ANALYSIS
of Existing International Methodologies and Best Practices for Monitoring Debris Flow Hazards and High-Mountain Lake Outburst Events

In general terms, the concept of monitoring is understood as "a system of continuous observation of phenomena and processes occurring in the environment and society, the results of which serve to inform management decisions aimed at ensuring the safety of people and economic assets" [1]. Within this system, the evaluation and control of an object, as well as the management of its state, are carried out depending on the influence of specific factors.

For the context of Kazakhstan, a more detailed definition of debris flow hazard monitoring has been developed, which is understood as "the regular measurement, analysis, and forecasting of characteristics indicating the potential formation of debris flows; the observation of debris flow processes influenced by changes in formative factors; the temporal and spatial forecasting of debris flow characteristics; and the early warning of populations and emergency services about the threat or occurrence of a debris flow, with the implementation of management decisions to prevent damage" [2].

Arguably, the primary component of a debris flow hazard monitoring system is the early warning of debris flow occurrences, directly aimed at saving human lives and reducing immediate material losses. The United Nations Office for Disaster Risk Reduction (UNDRR) defines early warning as "the provision of timely and effective information by competent institutions, enabling people at risk to take actions to avoid or reduce risk and to prepare effective response measures" [3].

The history of human civilization in mountainous regions includes episodes directly associated with glacial disasters in the post-glacial period, as well as practices and methods of hazard monitoring developed in response to emerging threats. One of the most significant glacial disasters is the breach of temporarily glacier-dammed lakes. The formation of other well-known moraine-dammed mountain lakes, caused by landslides or rockfalls, produces a similar situation, although such lakes may persist for hundreds or even thousands of years. Glacier dams, however robust, are inherently temporary, and their failure or breach is only a matter of relatively short time.

While glacial lake outbursts are relatively rare for an individual geographic site, they are frequent and widespread in mountainous regions. Observations of glacial lakes and their breaches, as the most visible part of a monitoring system, span several centuries. Many events related to glacial hazard monitoring have been documented in Central Europe, particularly in the Alps. Numerous glacier-dammed lakes in this region have breached multiple times. For example, the documented history of repeated breaches of Lake Mattmark, formed by the blockage of the Saaser Visp Valley by the Allalin Glacier, spans the period from 1589 to 1920 [4]. Lake Rutor, associated with the glacier of the same name, experienced repeated outbursts from 1594 to 1864, and Lake Eissee, dammed by the Fernagt Glacier, breached between 1600 and 1848 [5]. Lake Märjelen, near the Great Aletsch Glacier, breached repeatedly from 1813 to 1947 [6].

Glacial lake outbursts are also widely documented in Norway. Lake Demmevatn, dammed by the Rembesdalskaak Glacier, experienced breaches from 1891 to 1938, and Lake Melhedalsvang, near the Melhedal Glacier, from 1855 to 1901 [7]. Breaches have been observed in Iceland, where the largest body of water, Lake Grímsvötn, with a volume of approximately 7 km³, accumulates water from subglacial melting driven by volcanic heat. Outburst floods occurred regularly there from 1861 to 1971 [8, 9].

In Alaska, notable examples include Lake George, formed by the Nick and Tulsequah Glaciers, which emptied regularly from 1899 to 1951 with peak discharges of 10,200 m³/s [10], and Lake Tulsequah, which breached from 1910 to 1958 [11]. Glacial lake outbursts are also known in the subpolar northern latitudes, including Svalbard, Greenland, the Canadian Arctic Archipelago, and Novaya Zemlya [7, 12, 13].

The Andes in South America have experienced numerous glacier-dammed lake outbursts. Significant cases include the Lake Rio Blanco breach in 1913 [14], and in 1934, a dammed lake formed by the advance of the Nevado Glacier caused major destruction in the Mendoza River Valley [15].

Asia has also recorded significant outburst floods, particularly in the Karakoram, Himalayas, and Tibet. Over the last 150 years, more than 50 glacially dammed lake breaches have occurred in the Karakoram [16]. The largest lake, Gapschen, in the Shyok River Valley, dammed by the Chong-Kamdan Glacier with a volume exceeding 3.5 km³, experienced multiple breaches between 1780 and 1932 [17].

This brief overview of glacier-dammed lake outbursts demonstrates that their heightened activity coincided with the so-called Little Ice Age, when significant climate cooling led to the expansion and active advance of glaciers in various mountain regions of the world. The increased risk of outbursts necessitated the establishment of monitoring of glacial lakes even when scientific understanding of hazardous processes was in its infancy.

It is therefore evident that human concern for the prevention of glacial hazards has a long history. As in many other areas, historical practices were sometimes driven by ignorance or superstition. For instance, in 1607, a chapel was built on Lake Rutor in the Alps; in 1677, a vagrant suspected of causing glacial floods was executed at Lake Eissee (Fernagt Glacier); and in 1718, a religious procession was organized on the Gurgul Glacier in the Lang Valley. All these measures were undertaken solely to prevent glacial debris flow hazards [18, 19].

In many cases, residents of downstream settlements would independently send observers upstream to provide timely reports on the formation of glacier-dammed lakes prior to their potential outburst. As a rule, these early forms of organized early warning systems proved to be effective.

In the twentieth century, the glacial situation in mountainous regions changed significantly. Glaciers stabilized, retreated, and widely entered stages of degradation. River valley blockages caused by active ice nearly disappeared. At the termini of mountain glaciers, modern moraine ridges formed, behind which moraine-dammed glacial lakes appeared. Following retreating

glaciers, these lakes developed rapidly, increasing in volume and, upon reaching significant size, began to breach, generating glacial floods and debris flows.

During the 1940s and 1950s, active lake formation in the Cordillera Blanca (Peru) resulted in catastrophic debris flows. On 13 December 1941, in the upper reaches of the Cope River, a debris flow from the breach of Lake Palcacocha destroyed the city of Huaraz. Under similar circumstances, on 17 January 1945, a large area of the Chevin-de-Uantar region was devastated, with layers of debris burying remnants of ancient Peruvian architectural structures, including the famous Castillo. These events prompted the government to establish a comprehensive program of preventive measures for glacial lakes, including the creation of monitoring and early warning systems in the most hazardous river valleys [20, 21].

On 22 August 1954, a lake breached at the confluence of the Chieva and Roseg Glaciers in the upper reaches of the Inn River (Rhaetian Alps). In the Western Alps, in the Gadmen Valley near the Stein Glacier, a lake breach occurred in late July 1956 due to the failure of a moraine dam, producing a substantial outburst flood along the Gamderwasser River. In Switzerland, near the Flüchorn Peak at the Valais Glacier, lake outbursts in 1957 and 1968 generated debris flows with volumes of up to 400,000 m³, impacting the Saas-Balen area. In response to the surge of glacial debris flows, several Alpine countries in Europe implemented population monitoring and early warning measures [22, 23].

In the Himalayas, on 21 September 1964, Lake Gelhaipuco in the upper Pumqu River Basin, with a volume of approximately 25.5 million m³, breached. The lake level dropped by 40 meters, nearly destroying the dam. A powerful flood and debris flow followed, damaging the Chentang–Raivo roadway. In the Pumqu Valley, the flow caused severe damage to neighboring areas in Nepal.

On the night of 11 July 1981, a lake in the upper reaches of the Zhangzangbo Valley, 1.7 km in length and covering 0.643 km², suddenly breached. The flood peak occurred 23 minutes after the breach began, with a discharge of 1,600 m³/s and a total flood volume of approximately 19 million m³. A 50-meter-deep and 40–60-meter-wide breach formed in the modern frontal moraine. The debris flow destroyed a roadway and bridge between Nepal and China and damaged the water intake of the San Koshi hydroelectric station, resulting in significant material losses in Nepal.

At the boundary of the Kangma and Sikkim river basins in Sizang (Tibet), at an altitude of 4,560 m, lies the moraine-dammed Lake Xubixiamma, 450 meters long and over 100 meters wide. The terminal moraine rises 70 meters above the riverbed. On the night of 10 June 1940, a glacier behind the lake collapsed into it, triggering a wave that breached the dam and caused the lake to overflow. Water marks indicate peak discharges of 3,690 m³/s and flow velocities of 7.7 m/s, with the event concluding within approximately 30 minutes. The outburst caused water levels in the Xiasima River at Yadong to rise by 4–5 meters, flooding streets and destroying several houses.

Chinese reports also record the outburst of Lake Sangwang on the Bhutanese border, which occurred on the night of 16 July 1954. The event generated a 40-meter-high wave that traveled down the valley, forming an alluvial fan up to 3–5 meters thick on the plain [24].

On the night of 7–8 July 1998, the breach of a mountain lake near the Alaudin and Artabashi Glaciers on the northern slope of the Alay Range produced a powerful debris flow along the Aksu–Shahimardan-say river system. According to operational assessments by the Kyrgyz Ministry of Emergency Situations from helicopter surveys, the disaster was caused by the subsidence and partial failure of a moraine dam at approximately 3,700 meters, resulting in the release of about one-third of the glacial lake volume into the downstream valley. The resulting debris flow swept along the Aksu River and then along the Shahimardan-say River into the Fergana Valley. The densely populated southern Fergana Valley included several settlements in the Kadamjay District of the Kyrgyz Republic and the Shahimardan enclave of Uzbekistan. According to operational data, dozens of houses, bridges, infrastructure, and hydraulic structures were destroyed, and 46 people lost their lives.

These cases illustrate that breaches of moraine-dammed glacial lakes (the Kazakh equivalent being moraine or moraine–glacial lakes) have become widespread phenomena, replacing the nearly extinct breaches of lakes dammed by active ice.

With the advancement of debris flow science, modern methods for monitoring glacial debris flow hazards have developed significantly. Observation and control of glacial lake development are now primarily conducted through remote sensing, including satellite imagery, UAV surveys, GIS applications, and Digital Elevation Models for obtaining morphometric characteristics of glacial lakes, detailed analysis of visual information, identification of structural elements of moraine dams, and mapping of glacial outflow pathways.

The identification of potentially hazardous glacial lakes and the assessment of associated risks, including ranking critical lakes, is a primary task. Once critical lakes are identified, engineers, planners, and scientists must design and implement risk reduction measures. These measures include monitoring to detect hazardous changes in time, early warning systems to provide populations and stakeholders with sufficient time to act, and mitigation measures to alter conditions and thereby reduce risk.

Effective monitoring of potentially hazardous lakes and the implementation of early warning systems are a critical component of disaster preparedness, as they can significantly reduce human casualties and material damage. These systems can utilize satellite imagery, unmanned aerial vehicles equipped with portable cameras, telecommunications, and broadcast networks. The following summarizes international experience in organizing and conducting debris flow hazard monitoring and high-mountain lake outburst monitoring.

India, Nepal, and Bhutan. These countries have made substantial progress in monitoring and early warning for debris flow hazards. In India, the National Commission for Climate Change Mitigation and Adaptation also undertakes efforts in this field. Notably, an early warning system exists in the Satluj River Basin. Measures have been implemented for flood monitoring and early warning, particularly for flash floods [25], which also apply to outburst floods. Telemetry stations installed by the Snow and Hydrology Department of the Central Water Commission at Sumdo (confluence of the Parechu and Spiti Rivers), at the confluence of the Spiti and Satluj Rivers, and as part of the Napta-Jakri project in Dubling, are designed to monitor any increases in water levels and transmit data. These measures aim to address shortcomings in early warning systems identified following the 2000 flood and to ensure the safety of hydroelectric projects. A similar wireless

network is employed by border security forces at Recong Peo. Bhutan's National Climate Change Adaptation Action Plan places significant emphasis on reducing vulnerability to glacial debris flows. India's Automatic Geological Hazard Early Warning System integrates hazard assessment with warning dissemination [29].

This system is proposed to be built on Internet and cellular networks using georeferenced data, with modules for data input, processing, hazard assessment, output, and warning dissemination. Its flexibility allows the integration of multiple hazard assessments and communication systems, resulting in a comprehensive early warning network. The system was trialed for landslide hazard assessment in India, incorporating landslide-inducing factors, rainfall forecasts, and a landslide hazard map, with modeling intervals of 10–50 seconds. Such a system is particularly useful in densely populated areas.

Early warning systems in the Tsho Rolpa and Tamakoshi Valleys, Nepal. Tsho Rolpa Lake in the Tamakoshi Basin, Eastern Nepal, fed by the Trakarding Glacier, is one of the few glacier lakes studied in detail, including field investigations of the lake and downstream valley [26]. Research in the 1990s indicated that the lake, which had risen to the moraine saddle acting as a natural dam, posed a very high risk. Concerns arose that the downstream Rolwaling Valley could be flooded by a catastrophic outburst, potentially causing significant human casualties and severe damage to infrastructure, including the 60 MW Khimti Hydroelectric Project. Documented attempts to reduce the risk were extensive. While an early warning system was deemed effective, local interference posed challenges.

Early warning is required only during periods of identified significant risk, such as during project construction or other circumstances. In June 1997, the Government of Nepal installed an emergency early warning system for local villages and the hydroelectric project, due to the rapid deterioration of the moraine dam and rising lake levels. Warning systems were established in the Rolwaling and Tamakoshi Valleys. Military camps were positioned at the moraine edge and in Na, the village closest to the lake, while police posts were installed in Na and Bedding. These posts were equipped with high-frequency radios maintaining regular contact with headquarters in Kathmandu. Military posts also had satellite phones, one of which was used to communicate twice daily with the Ministry of Home Affairs Disaster Warning Service. In the event of a lake breach, Radio Nepal would broadcast an emergency alert [27].

In January 1998, a contract was signed with a Canadian company to develop the Tsho Rolpa early warning system, financed by the World Bank at a cost of USD 1,032,000. The first system was installed in May 1998. Breach sensors were designed to detect an outburst flood and transmit a signal to the control station, which would trigger the warning process. The population was alerted via audible alarms. The system is fully automated and requires no human intervention.

The debris flow detection system comprises six water-level sensors installed along the riverbank immediately downstream of the lake to detect a breach. Three sensors are connected via armored and shielded cables to two independent transmitting stations, located 80 meters above the sensors for safety. The sensors are positioned at different heights, enabling the identification of water rise stages. The sensor network detects the lake breach immediately and transmits an alarm signal within two minutes. A remote station in Na village warns the local population of the threat.

The warning system includes 19 alert and relay stations in 17 villages across the Rolwaling and Tamakoshi Valleys (see Figure 1). Warning stations are mounted on 4.67-meter masts, with antennas extending to 5 meters above ground. Lightning rods and solar panels are installed on the same mast. The transmitter and siren relay are housed in a metal box attached to the mast. Sirens operate on compressed air cylinders for two minutes, producing a sound of 80 decibels audible up to 150 meters, with backup electric sirens operating for four minutes. The system relies on line-of-sight radio technology, with signals relayed from station to station.

The early warning signal is transmitted automatically upon detection of a lake breach. A secondary component of the system is located at a meteor monitoring station in Dhangarhi, Western Nepal, capable of transmitting signals up to 1,600 km. Several warning and sensor stations can send and receive signals via this meteor station, providing additional system redundancy.

Figure 1. Early Warning System for Debris Flows in the Tamakoshi Valley: a – Lake Breach Detection Station; b – Debris Flow Warning Station with Siren.

Thus, the meteor monitoring station provides communication between stations located in the Rolwaling and Tamakoshi Valleys and the monitoring station in Kathmandu. In 2002, four years after installation, the early warning system ceased functioning despite its reliability and the use of advanced technologies. This failure was due to insufficient local community engagement and political instability in Nepal, during which public safety concerns became secondary. Consequently, the system was dismantled, and its components were repurposed by the local population. Residents believed the lake level had been reduced to a safe level and lost interest in the warning system. Additionally, several false alarms issued by the system contributed to its decline in credibility.

Early Warning System in Upper Bhote Koshi, Nepal. Another example of an early warning system is located in Eastern Nepal. Installed in 2001 for a hydropower project on the Upper Bhote Koshi [28], the system consists of two remote sensor stations and data loggers near the Friendship Bridge at the Nepal–China border. The loggers receive, analyze, and transmit data from the sensors. In the event of a rapid rise in water level, the system sends an alert to the hydropower project. The system includes seven lake breach sensors at the Friendship Bridge, one of which is an ultrasonic water-level sensor, and six are float-type sensors. The system operates on VHF radio signals, with an alert siren powered by compressed air, producing a sound of 127 decibels audible at 33 meters. Five such stations are installed along the river, but the system is operational only at the Nepal–China border.

It takes only six minutes for the alert signal to reach the hydropower project. To be fully effective, the system would need to be extended upstream into China. As of 2009, the system remained operational primarily to support the hydropower project.

Monitoring of Imja Lake in the Everest Region, Nepal. Imja Lake is one of the fastest-growing lakes in the Himalayas. ICIMOD monitors the lake to develop an early warning system. A remote sensor system, employing geo-ICT tools and technologies, was developed in cooperation with the Department of National Parks and Keio University, Japan (Figure 2) [28].

Figure 2. Monitoring System for Imja Lake: a – Upper field server at Imja Lake; b – Solar panel of the field server; c – View of the lake from the upper field server; d – View from the lower field server toward Namche Bazaar.

Two observational devices, or field servers—Internet-enabled robotic systems for field monitoring—were installed on the lake shore at an elevation of 5,000 m and near the nearest

settlement, Namche Bazaar, in 2007. The field servers capture images of the lake and Namche Bazaar, as well as meteorological data, which are transmitted in real time via Wi-Fi to a server in Japan. The Department of Hydrology and Meteorology conducted outburst flood modeling using a dam breach model. Detailed hazard mapping and population risk assessments related to landslides and debris flows are also planned.

The International Centre for Integrated Mountain Development (ICIMOD) is a regional intergovernmental training and knowledge-sharing centre serving eight member countries of the Hindu Kush Himalayan region—Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan—as well as the global mountain community. ICIMOD conducts outburst flood modeling for multiple lakes, including the assessment of socio-economic vulnerability for downstream areas. Areas and settlements have been classified into four risk levels, based on potential losses under worst-case lake outburst scenarios.

Nepal's Department of Hydrology and Meteorology developed a flood forecasting system for the Karnali River Basin based on probabilistic modeling with visual representation of results [26]. This system has increased lead times from 2–3 hours to 7–8 hours and is planned for nationwide implementation. Nepal currently operates 286 meteorological stations and 170 hydrological posts. In the Karnali Basin, seven hydrological posts and 25 rainfall measurement stations function automatically, maintained by local communities. The automated rain gauge network is integrated with the national early warning system via the Internet, transmitting data every 15 minutes. During rainfall events, flood warning bulletins are published on the government website and disseminated to local communities through communication channels, including messaging applications. Warnings are issued automatically when critical thresholds are exceeded. Sirens are activated at critical water levels, and alerts are sent to local authorities, emergency services, the army, and media outlets. Local warning systems, such as sirens and loudspeakers, are also mobilized, alongside first response, search, and rescue teams.

Early Warning System in Lunana, Bhutan. The Lunana area, located in the upper Pho Chhu River Basin in west-central Bhutan, has been a focus of Bhutanese authorities due to its hazard potential. The outburst of Lugge Tsho Lake on 7 October 1994 caused substantial damage and 23 fatalities [26]. A manually operated early warning system was installed by the Flood Warning Section of the Department of Energy. Two staff members were permanently stationed at Lugge Tsho Lake, equipped with wireless and satellite phones for reporting water levels and issuing alerts to local populations. Several rain gauges were installed on the lake and along the river. The Japan International Cooperation Agency (JICA) and Bhutan's National Heritage Commission signed an agreement to study outburst floods, develop a satellite data-sharing network for research, compile a historical lake inventory, assess risk factors and mechanisms of outburst floods, and recommend effective mitigation measures, including early warning systems.

An effective early warning and monitoring system has also been established for Cirenmaco Lake, situated at an elevation of 4,612 m in Tibet, near the China–Nepal border, within the Poigu River Basin (Figures 3 and 4).

Figure 3. Early Warning System Installed at Cirenmaco Lake, Comprising: a – Monitoring of the lake and glacier; b – Monitoring of the surrounding environment and river; c – Monitoring of lake water level; d – Monitoring of river water level; e – Dynamic monitoring of the moraine dam.
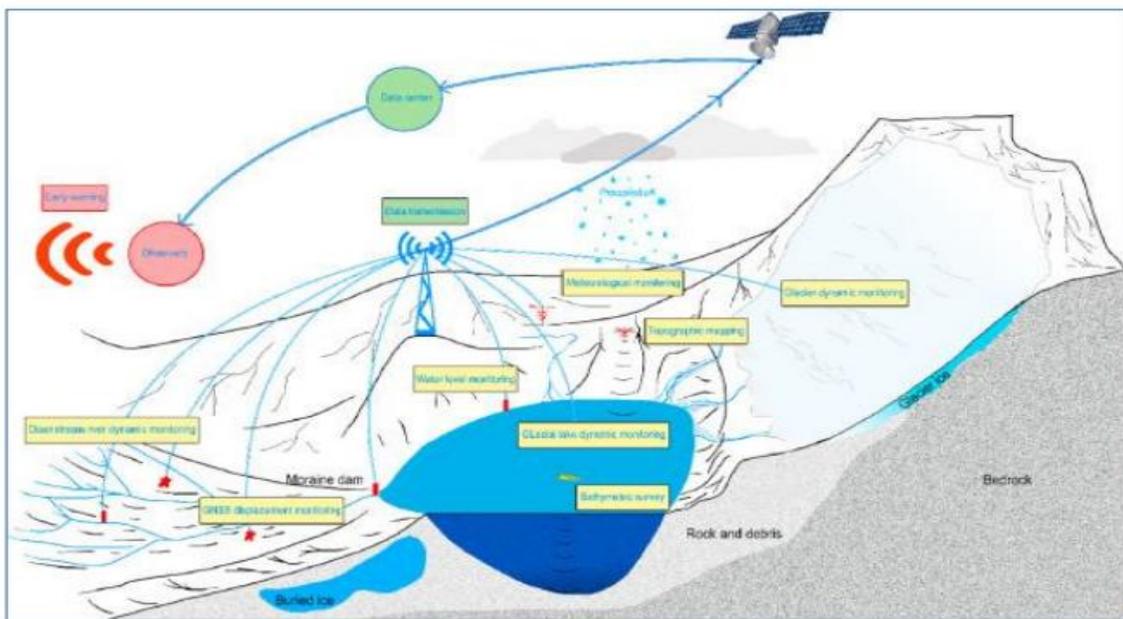

Figure 4. Diagram of the Main Components of the Early Warning System at Cirenmaco Lake.

Overall, the early warning system at Cirenmaco Lake encompasses monitoring of the lake, glacier, and outflowing river, including observation of water levels, the dynamic condition of the moraine dam, bathymetric monitoring, topographic mapping, data transmission, and early warning signal processing.

Early Warning Systems in Europe. In 1995, four seismometers were installed in the Eastern Italian Alps at intervals of 1 km on sections not directly exposed to debris flows. On 22 June, 5 July, and 8 July 1995, three debris flows were recorded, allowing the estimation of their travel speeds. Seismometers are capable of detecting debris flows at a distance when integrated into an automated monitoring and warning system [30].

In the Swiss Alps, an early warning system for debris flows operates in the Canton of Valais [31]. Since 2000, a debris flow monitoring station has been active in the Illgraben Valley within the Rhone River Basin. The warning system consists of four modules: hazard awareness and preparedness, debris flow detection and alerting, geomorphological observation of debris flow sources, and a weather-forecast–based early warning module. The system automatically issues an alert 5–15 minutes before the arrival of a debris flow or flood. In its first year, 20 automatic alerts were issued—20 visual and siren warnings—for three debris flows and sixteen floods, with only one false alarm. All events were caused by precipitation exceeding critical intensity and duration thresholds.

The increasing frequency and severity of individual hydrological hazards in Switzerland prompted the development of a comprehensive information platform for natural hazards [32]. Its objective is to provide integrated, real-time, visually accessible safety information through warning centers (Figure 5).

Figure 5. Automated Monitoring Station at a Glacial Lake (Bernese Alps, Switzerland).

This enhances coordination between warning centers, particularly when issuing joint bulletins for critical, multi-hazard events. The platform is intended to serve as a central information hub for natural hazards in Switzerland and is based on Internet technologies.

In the province of Bolzano-Bozen in the Eastern Italian Alps, a new debris flow monitoring and early warning station has been established in the Gadria River Basin [33]. The station comprises rain gauges, radar sensors, geophones, video cameras, piezometers, and soil moisture sensors. Radio technology is used for data transmission and alert dissemination. The station has been operational for three years, recording two debris flows. The information and warning system for small- and medium-sized debris flow catchments has been successfully tested in multiple regions of Switzerland, collecting data such as weather forecasts, precipitation measurements, water levels, and discharge modeling [34].

The Swiss company Geopraevent develops and installs natural hazard monitoring and early warning systems for debris flows, avalanches, and landslides. In the Spreitgraben Valley, where debris flows threaten a roadway, Geopraevent installed a monitoring system including several trigger wires stretched across the debris channel, a radar water-level sensor to estimate debris flow magnitude, and an infrared-equipped webcam for real-time day-and-night observation. The monitoring system is integrated with a warning system that activates when measured parameters reach critical values. Alerts include automatic traffic lights, sirens, and SMS notifications to local authorities.

At the request of the Government of Georgia in 2014, Geopraevent installed a debris flow early warning system in a valley affected by regular rock and ice avalanches from Mount Kazbek [34]. These avalanches and resulting debris flows block the strategically important Georgian Military Road connecting Georgia and Russia. The system consists of two stations: one monitoring the Devdorak Glacier, where ice-rock avalanches originate, and a second observing the debris flow channel. Two cable-trigger devices are installed to detect debris flows. The station locations were selected to provide sufficient time for road closure and evacuation of people and vehicles. Upon debris flow occurrence, the border service receives an automatic radio alert, and SMS notifications are sent to local authorities, who can monitor the situation in real time, ensuring safe transit along this strategic road.

In cooperation with the Government of China, Geopraevent installed a monitoring station at Kyajar Glacier Lake in Xinjiang. The lake, with a volume of 20 million m³, has experienced several outbursts causing destructive floods on the Zharkent River. A webcam is installed on the glacier, and several radar water-level sensors are located in the river channel. Data are transmitted multiple times per day via satellite to a central portal. When water levels reach critical thresholds, the system automatically issues SMS warnings to local authorities. The first phase of the system was installed in 2011, and the glacier station in 2012.

At three glacial lakes beneath Plaine Morte Glacier in the Oberland region of Switzerland, subaqueous pressure sensors were installed to monitor lake drainage through underground channels. River-level sensors were installed in the outflow channels, with continuous data transmission to a portal. Sudden drops in lake levels or rises in river levels automatically trigger warnings to local authorities via SMS.

Automated early warning systems for moraine-dammed glacial lake outbursts are also applied in Peru. An example is the system established in the Santa River Basin at Lake No. 513, located at 4,428 m above sea level (Figure 6).

Figure 6. Monitoring station and transmission center at Lake No. 513 (Peru).

Experience in developing an early warning system for debris flow hazards in Kyrgyzstan. At the Institute of Automation and Information Technologies (IAIT) of the National Academy of Sciences of the Kyrgyz Republic (NAS KR), scientific research on the development and implementation of information technologies for flood and debris flow monitoring and early warning has been initiated and actively progressing in recent years [35].

Valuable practical experience in implementing modern information technologies for flood and debris flow monitoring has been gained by IAIT scientists through the development and deployment of a system for warning about the onset and passage of catastrophic floods and/or debris flows caused by heavy rainfall in the Ala-Archa River Basin, or by the outburst of moraine-dammed (hazardous) glacial lakes such as Aksai, Ala-Archa, and Adygene, located in the Kyrgyz Range and forming the Ala-Archa River catchment. The operation of the developed system allows real-time risk assessment from potential catastrophic floods and debris flows and enables early-stage warning of residents in the Ala-Archa River Valley, the city of Bishkek, and numerous visitors to the Ala-Archa State Nature Park.

The effectiveness of the system was demonstrated on 31 July 2012, when a natural dam at the high-altitude Tez-Tor Lake in the Adygene Gorge failed at approximately 09:00 local time [35]. As the resulting catastrophic debris flow passed along the Adygene River, the warning system was triggered, and the emergency radio signal was received by the central station. To prevent loss of life among park visitors and staff, emergency measures were taken to alert all personnel, residents, and visitors before the arrival of the main flood wave, and they were evacuated in advance.

To expand the system's functional capabilities and enhance reliability, a hardware–software suite was developed to connect the system's base station to the Internet. Each base station is equipped with an automated operator control panel and is linked to a central server, which includes a centralized database and allows remote monitoring of environmental parameters collected by the monitoring stations via the Internet. The automated monitoring and warning

system (AMWS) has a two-tier architecture. This structure enables operators at base stations to respond promptly to the emergence of catastrophic debris flows and floods.

Based on the AMWS, a unified coordination center can be established to oversee debris flow and flood situations at the national level. Monitoring data are available in real time to any authorized Internet user. System security and resilience are ensured by specially developed AMWS operating algorithms and an anti-vandal video surveillance subsystem for peripheral equipment. The anti-vandal subsystem records video and transmits images to the base station if a moving object appears within a monitored sector up to 7 m away. Video clips are recorded only when an abnormal event occurs within the monitored sector.

In case of an emergency, the base station operator is immediately notified, and a warning is issued to potential intruders to prevent unlawful actions. A pre-recorded audio message is played through loudspeakers, activated automatically in such situations.

Geographic Information System (GIS) technologies, when sufficient source data are available, are a highly effective tool for storing, processing, and analyzing observation results [36]. One of the key advantages of GIS is its ability to perform multi-level synthesis and analysis. By integrating thematic data of various types and analyzing the results, researchers can derive new information and conduct comprehensive assessments of multiple factors and conditions influencing debris flow formation, including spatial datasets accumulated from historical studies of the debris flow area. For this reason, GIS has become a widely recognized tool for monitoring and forecasting emergencies. Its usefulness is further enhanced by the ease of working with spatially referenced data within GIS frameworks and the extensibility of widely used GIS software such as ArcGIS, MapInfo, ArcView, and others.

The Automated Monitoring System of Environmental Parameters (AMWS) for mountainous territories collects and transmits information on environmental parameters that significantly influence the formation of debris flow and flood hazards in mountain river basins. The proposed AMWS integrates the functions of a distributed monitoring system, which ensures remote data collection and preliminary processing of environmental parameters in mountain areas; an information system, which provides long-term storage of monitoring data and automated user access; and an alert system, which issues emergency warnings of potential disasters.

The system enables monitoring of a wide range of environmental parameters in mountain regions. Peripheral modules of the AMWS can connect to any sensors with analog or discrete outputs, as well as sensors with digital interfaces such as SPI, I2C, and RS-232/485.

Continuous monitoring is possible for parameters including:

● Water levels of hazardous lakes and rivers;
● Soil and air temperature and humidity;
● Pressure;
● Precipitation presence and intensity;
● Ground vibration;
● Wind speed and direction;
● Acoustic noise intensity;

- Detection of moving objects within a controlled sector.

Detection of a natural emergency occurs when any monitored parameter exceeds its maximum allowable value, such as a river's water level or an abnormal rate of change. These threshold values are set by the operator during system initialization. Upon detecting an emergency, the base station's alarm device is triggered, and the operator is notified via the operator interface.

For the proposed monitoring system in the Ala-Archa area, a working prototype of a typical "cluster station" was developed for installation at six hazard zones for floods, debris flows, avalanches, and landslides. The use of a specialized CR10X measurement and control module significantly expanded the system's capabilities. The module (datalogger) provides both measurement and communication functions.

The CR10X module includes full data processing and mathematical computation tools, as well as programming instructions for controlling the data logger. It has terminals for eight analog and six digital sensors, direct communication and telecommunications connectors, external device control, and non-volatile memory. A lithium battery powers the real-time clock. Electronics are housed in a sealed stainless steel case, protected against malfunctions.

When assembled with additional elements (sensors, modems, power supply, solar panels, battery, mounting frame, etc.), the CR10X forms a multifunctional measurement and control system. Similar systems are widely used globally, including in the USA, Canada, Israel, the Czech Republic, China, and Kazakhstan. Examples exist of CR10X dataloggers being deployed in unattended automated meteorological stations, including in Kyrgyzstan [37].

During module testing, a range of sensors was connected (temperature, humidity, wind speed and direction, solar activity, detonation, water level, etc.) with standard output signals. Standard pressure and temperature sensors for water, air, snow, and soil from companies such as Bosch, GM, and Russian manufacturers were also used; their small size allows for discrete installation. The monitoring system can operate in automatic and manual modes.

The autonomous monitoring system has a block-modular design composed of standardized industrial modules and elements, eliminating the need for typical certification and testing procedures. The AMWS is compact (approximately 30 kg), lightweight, and rapidly deployable, using widely available commercial modules, including on the secondary market in Kyrgyzstan.

AMWS can be installed in a hazard zone using pack animals, motorized vehicles, or on foot. A mobile version was developed and mounted on a VAZ-2109 vehicle for transport and temporary installation in mountainous terrain.

A key advantage of the CR10X module is its ability to interface with various data transmission channels between cluster and central stations. These include wired (twisted pair, coaxial, telephone line), mobile cellular, radio, and Internet (fiber-optic, wireless Wi-Fi, WiMAX) communication channels.

Some limitations of mobile cellular communication have been confirmed. Field tests revealed signal inconsistencies on relatively flat terrain and complete loss of coverage in valleys, particularly on forested slopes. Alongside standard cellular networks, trunked professional mobile

radio (PMR) systems are now used. Trunking—a two-way mobile radio system—utilizes ultrashort wave bands.

In practice, PMR systems function similarly to cellular networks: user terminals and base stations (BS), range-extending repeaters, and a controller manage station operations, handle repeater channels, and provide access to the public telephone network. Trunked networks may be single-zone (one BS) or multi-zone (multiple BS). Both analog and digital trunked communication systems are in use.

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