central moraine. The two main detachments were estimated at ~ 1.3 million m³ and ~ 300,000 m³. Post-event drone imagery revealed steepening of the southern wall and the formation of fresh vertical cracks and probable shear fractures, indicating ongoing instability. The exposed rock mass is highly susceptible to weathering processes, such as freeze-thaw cycles, precipitation, and glacial meltwater infiltration, reducing shear strength along discontinuities.

Data-driven hazard mapping using geomorphological analysis and process-based simulation

The hazard assessment was based on detailed geomorphological mapping to spatially delineate release, transit, and deposition zones, with emphasis on slope movements and other mass wasting indicators. The aim was to identify controlling conditions and characterise hazard sources, mechanisms, magnitudes, and frequencies. The fast-moving debris flow likely entrained unconsolidated glacial sediments from the valley floor, moraine material (grey schist) from the left-lateral mid-valley moraine, and debris-covered ice from the lower Murkvami glacier tongue. The flow overtopped the moraine separating the two sub-catchments. Dimensions of the initial deposition in the Mestiachala valley were measured using a TruPulse with an area of approximately 350 m x 260 m and a thickness of 6–8 m, terrain analysis resulted in at least two distinguishable waves. Terrain analysis revealed at least two distinct waves, with an estimated total volume of 540,000–730,000 m³ (~ 270,000–365,000 m³ per wave). Given the estimated volume and assuming a water content of up to 75%, consistent with the rapid flow indicated by the deposition pattern, a liquid discharge of approximately 90,000–120,000 m³ is inferred following equation (1) as

$$C_V = \frac{V_{Debris}}{V_{Debris}+V_{Liquid}} \qquad (1)$$

with $C_V = 0.75$, V_{Debris} being the volume of the solid and V_{Liquid} the volume of the liquid part of the debris flow. Aside from minor ponding, no field evidence indicates prolonged blockage of the Mestiachala River; a rapid breaching immediately after the event is likely. Downstream sediment deposition at HPP1 primarily resulted from channel erosion below Intake 1, with incision depths of approximately 2–3 m. The final hazard map (Fig. 2) formed the basis for documentation in accordance with relevant Austrian Standards (e.g., ONR; Fig. 3).

Using r.avaflow, flow velocities, heights, and impact pressures were back-calculated. Simulations were based on DEM-derived topography, with initial conditions and model parameters adapted from literature and prior r.avaflow applications [*Mergili et al., 2020*]. Parameter calibration aimed to optimise agreement with observed impact areas and deposited volumes. Fig. 4 (left) illustrates deposition heights along the full track of the 2019 compound event. Significant deposition occurred below the middle moraine – separating the Murkvami and Banguriani valleys – due to reduced slope gradient. Similar deposition areas were also mapped along the transit path of the rock-ice avalanche in the Murkvami tributary. Modelled deposit heights of up to 10 m align with field measurements. Overtopping of the medial moraine produced deposits up to 2.2 m. The highest accumulation occurred at the Mestiachala confluence, where deposition reached 18–20 m (including pore space), consistent with geoelectric and in situ surveys. The initial rock-avalanche rapidly increased in speed after their release and moved downslope with frontal velocities exceeding 27.5 m/s (Fig. 4 right). When reaching the glacier tongue velocities between 20.7 and 27.5 m/s were observed, as well as an entrainment of ice in the flow. Speed decreased in gentler terrain but increased again near the valley junction due to slope steepening. The mass movement reached an average velocity of 15 m/s (54 km/h), implying a travel time of around 240 seconds (4 minutes) from release to deposition. The hazard assessment conducted for Murkvami Valley was extended to the entire area, resulting in recommendations for technical mitigation, monitoring, and early warning measures.

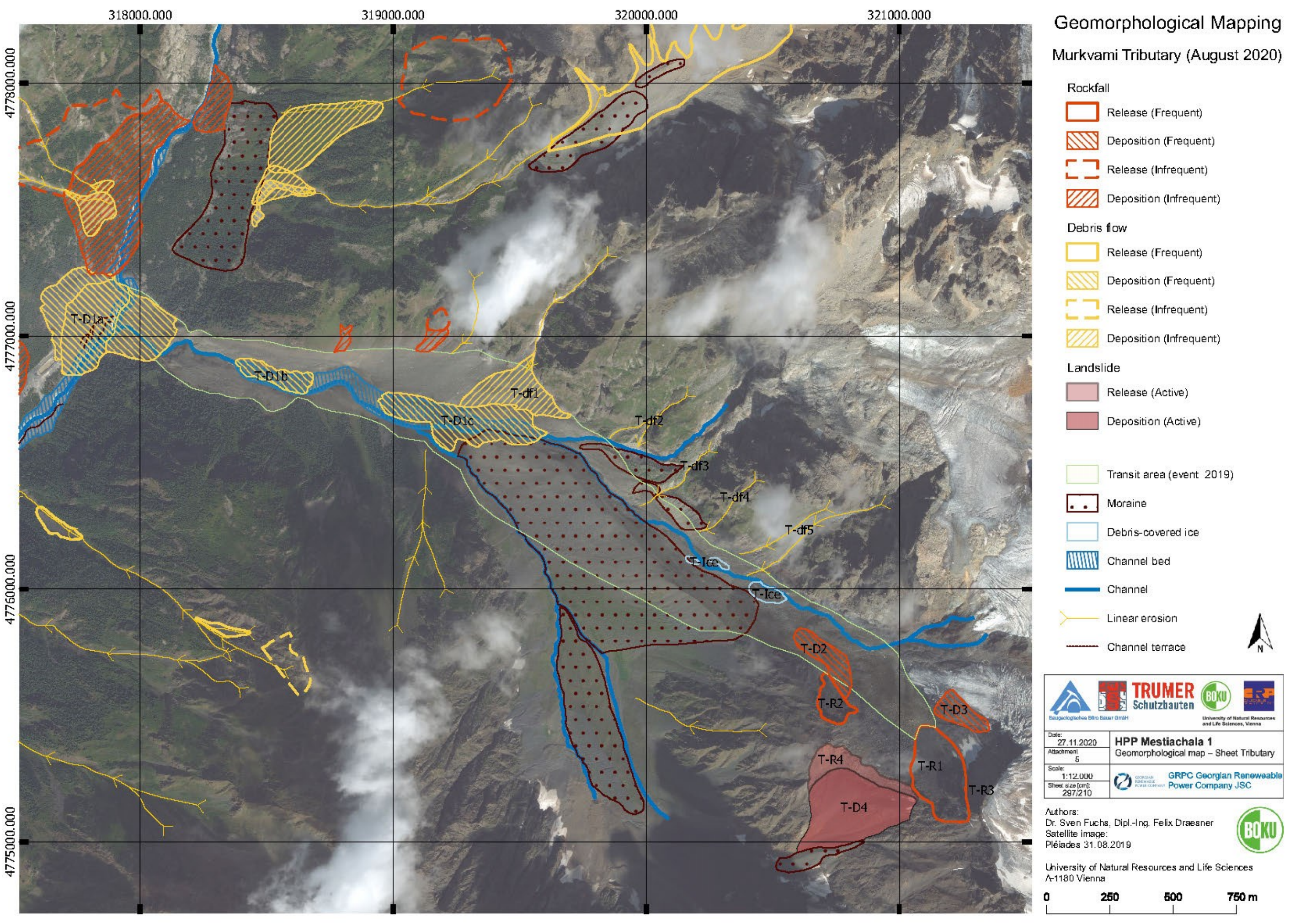

Fig. 2. Geomorphological map of the Murkvami valley, showing rockfall (red) and debris flow (yellow) processes as well as the overall landslide susceptibility as well as other morphological and hydrological features. Source: [*Fuchs et al. 2020*]

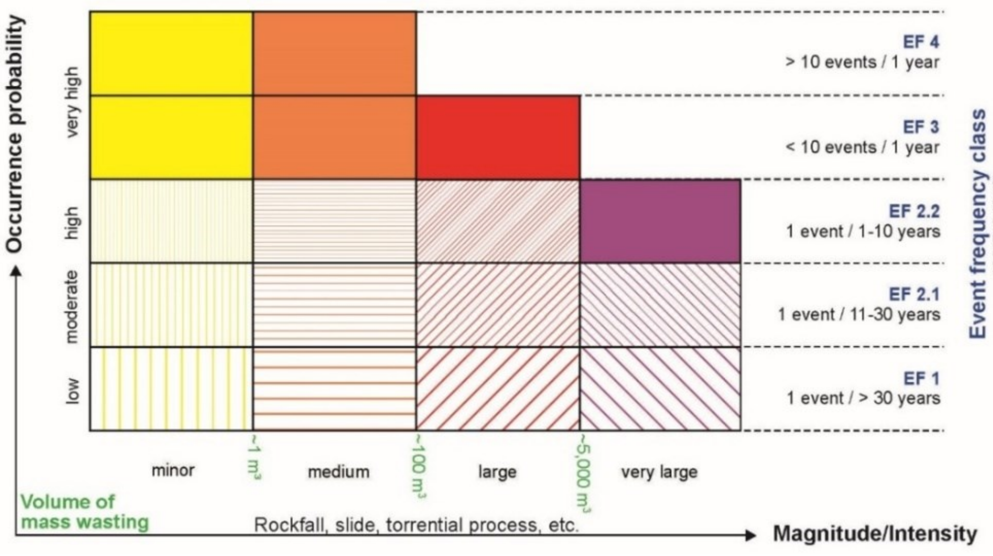

Fig. 3. Geohazard matrix for mass wasting processes differentiating volume (intensity) and frequency of rockfall, sliding processes and torrential processes. Classification based on the Austrian Standard ONR 24810:2020 01 with minor adjustments [*Austrian Standards Institute, 2017*]

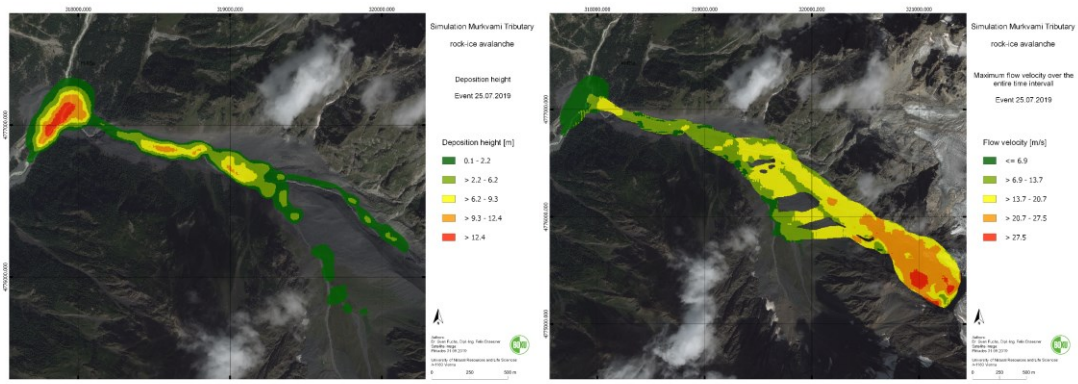

Fig. 4. Simulation of the 2019 event in the Murkvami valley; deposition height (left) and velocity (right). Source: [*Fuchs et al., 2020*]

Targeted protective engineering where technically viable and cost-effective

Technical rockfall protection measures were installed in high-risk areas with vulnerable infrastructure, particularly the newly relocated intake structure of the Mestiachala HPP. This structure was moved following the 2019 event to avoid zones prone to large compound hazards. In addition to rockfall events, the future location of the rockfall barrier was also identified as an active avalanche path, requiring consideration of an additional load scenario (avalanche impact) during the design and verification process. Simulations indicated rockfall energies of up to 1,050 kJ and bounce heights of up to 3 m at the barrier site. These values informed the design parameters – energy absorption, height, length and anchorage – according to ONR 24810. Due to the ‘high economic consequences’, the barrier was classified as consequence class CC3, necessitating a safety factor of 1.15 for both load and resistance. To prove the concept with CC3, a safety factor of 1.15 must be applied to both the load and the resistance. In accordance with this concept, a Trumer Schutzbauten rockfall barrier with 2,000 kJ of resistance (TSV-2000 ZD H4), which has been tested and certified in accordance with ETAG 27 and the European Technical Assessment ETA-14/0357, has been installed.

Fig. 5. A Trumer Schutzbauten TSV-2000-ZD H4 hinged rockfall barrier with 8 m post spacing has been installed to protect the new intake building of the Mestiachala HPP

Integrated monitoring and alert systems combining remote sensing with in-situ catchment data

For the monitoring and alarm system to be effective, the information and alarms issued must be reliable, provide sufficient information for sound decision-making, and be timely enough to allow appropriate action to be taken. In this context, the main design parameters of the sensor system are therefore: 1) the magnitude(s) of critical events that the system must be able to reliably detect; and 2) there must be sufficient lead time between event detection and alarm dissemination, and the event's impact on the endangered structure. The necessary lead time for alerts is mainly determined by the time required to evacuate people from the affected areas. According to the provided flood response measures plan [*Mestiachala Energy, 2023*] up to six minutes are needed to evacuate people from the powerhouse building to a safe location. Ideally, therefore, the monitoring system should deliver an alarm regarding a critical event six minutes before it affects the powerhouse.

For processes such as debris flows in main channels, critical event magnitudes are derived from 100- and 500-year flood design discharges upstream of the intakes. For the new intake 1, for example, numbers are 124.7 m^3/s and 178.18 m^3/s for the 100-year and 500-year event, respectively [*Hydroconsult, 2019*]. Additionally, the system can differentiate between flows with low and high sediment content, enabling a more accurate assessment of the event's impact on the structure, including the potential blockage of the flushing gate channel. A debris flow event with a 100-year discharge poses a much higher threat than a low sediment discharge of the same magnitude and should therefore be dealt with differently in terms of the required actions. Based on modelling results for extreme debris flow events in the Mestiachala valley, flow velocities of 8–13 m/s can be expected [*Fuchs et al., 2020*]. Fig. 6 shows the respective available lead time for a monitoring station positioned upstream of the powerhouse, depending on its position along the valley. In order to provide the required lead time of six minutes, plus one minute for data processing and alarm dissemination, a monitoring station needs to be positioned within the areas shown in green (seven minutes or more).

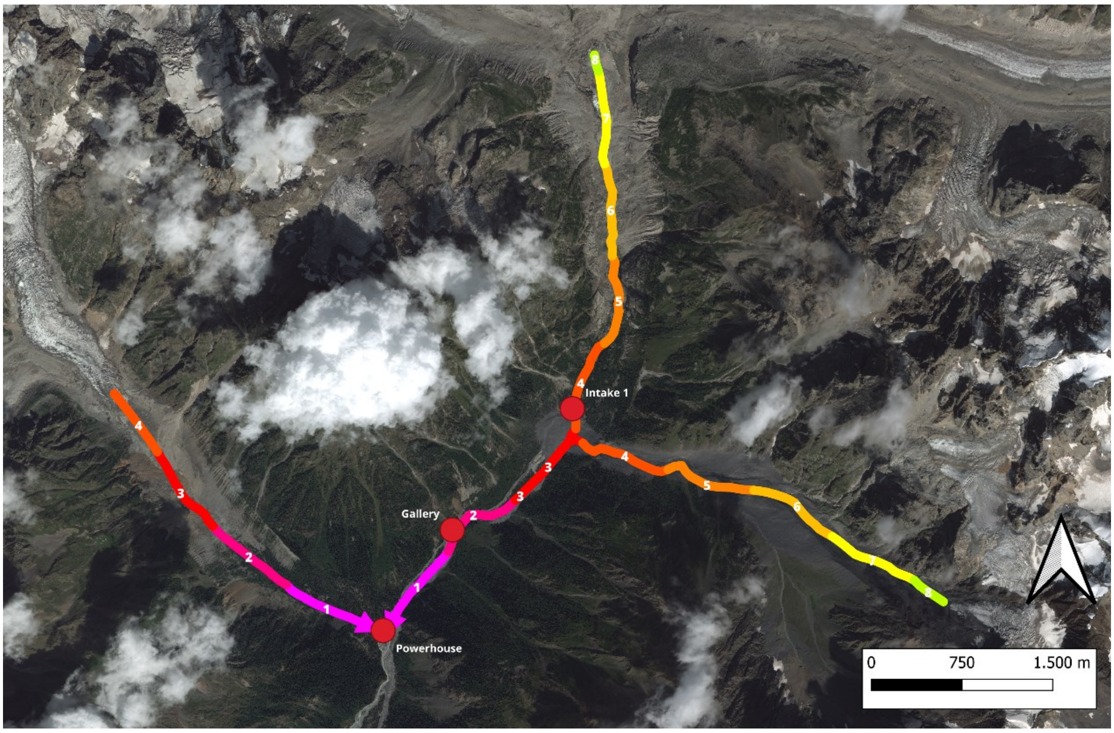

Fig. 6. Available lead time for large flow-type events with an average velocity of 13 m/s for a monitoring station position upstream of the powerhouse, depending on the location along the valley

The AFRY Hydro DSS system acts as the central data platform for the geohazard early warning system. Data collected by the ground-based monitoring system through the LoRa® network is automatically forwarded to a local computer system for analysis and alarm generation. Alarms and automatic notifications are sent to relevant stakeholders in a timely and accurate manner via email and SMS, and an acoustic alarm system has been installed at the powerhouse.

An early warning system that can predict potential hazards with longer lead times is currently under development. This system will require longer observation times and data analysis from the installed monitoring stations and weather station, as well as the correlation of the measured data with the Global Precipitation Monitoring (GPM) and Global Forecasting System (GFS). Over the next few years, warning levels based on thresholds for different hazardous processes can be defined using a data post-processor.

Ongoing high-resolution surveillance via local and drone-based remote surveys

In the inaugural year of its operation, the aircraft completed over 250 autonomous flights, accumulating a total distance of 1,041 kilometres. As a consequence of the drone survey, 1,512 locations have been identified for further investigation, and a dataset comprising almost 2,100 high-resolution images has been compiled. The images are analysed on a weekly basis by experts to interpret changes visible in the terrain, such as rockfall events, gully erosion, cracks and new joints in the rock cliff from the 2019 event, and the formation of new glacial lakes or the damming of such. The weekly drone reports and images are also integrated into the AFRY Hydro DSS web-based platform. This allows the operator to review and analyse all relevant data, images and reports in one place.

In four cases, the drone was deployed to undertake an emergency mission. The objective of this mission was to ascertain the cause of a sudden change in the discharge of the Mestiachala river or a sudden change in the water's colour. Such changes can be indicative of a damming event. It is evident that such emergency starts and clarifications must still be performed manually. These are operated remotely by UAV pilots located in Austria, and this is accomplished within a short time.

In summary, it can be posited that the utilisation of unmanned aerial vehicles (UAVs) for the surveillance of the catchment area offers a substantial added value in conjunction with stationary monitoring systems. In instances where ground-based monitoring stations are unable to provide adequate oversight, or in areas that are inaccessible by ground-based stations, visual assessments can be conducted by airborne surveillance. This facilitates the timely identification of morphological alterations or significant gravitational phenomena. Moreover, from an economic standpoint, drone flights exhibit a marked superiority in efficiency when compared with conventional helicopter flights or the development and manual inspection of these areas within the catchment area.

Fig. 7. DJI drone dock 2 taking off from the intake building of Mestiachala HPP

Discussion

The integrated framework presented here signifies a substantial advancement in natural hazard assessment and risk management, particularly in remote mountainous regions. The approach is characterised by a concerted integration of field-based hazard assessment, process simulation, engineering design, real-time monitoring, and UAV-based local-scale surveying. This multidisciplinary strategy utilises the complementary strengths of remote sensing, spatial analysis and geospatial visualisation to enhance understanding and prediction of debris flow hazards.

Field investigations remain fundamental, providing a foundation for assessments that are grounded in geomorphological, hydrological, and geological evidence. This evidence informs the development of realistic risk profiles. Process simulations extend this understanding by replicating complex dynamic events, such as debris flows, rockfalls and floods. This allows for scenario testing that quantifies hazard magnitude and potential impacts. This aspect is instrumental in informing the engineering design pillar, thereby enabling the implementation of site-specific, cost-effective mitigation measures that address both safety and environmental concerns. The integration of contemporary monitoring technologies, encompassing satellite data, ground-based sensors, and drone surveys, facilitates the acquisition of real-time situational awareness and the provision of early warning capabilities, both of which are pivotal for the timely implementation of emergency responses. Continuous UAV monitoring provides a detailed and up-to-date perspective on catchment changes, thus supplementing traditional data sources and supporting adaptive management.

Nevertheless, challenges persist in the refinement of these methodologies to enhance their accuracy, efficiency, and accessibility. The enhancement of predictive capabilities and the facilitation of sustainable hazard management in vulnerable mountain communities will be significantly impacted by advancements in sensor technology, data integration, and modelling fidelity.

The collaborative endeavour undertaken by Caucasus Science and Engineering LLC (CSE) and its partners serves as a prime exemplar of the efficacy of multidisciplinary and multi-institutional cooperation, thereby unifying expertise, resources, and innovation to develop and implement this holistic approach. Their work establishes a novel benchmark for natural hazard risk management, proffering scalable solutions that demonstrate adaptability to diverse mountainous settings on a global scale.

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