Glacial Lake Outburst Flood (GLOF) Monitoring and Early Warning System

Glacial Lake Outburst Floods (GLOFs) are sudden, high-magnitude floods that occur when a mountain dam containing a glacial lake fails. These natural dams, often formed from ice, rock, or moraine deposits, can be destabilized by a variety of triggers such as intense rainfall, rapid snowmelt, seismic activity, glacier calving, or internal erosion. When failure occurs, millions of cubic meters of water can be released within minutes to hours, creating destructive flood waves that travel far downstream.

GLOFs pose significant risks to mountain communities, critical infrastructure, agricultural land, and ecosystems. In many high-altitude regions, the impacts can be particularly severe due to the narrow valleys and steep gradients that amplify flood velocity and erosive power. Historical events have shown that even small glacial lakes can produce devastating downstream damage if not closely monitored.

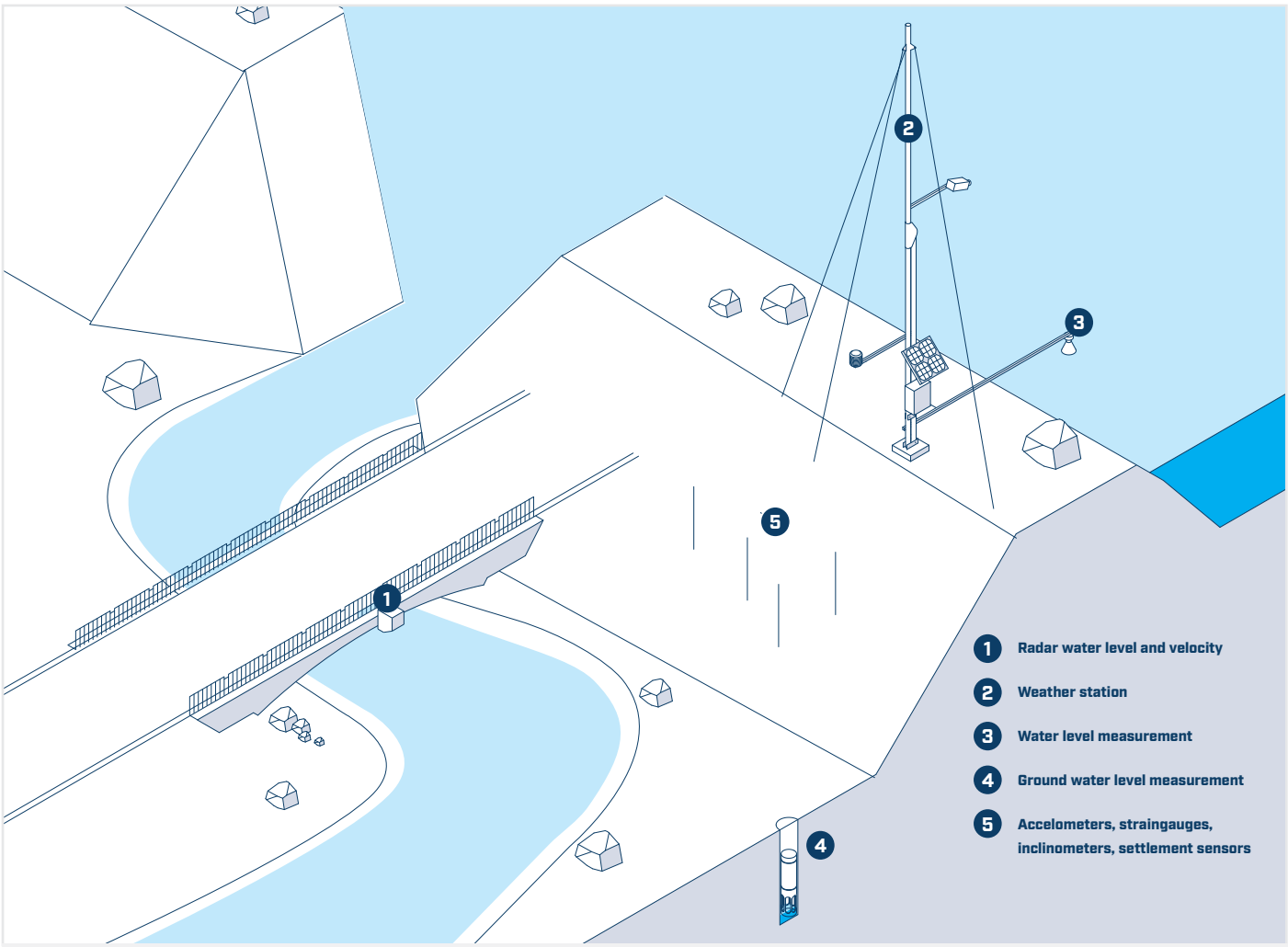
The MicroStep-MIS GLOF Monitoring and Early Warning System is a comprehensive solution for detecting, monitoring, and mitigating these hazards. It combines advanced meteorological and hydrological observation networks, geotechnical stability monitoring, remote sensing, and real-time data integration. The system continuously assesses lake conditions, catchment weather, and glacier dynamics to provide timely risk assessments and early warnings.

Designed for operation in harsh, high-altitude environments, the system's modular architecture allows for customization to local conditions, whether in the Himalayas, Andes, Alps, or other glaciated mountain ranges. Field-proven sensors, robust communication channels, and advanced modeling tools ensure decision-makers receive reliable and actionable information.

The goal is to reduce loss of life and damage to property by enabling proactive responses, targeted evacuations, and long-term risk management strategies for glacial lake hazards.

Collection and Pre-Processing of Data

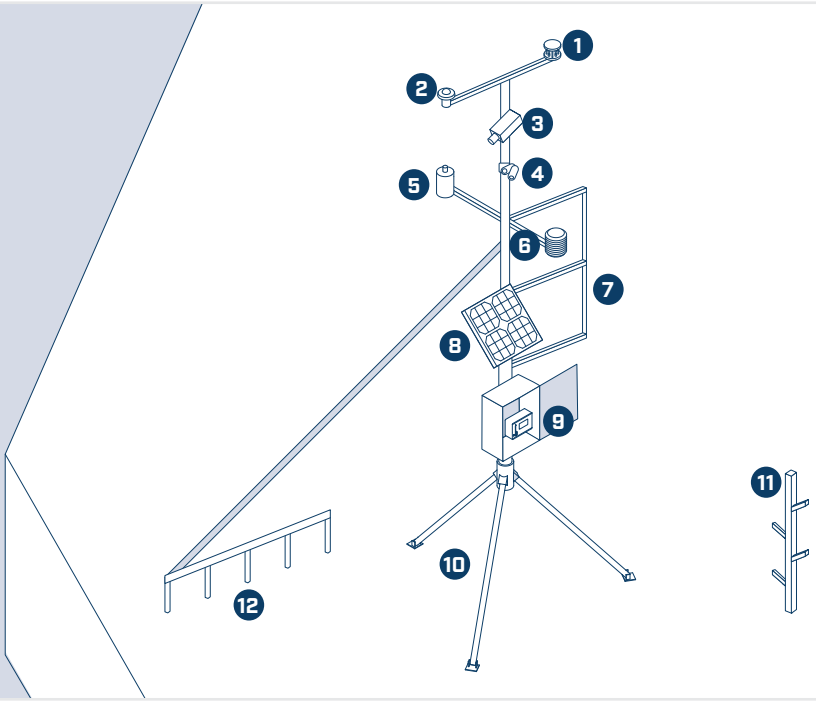
Collection and pre-processing of the measured data are ensured by a smart data logger, capable of operating reliably in remote, high-altitude environments. The recommended collection unit is the Data Logger AMS 111 IV, designed for continuous acquisition from meteorological, hydrological, cryospheric, and geotechnical sensors deployed around the glacial lake and its catchment

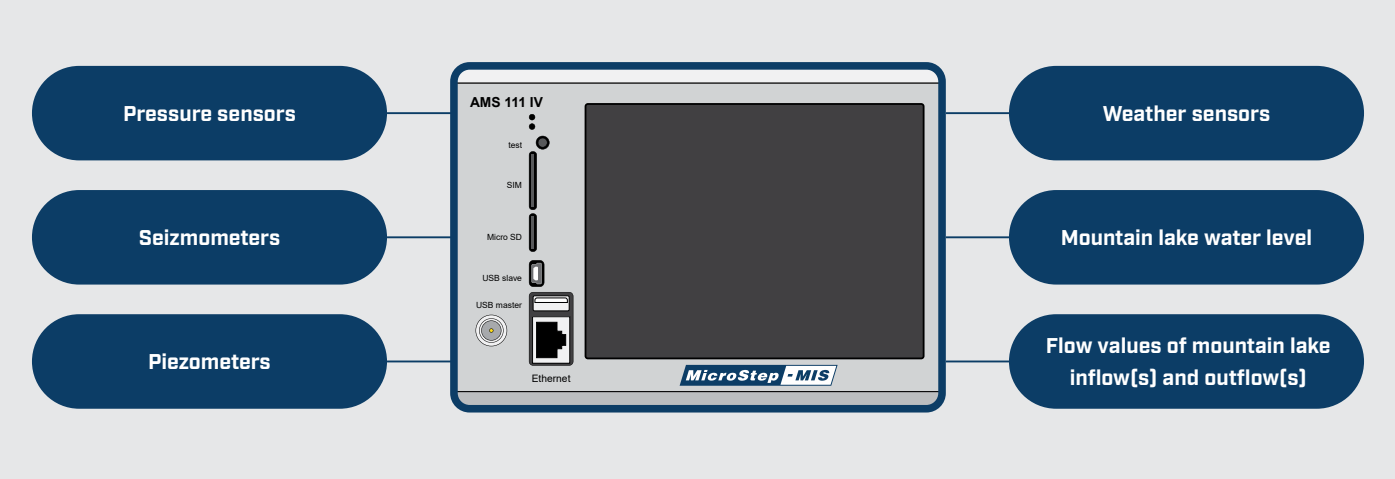


The GLOF system collects data from:

- ***Weather conditions*** *- temperature, precipitation, humidity, atmospheric pressure, wind speed/direction from high-altitude weather stations*
- ***Glacial lake parameters*** *- water level, surface temperature, ice cover extent, inflow/outflow rates, and wave characteristics*
- ***Snow and ice conditions*** *- snow depth, snow surface temperature, snow temperature profiles, solar radiation*
- ***Stability indicators*** *- Inclinometers, settlement sensors, strain gauges, and accelerometers to detect mountain lake deformation or instability*

1. Wind speed and direction sensor
2. Solar radiation sensor
3. Camera
4. Snow surface temperature
5. Snow height sensor
6. Relative humidity and temperature sensor
7. Snowdrift sensor
8. Solar panel
9. Data logger
10. Meteorological mast
11. Snow temperature profile
12. Snow pack analyser





Data Integration System

MicroStep–MIS has developed a proven integration platform, **IMS4**, which is the ideal solution for GLOF data processing and storage. The system enables real-time visualization of data, configuration of system accessories, and setup of automated routines for monitoring and alert generation. The system:

- Runs in modular form on Microsoft Windows® or Linux® platforms.
- Is based on industry-proven technologies – Java, XML, relational SQL databases.
- Has Web and Application servers integrated within the IMS Central Computer.
- Is compliant with applicable regulations and recommendations (WMO, EU, OGC, ISO, OASIS) and can be adapted for compatibility with national standards.
- Is available in multiple language versions.

The system uses a proven database based on WMO-recommended practices for climatological and hydrological data processing (WMO Guide No. 100). It follows the WMO recommendation of an RDBMS, with a modular architecture that gives the end-user extensive customization options.

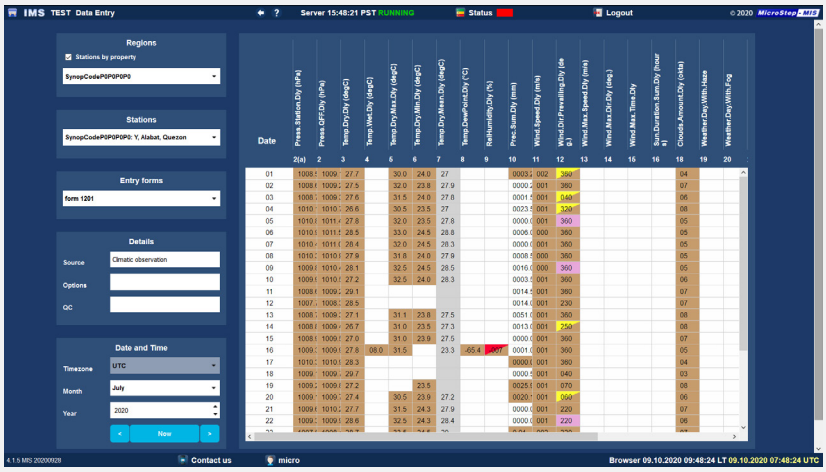
Additional non-standard input and output modules can be implemented and integrated at any time.

Integration of diverse data sources is possible, including automated weather stations (AWS), radar, satellite, aerial surveys (AHS), historical observations, buoy and sonar measurements, radiation monitoring, air quality sensors, glacier motion detectors, geotechnical stability sensors, and other technical parameters related to the glacial lake and surrounding slopes.

Database Capabilities

The database can store textual and numerical data, graphical information, and animations. It is capable of receiving, decoding, and archiving the following data types from various sources:

- Data electronically imported from third-party database systems.
- Data manually entered or transmitted via SMS from manned observation stations with regular or irregular schedules.

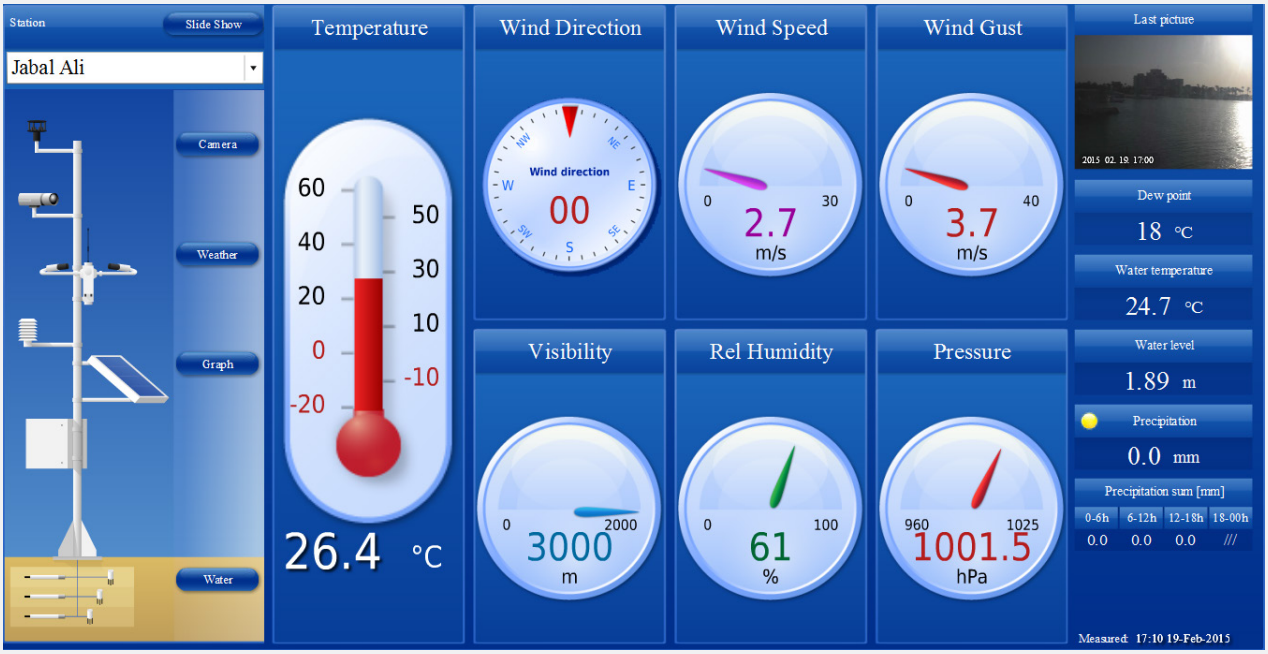


- *Original data - correct*
- *Suspect, but not erroneous data*
- *QC generated values*
- *Manually entered or overwritten data - correct*
- *Original data - not yet pass by QC*
- *Erroneous data*

- Data from meteorological messages received via GTS2 or other distribution systems.
- Data collected from automated weather stations (AWS), delivered in various formats.
- Remote sensing data – radar, optical, and satellite imagery for glacier and lake monitoring.
- Model predictions – numerical weather prediction (NWP) outputs, hydrological model outputs, glacier melt forecasts, and outburst flood simulations.
- Data from glacial lake and slope stability monitoring systems – including inclinometers, accelerometers, settlement sensors, and pressure meters installed in moraine or mountain lake.
- Any other numerical, textual, binary, or graphical data, in line with user requirements, can be integrated into the CLDB after appropriate processing and quality control.

Forecasting System

To effectively reduce GLOF risk, the operator must have reliable information about upcoming conditions in the glacial basin. Changes in weather, snowmelt, and hydrological inputs can significantly influence the stability of the moraine and the volume of water stored in the glacial lake. Strategic decisions must be based on accurate and timely forecasts of these evolving conditions.



IMS4 enables visualization of data measurement | *Meteorological and hydrological, as well as data from other monitoring devices.*

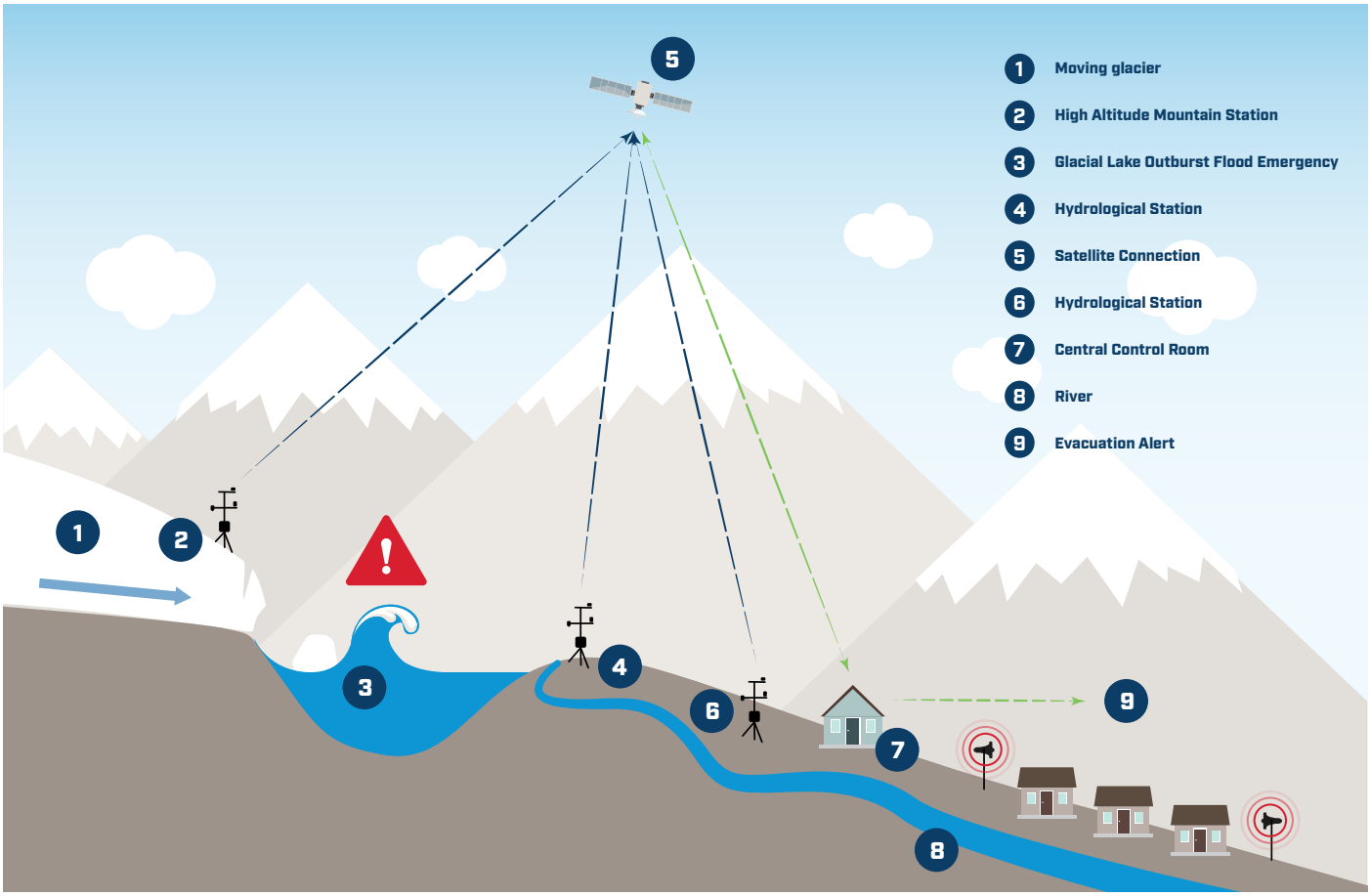
Weather forecasting focuses on the area of the glacial lake and its upstream catchment. Forecast parameters should include temperature, precipitation, humidity, atmospheric pressure, and wind speed/direction. Weather radar data, while not essential, can provide valuable additional insight into approaching storm systems and precipitation patterns.

For the entire watershed, weather forecasts should emphasize parameters critical for hydrological modelling - primarily precipitation (rain and snow) and air temperature - which directly affect snowmelt rates and potential lake inflow.

The hydrological forecast area extends from the highest points of the watershed down to the glacial lake profile. Inflow to the lake can be predicted using a network of hydrological models, including rainfall–runoff models, flow routing models, and one-dimensional (1D) hydrodynamic models. These models can be interconnected to provide real-time forecasts, allowing operators to anticipate rapid water level rises and assess potential triggers for outburst scenarios.

Rainfall-runoff models transform rainfall and snowmelt into runoff, which can be directly used to compute inflow to the glacial lake. These models can operate on minute, hourly, or daily time steps, depending on the requirements of the GLOF monitoring and early warning authority.

Flow models are often integrated with rainfall– runoff models in a single modelling package. Most R–R models include routines for calculating the movement of an outflow wave along a downstream channel, with at least a basic lag method.



Hydrodynamic models are used for detailed computation of flood wave transformation within the downstream river system. While not typically used for daily operations, these models are highly valuable during the planning and preparedness phase for simulating potential outburst scenarios and assessing the consequences of different breach conditions.

Connecting all above-mentioned models to one structure enables easy and accurate use of modeling tools for providing the most appropriate decisions for responsible operators of reservoirs.

By integrating all of the above-mentioned models into one framework, operators gain a powerful toolset for making informed and timely decisions to mitigate GLOF risk.

GLOF Decision Support System (DSS)

The DSS supports operators in making the right decisions at the right time. It integrates all available safety, meteorological, hydrological, and geotechnical data to provide a complete picture of glacial lake stability and potential hazard evolution. All information is displayed in a user-friendly format - including graphs, tables, and interactive maps.

Operators have real-time and forecasted overviews of lake water levels, inflows, and expected outflows. The system provides recommendations on the most appropriate actions to take under current and predicted conditions, including measures related to lake safety. The continuously available database includes an archive function, allowing the use of historical analogs and good practice references to guide decision-making.

Key objectives of the DSS:

- Continuous Monitoring Integrity of the Glacial Lake and associated natural dams (moraine or ice).
- Safety of downstream populations and infrastructure.
- In some cases, optimal management of water stored in the lake to minimize hazard potential.

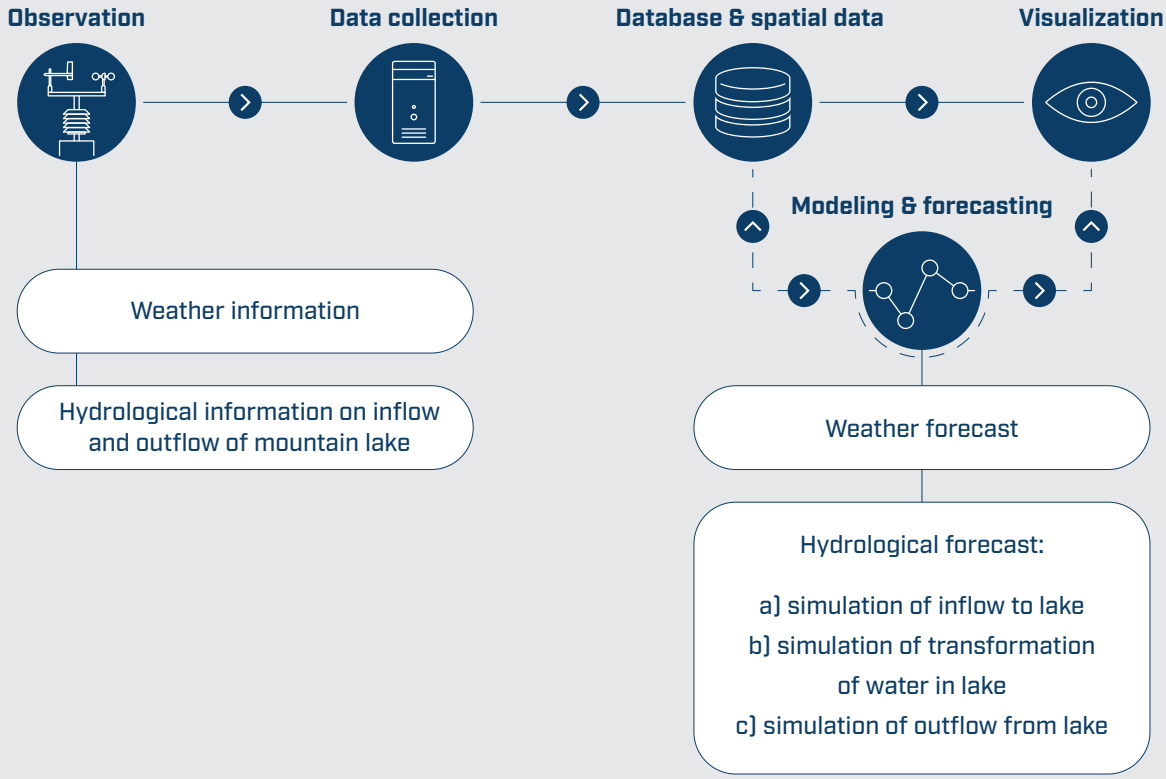
Warning System

Warnings are a critical output of the GLOF Monitoring and DSS. They can be:

- Internal - for the system operator.
- External - for the public and authorities.

Internal warnings are generated when monitored parameters exceed predefined thresholds, such as:

- Exceeding safety thresholds for glacial lake stability (moraine/natural dam deformation, slope instability).
- Exceeding thresholds for surrounding terrain stability (levee/embankment conditions, groundwater levels).
- High measured water levels in the lake or abnormal inflow rates.
- Extreme measured weather parameters (wind, precipitation, temperature changes).
- Forecasted water levels or inflows exceeding safe limits.
- Forecasted extreme weather events that could trigger instability.
- Technical failure warnings (sensor malfunction, communication loss).
- Other user-defined conditions.



These alerts appear in the operator's visualization interface as text messages or in graphical formats.

External warnings are predefined to notify at-risk communities, local authorities, and emergency services. Typical triggers include:

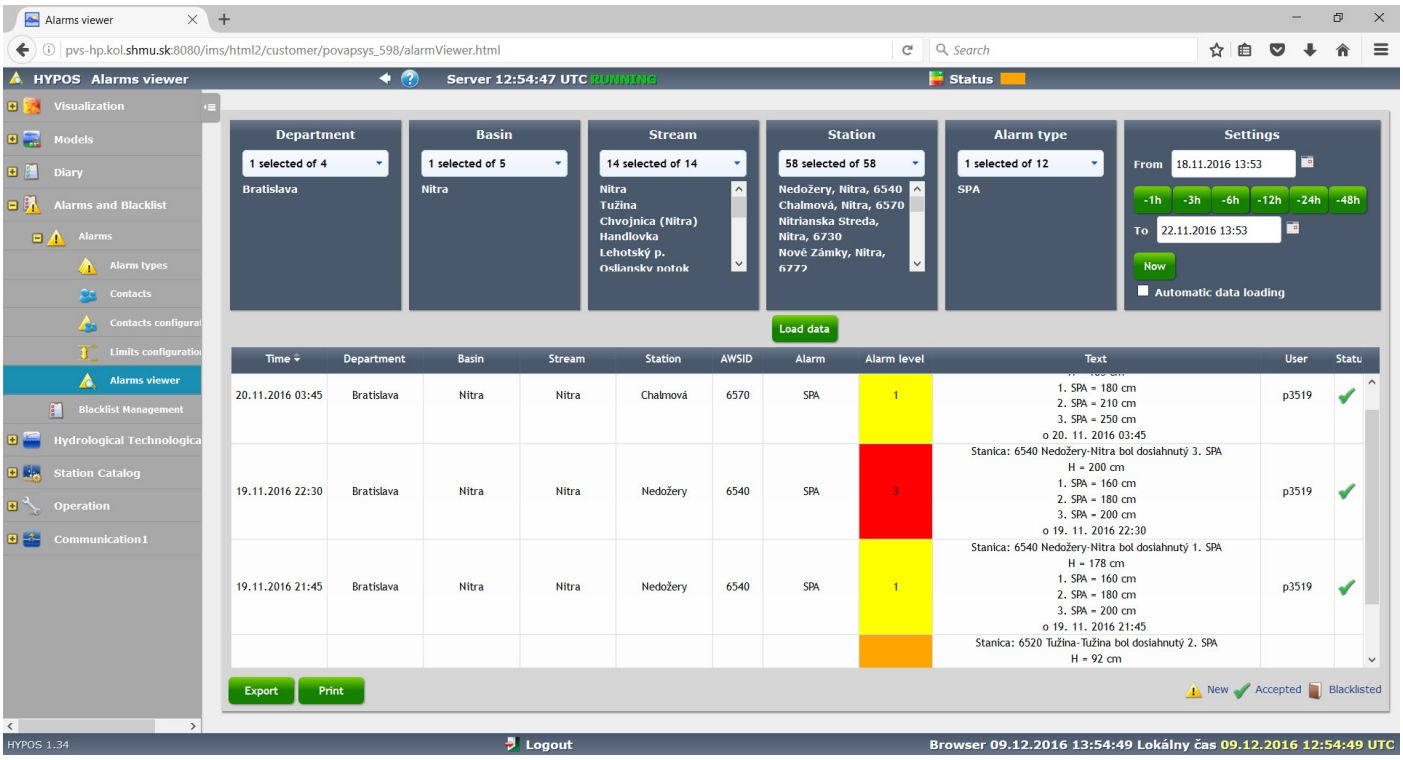
- High measured or forecasted lake water levels.
- High measured or forecasted outflow from the lake.
- Dangerous conditions in or around the lake (waves, sudden currents, ice movement).
- Imminent or likely moraine/natural dam failure.

Warnings can be disseminated through sirens, SMS notifications, email, mobile applications, radio, TV, or satellite communication to ensure rapid delivery to remote areas.

The Common Alerting Protocol (CAP)

The IMS Warning Suite is a specialized component of the MicroStep-MIS Integrated Monitoring System, designed to support forecasters in monitoring real-time weather conditions and issuing timely, accurate warnings to the public. It provides an intuitive interface for viewing meteorological data, model outputs, and observations, enabling rapid assessment of developing hazardous situations. Forecasters can create, manage, and disseminate warnings directly through the system, with support for configurable alert types and geographic targeting. The system is tightly integrated with the Common Alerting Protocol (CAP), ensuring that all warnings are standardized, machine-readable, and can be distributed across multiple communication channels simultaneously. This comprehensive approach improves public safety by streamlining the alerting process and enhancing situational awareness.

The Common Alerting Protocol (CAP) is a standardized data format used for exchanging public warnings and emergency



alerts across different systems and communication networks. It enables consistent alerting messages to be disseminated simultaneously via various media such as SMS, email, radio, and web.

The Common Alerting Protocol (CAP) is an open, international standard for exchanging public warning messages and alerts across different systems, platforms, and applications. Developed and maintained by the Organization for the Advancement of Structured Information Standards (OASIS), CAP is designed to facilitate the dissemination of alerts in a consistent and unified format.

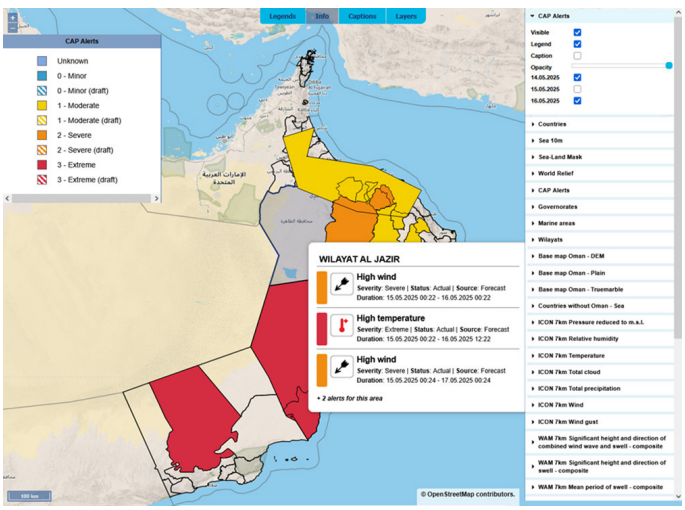
The primary purpose of CAP is to enable a standardized and interoperable format for alerting messages. It ensures that critical information related to emergencies, disasters, or any other significant events can be communicated effectively and efficiently to the right audiences. CAP allows for the integration of alerting systems across different regions, technologies, and organizations, making it a powerful tool for emergency communication.

Key objectives of CAP are:

- **Interoperability** - Ensures that alert messages can be exchanged between various systems and platforms without compatibility issues.
- **Consistency** - Provides a standardized structure for alert messages, making them easier to understand.
- **Scalability** - Supports the distribution of alerts to multiple platforms, including SMS, email, social media, and public warning systems.
- **Security** - Offers mechanisms to ensure the authenticity and integrity of alert messages.

A CAP message is composed of several key elements/ attributes that provide comprehensive information about an alert. Some of the notable attributes are:

- Identifier - A unique identifier for the alert.
- Sender - Information about the issuing authority.
- Sent Date and Time - The date and time when the alert was issued.



- Status - The current status of the alert (e.g., actual, exercise, test).
- Message Type - The type of message (e.g., alert, update, cancel).
- Scope - Defines the intended audience of the alert (e.g., public, restricted).
- Information Block - Contains detailed information about the event, including severity, urgency, and location.

CAP is widely used in various domains where timely and accurate alerting is critical. In emergency management, it is used by national and local governments to broadcast alerts for natural disasters (e.g., floods, earthquakes, hurricanes). For public safety, it is employed by law enforcement agencies to issue warnings related to public safety threats. It is utilized by meteorological organizations as weather warnings to provide real-time weather alerts to the public. For transport safety, it is used in aviation and maritime sectors for safety alerts and navigation warnings.

Common Alerting Protocol provides unified communication, enabling consistent and clear messaging across multiple platforms. It ensures rapid dissemination of information, allowing for fast and efficient distribution of alerts to various channels. The protocol supports cross-platform integration, making it compatible with a wide range of alerting systems and devices. Moreover, CAP offers enhanced security, ensuring the authenticity and integrity of alert messages through secure protocols. It is a crucial tool for ensuring that critical information reaches the right audience at the right time. With its standardized format and interoperable design, CAP has become a globally recognized solution for public alerting and warning systems, enhancing the effectiveness of emergency management and public safety initiatives.

MicroStep-MIS offers full CAP integration within its Integrated Management System (IMS), providing users with a seamless solution for issuing and managing alerts. This integration allows organizations to utilize CAP for efficient, accurate, and reliable alert dissemination across various channels. The designated CAP modules offer:

- **User-Friendly Interface:** The IMS system provides an intuitive interface for creating, issuing, and managing CAP alerts.
- **Multi-Channel Distribution:** Alerts can be automatically distributed to multiple platforms, such as WMO repository, National CAP Alert Feed Hubs and other 3rd party systems.
- **Customizable Alert Templates:** Users can define and customize CAP templates to suit specific requirements.
- **Secure Messaging:** The IMS ensures that all CAP alerts are securely transmitted and verified for authenticity.
- **Real-Time Monitoring:** The system allows for real-time monitoring and management of issued alerts, ensuring transparency and accountability.