Design and Implementation of an Advanced Glacier Lake Outburst Flood Early Warning System (GLOF EWS) Using LoRa IoT devices

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Abstract.
This paper describes the creation and deployment of a Disaster Early Warning System (DEWS) designed to detect Glacial Lake Outburst Floods (GLOFs). This system is a ***C***omprehensive ***I***ntegrated d***I***saster p***R***evention ***C***onfiguration (CIIRC)that has been built to withstand sub-zero temperatures and harsh weather conditions while displaying durability and resilience. GLOFs pose a significant risk to communities living near glacial lakes, necessitating the use of advanced monitoring equipment. The proposed system may transfer crucial data in real time from remote glacier lake monitoring stations to a central hub via radio frequency/ long-range communication, or satellite communication technology. Key properties such as lake water level, temperature, hydro pressure, and seismic activity are continuously recorded and transmitted from remote areas to a central monitoring station (CMS). The CMS examines incoming data using risk assessment algorithms (thresholds), which provide warnings and notifications as soon as potential GLOF issues are detected. The integration of this DEWS with local emergency response plans allows for more prompt and informed decision-making, which helps to mitigate GLOF-related tragedies. This comprehensive system intends to improve community resilience by delivering early warnings and facilitating proactive reaction measures.

Keywords: GLOF, EWS, Disaster, Pressure sensor, LoRa.

1 Introduction

A GLOF is defined as a rapid and catastrophic overflow due to the breakage of the moraine dam which dams a glacial lake. Normally, the moraine dams of a glacial lake comprise unconsolidated rocks and sediments, which are sensitive to climatic changes and inputs generated by seismic activity as well as anthropogenic factors [1]. However, GLOF disasters may lead to destruction in the lower areas. This results in severe destruction and loss [2], [3] Climate change is resulting in increased incidence and intensity of GLOFs. Hence, the current need to increase early monitoring and risk mitigation of GLOF. Effective early prediction of GLOF It will update you on dangers of GLOF in advance. This can be done with various methods like

- Remote Sensing: Besides the satellite image, there is other remote sensing-based data that could be used in monitoring the changes in the size of glacial lakes, water level, among other indicators of GLOF risk.

Ground-based monitoring: Ground-based stations are also used in gathering data on several parameters, including water levels, turbidity, and many more.

- Numerical modeling: Numerical models can simulate how glacial lakes and moraine dams behave under different conditions.

GLOF mitigation aims at reducing the chances of a GLOF happening or its impacts if one happens. Some of the possible strategies adopted include:

- Water level in the glacial lake: It can be drained with a controlled release or even by developing tunnels or spillways.
- The moraine dams may be reinforced by either adding more material within the dam or constructing support structures.
- Relocation of communities and infrastructure outside hazard zones of GLOFs is considered the most effective measure of mitigation taken in the long term.
- Early Warning Systems (EWS): EWS may give the communities an opportunity to evacuate before the occurrence of a GLOF event. Most EWS depend on the combination of several early detection means with a communication system that issues warnings to affected communities.

The work on GLOF early detection and mitigation has been ongoing, and the new methods and technologies are in the pipeline very continuously. The most important thrust in such work is on making more appropriate and reliable techniques for early detection. The other key areas of research include developing cost-effective sustainable mitigation. In the current focus, this research relates to the design of DEWS for GLOF with real-time measurement and communication of data, analysis, and action.

2 Literature review

GLOFs are one of the foremost natural hazards occurring in mountainous regions, especially in the Himalayas and Andes. This is following the breach of the glacial lake dam, releasing a massive amount of water and debris that travels downstream. GLOFs also trigger incredible damage to structures, properties, and human life. Of late, there has been more frequency and intensity along with climate and glacier retreat. This requires GLOF detection with adequate EWS in place to mitigate the risks associated with such floods.

There are several studies that have been conducted on GLOF detection and EWS. For example, Wang W (2022) et.al [4] designed an early warning system for the Cirenmaco glacial lake located in the central Himalayas. The system is more interested in monitoring and providing various features with timely warnings rather than specific flood features. Another study about the computational challenges and solutions involved in the development of GLOF early warning system by Kumar B (2022) et.al [5]. It believes that an early warning system is required to monitor vulnerable glacier lakes and provide robust tools to the disaster managers to plan mitigation, thus saving human life and property. International Centre for Integrated Mountain Development (ICIMOD) has also made some studies on GLOF detection and EWS. In the report of Mitigation (2008) [6], ICIMOD speaks about EWS, monitoring, and GLOF mitigation measures. The GLOF warning systems were based on 'extended line of sight' (ELOS) VHF radio technology. The warning signal would be transmitted via ELOS ground wave.

An early warning system on glacial lake outbursts to save lives and livelihoods of Nepal Himalaya communities was developed through a joint initiative of the Government of Nepal, UNDP in Nepal, and the Global Environment Facility [7]. The system encompasses hydro-met stations; GLOF sensors automated early warning sirens and a linked dynamic mass SMS alert system polygon. The system benefits more than 71,000 vulnerable people; both the local and the tourists visiting the Everest Region of Nepal. The system has the potential for replication and upscaling, with 21 critical lakes in Nepal and 25 in Tibet, China. Integration of climate actions in the routine planning and implementation holds the key for resilient and sustainable development. Among these, Kumar B (2020) et.al [5] proposed an ultrasonic sensor-based design architecture of a GLOF early warning system. The study majorly depicts the need to have an early warning system, especially one that detects GLOFs in real-time with timely warnings to the communities at risk.

The monitoring of GLOF and EWS is crucial for risk management associated with GLOF. This includes the deployment of remote sensing, ground-based sensors, and machine learning algorithms that incorporate data collection, processing, and analysis methods in the detection and prediction of GLOFs. These systems have been evaluated based on real-world data compared with existing GLOF detection and EWS. Besides this, new insight coupled with enhanced process understanding facilitated from reconstructing past GLOFs has contributed significantly to effective detection of GLOFs and EWS [8].

3 Insights for CIIRC design

- Measuring Water Pressure:

Measured at the installation point, the system measures the pressure of water within streams or rivers and in glacial lakes. Sudden changes in pressure may indicate a rising level of water-a warning sign for possible GLOF. A rise in hydro pressure could initiate subglacial conduits or tunnels, which would further weaken the glacier dam. By monitoring hydro pressure, the likelihood and triggering of a GLOF can be reflected and a prognosis drawn on the potential for dam failure.

- Measuring Water Level:

The system also monitors the fluctuations of the water level in the lake, which will trigger alarms with quick increases. Rapid rises in water level might be indicative of sudden water inflow, perhaps due to a breach in a glacier dam or icefall collapse. Ongoing monitoring of water level conditions can hence provide advance warnings to communities downstream.

- Measuring Temperature:

Continuous monitoring of temperature offers valuable information relating melt rates with changes in lake, river, and stream dynamics. Changes in lake water temperatures may indicate changes in the amount of glacial meltwater input, which can be due to increased ice melting or changes in the environment of glacial regions. Monitoring this change identifies the actual stability of the glacier lake. Statistical anomalies in lake water temperature, among other monitoring parameters, can generate alarms and warnings. A quick and steady rise in temperature may be an initial sign of the changes in the glacial environment and may give an early prelude to a GLOF.

- Measuring Seismic activities:

It can capture sudden movements or changes in the glacier structure that may be a precursor to a GLOF event, providing more detail about the evolving dynamics. Recording acceleration or changes in velocity can add valuable data in many ways. Abrupt changes in seismic activity near the glacier dam may indicate structural weaknesses or failure points. Continuous monitoring will be able to deliver an estimation of probable loss due to dam failure and subsequent water overflow. Seismic signals that occur with a GLOF can be studied to determine more about the dynamics of the events, including the time of occurrence and the magnitude. This information will be used in understanding the characteristics of the flood and increasing the ability to analyze future risks. Pressure sensors combined with seismic sensors will enable subglacial processes to be monitored. For instance, even the process of creating subglacial conduits or tunnels may affect pressure dynamics and cause seismic signals. Integration of pressure and seismic data could thus offer a more defined view of subglacial activity.

4 The DEWS Design flow

The proposed PSA based DEWS has been presented in a block diagram in figure 1. The proposed DEWS, therefore, caters to a specific requirement such as glacial lake monitoring and assessing the risk of GLOFs. The system, thus, is provided with Pressure Sensing Apparatus (PSA) along with a communication system, well suited to provide real-time data, such as hydro pressure and water level measurements and temperature measurements. The system can also incorporate a seismic sensor for instance accelerometers for monitoring the seismic activity.

It has advanced communication interfaces such as RF/long range (LoRa)/ SATCOM modules (transmitter module at GLOF site and receiver module at central monitoring station) for early warning capabilities. Integrated data loggers of the pressure sensor (DCX-22) can be programmed to record and transmit the data to a central monitoring station at regular intervals (minimum interval of 1min). Real-time data transmission can be derived from satellite communication, with suitable uplink and downlink facilities or through any other form of wireless RF communication means thus ensuring real-time monitoring at the location. The moment remote-sensing-based data from the DEWS is available, a DAS comes into play as a fundamental part of the early warning process.

The DAS is under constant surveillance, checking the real-time data against set thresholds and patterns. Such thresholds are mostly set by topographical data and are carefully fine-tuned by the insights gained from historical and researched contexts. The data acquisition system instantly sends an alarm signal whenever deviations cross a set threshold. The risk is thus passed to the concerned authorities, usually present at site in the locality; in this case, the local community in-charge / National Disaster Management Authority, NDMA through the signal and hence causes an urgency call for action. Advanced communication technology hastens the alarm signal and disaster management becomes urgent with a current emphasis. With the NDMA being the custodian authority, it thus coordinates quick and prompt disaster response to manage or lessen the impending disasters. Such responses by the NDMA will include various emergency measures that involve the inclusion of immediate alerts to the communities at risk. Such alerts will include such actions as emergency evacuation messages to people living in the vicinity of the disaster, thus reducing possible risks and saving lives and livelihoods.

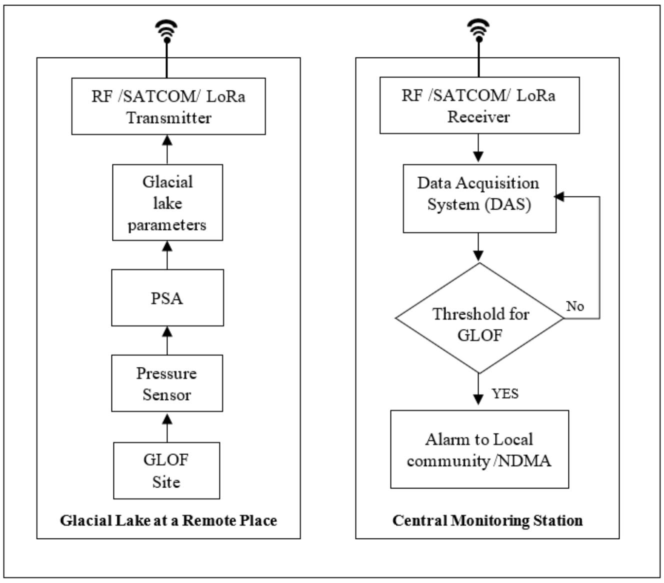

Fig. 1. Design flow

5 Proposed Pressure Sensing Apparatus (PSA)

Figure 2 Shows the graphic layout of the PSA. A high strength hose 10m long and 26mm in diameter is used, where accurate measurements of the pressure are ensured by the pressure sensor contained in this hose. This sensor is fixed on one end of an iron rod larger than the internal diameter of the hose at about 2cm in length. The rod is inserted in the hose using silicone sealant, but the lower end is held inside with hose clamps. It served the purpose by giving a waterproof seal and provides weight to stabilize the sensor's position. At the top of the hose, a T-junction is fitted so that a logger cable can be connected to connect up a pressure sensor to the data logger. The second leg of this T-junction feeds out to a 2-liter rubber expansion bladder. This bladder is normally half full; this way, volume changes in the antifreeze solution, such as those due to solar heating, build only enough pressure in the assembly that it can easily be sealed. The hose is filled with an appropriate quantity of antifreeze and water; the illustration here is 50:50 mix of ethylene glycol with water. It serves as the antifreeze solution. In establishing the installation of the PSA, a pole with a length of 5 meters is installed in the central region/ shallow side/ shallow bank of the stream/river. The length of the pole depends on the demand. The guides attached to the Teflon pulley hold the PSA on the pole. The pulley system makes sure that water level fluctuations do not pull the pressure sensor off of the river or streambed [9]. In case the PSA is deployed on an ice floor of a frozen pond/lake, this pulley arrangement allows the pressure sensor to dip as the ice melts, thereby ensuring that it remains in contact with the underlying surface of the pond or lake where the meltwater collects. The installation process involves using drilling equipment with extensions to a depth of 3 meters in the riverbed or streambed or frozen pond/lake.

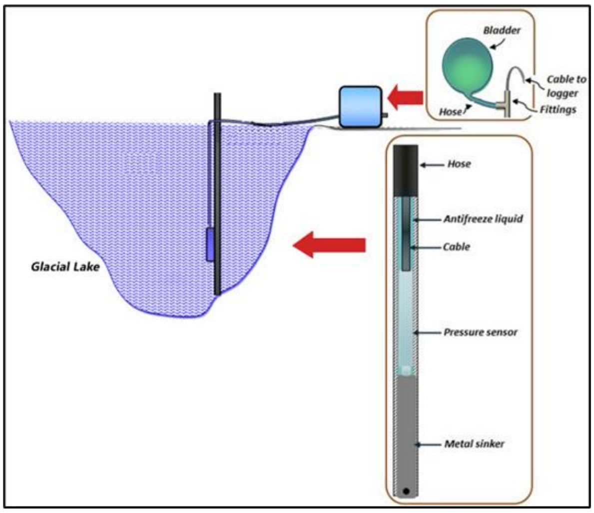

Fig. 2. Design flow

6 Pressure Sensing device

The DEWS can usually contain several sensors and equipment to measure water level, temperature, pressure, or a single pressure sensor like DCX-22 (which can work up to -10-degree celcius without the PSA setup / with PSA setup can work up to -80 celcius). The KELLER Druckmesstechnik AG, Switzerland sensor DCX-22 of figure 3 has a logger for data and can measure the water level, hydro pressure, and temperature. The pressure sensor used in the PSA is DCX-22 and is flexible to measure the water level or pressure of water and temperature. The sensor is also able to give accurate readings for submerged applications. With the data logger, which is equipped with a long-lasting battery, measurements can be recorded for long periods of time, from minutes to hourly intervals. Also, the pressure sensors are able to be calibrated by the users using the calibration program provided by the vendor. Sensors must be calibrated in an environment exactly the same as that in which they will be used. Sensors are often calibrated upright on a level surface. Sensor recalibration may be needed in several cases, such as when the sensor is serving under new or changed maintenance conditions, its measuring setup is altered, or its station has been in service for many years.

The pressure sensor, in combination with the data logger, can be programmed to acquire data on hydro pressure and temperatures for set time intervals. The result ensures that the collection of measurements during the monitoring period will be accurate. Nevertheless, it could be such that there will be cases wherein data gaps may have occurred through the exposure of the sensor to either freezing or low water levels, mostly. The densities of the surrounding environment should be considered when determining the height of a water level using the measurements of hydrostatic pressure acquired with the help of the pressure sensing device. Equation 1 supports the conversion of pressure readings in N/m2 to the corresponding height of the water column in meters. Another important consideration in the calculations is that the length of an iron rod needs to be added to the depth/water level for appropriate estimates.

$$d = \frac{P}{(\rho * g)} \tag{1}$$

where P = hydrostatic pressure (Nm-2), ρ = water density (kgm-3), g = gravitational acceleration (ms-2), d = height of water column (m).

Fig. 3. DCX-22 KELLER Pressure Transducer

7 Installed PSA at field

The configuration in figures 4 and 5 here constitutes the working scheme of the PSA: the RF transmitter is located at a remote position, while the RF receiver mounted with a Data Acquisition System (DAS) is located at the central monitoring station. This design, primarily aimed at the purpose of observing depth and water levels in lakes in Antarctica, promises much towards the detection of GLOFs. In fact, by serving as a DEWS, it can be fundamentally important in the premature observation and alerting authorities about possible GLOF catastrophes. As a result of unfavorable climatic conditions and inaccessibility of regular transportation for frequent visits, the system has been engineered to possess wireless communication capabilities. This allows real-time data transmission from the installation site to a central monitoring station about 2 kilometers off the lake site. Long Range (LoRa) transmitter and receiver modules are chosen in the wireless communications technology that will be made use of for this system since this will allow the transcription of critical lake parameters, like hydro pressure, temperature, and water level.

The system comprises reliable backup mechanisms in terms of power to continuously and uninterruptedly transmit and receive data. It employs the use of solar panels and insulation for the proper protection of the parts constituting the transmitter and receiver from probable disruptions through power and ensures a smooth, steady flow of data. The pressure sensor is programmed to become operational to serially measure the lake parameters at regular intervals. The acquired data is then sent to the central monitoring station, as exemplified in figure 5. This systematic approach, of course, allows comprehensive data to be collected but also ensures timely updates at the monitoring station-thus making the whole system of monitoring effective in the challenging polar environment.

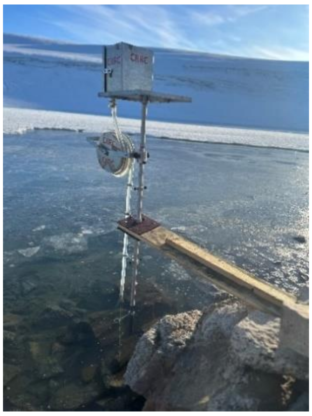

Fig. 4. Working model of PSA setup installed in a lake.

(a) (b) (c) (d) (e)

	A	B	C	D	E
1	Time	Timestamp	Date	CH1 Pressure(mbar)	CH2 Temperature(Â°C)
2	12:44:29	0.05	16-Jan-23	984.68	5.8
3	12:45:29	60.03	16-Jan-23	984.589	5.7
4	12:46:29	120.04	16-Jan-23	971.695	5.9
5	12:47:29	180.05	16-Jan-23	971.588	6.2
6	12:48:29	240.07	16-Jan-23	971.466	6.3
7	12:49:29	300.09	16-Jan-23	971.481	6.3
8	12:50:29	360.11	16-Jan-23	971.252	6.3
9	12:51:29	420.11	16-Jan-23	972.031	6.3
10	12:52:29	480.14	16-Jan-23	972.092	6.4
11	12:53:29	540.15	16-Jan-23	971.375	6.3
12	12:54:29	600.16	16-Jan-23	971.847	6.3
13	12:55:29	660.20	16-Jan-23	972.076	6.4
14	12:56:29	720.21	16-Jan-23	971.863	6.5
15	12:57:29	780.23	16-Jan-23	971.786	6.5
16	12:58:29	840.25	16-Jan-23	972.214	6.5

Fig. 5. (a) & (b) Transmitter module with solar panel and power backup (c) Sample data measured at 15min interval by PSA (d) Central monitoring station with receiver and (e) Sample of real time data received from PSA at 1 minute interval using LoRa receiver

8 Features of proposed DEWS

The proposed Pressure Sensing Assembly can come out as an important monitoring device for Glacial Lake Outburst Floods and therefore can help in the prevention or reduction of its impact. With an interfacing of an appropriate wireless communication system with the PSA, it is likely to provide real-time data to the NDMA via early warnings through PSAs in the following ways:

1. An Early Warning System: Place the PSA strategically around/at the glacial lakes. It will constantly observe the change in water pressure and lake levels. If the water pressure increases rapidly, along with an increase in the water level, that might depict a GLOF event. The sooner an event can be observed, the better it can alert downstream communities.
2. Real-time Data: The PSA can also forward in real time data concerning pressure levels and the temperature of the water. These data then forwarded to a central monitoring station for close scrutiny by experts to determine emerging trends that could characterise an impending GLOF.
3. Trend analysis: So, with this data for very long periods, the scientists and researchers get to understand how this glacial lake acts historically, thus they will be in a better position to identify some trends and patterns which may have been happening before these GLOFs. It means better predictions are made, and pro-active mitigations can be developed.
4. Risk Assessment: By these continuous updates of the lake conditions, PSA facilitates risk assessment towards GLOF. Information collected in this context may help policymakers decide about evacuations, infrastructure development, and so on.
5. Remote Access: The PSAs that are equipped with remote data transmission, can prove very useful in remote and inaccessible glacial regions. This will enable experts to monitor conditions and collect data even from challenging environments.

Regular maintenance and calibration of the PSA is essential to ensure that accurate data would be collected. Proper maintenance also prevents one from false alarms hence ensuring that one's PSA would still be reliable for GLOF monitoring. To minimize data loss from a low battery, a solar panel can be interfaced to charge the system. In a nutshell, PSA has become an essential tool in early warnings, assessments, and monitoring of glacial lakes, which contribute to preventing and mitigating the impacts of GLOFs, finally serving to safeguard communities downstream from ice melts that trigger outburst floods.

9 Conclusion

The development and deployment of a dedicated Disasters Early Warning System for Glacial Lake Outburst Floods are hence among the very important advances into mitigating impact involvement with this kind of catastrophic happening. Integration of satellite communication technology makes it possible to monitor remote glacial lake conditions in real time, thus enabling the early detection of potential GLOF risks. Combining data from sensors measuring the levels of water, temperature, and hydro-pressure activity, the system uses complex algorithms to riskassess and generate accurate alerts. The addition of a seismic sensor in this system will enable monitoring of seismic activity. Successful integration of this DEWS with local emergency response plans helps communities get warnings in time, or even permit an efficient evacuation and response strategy. Because climate change is increasingly influencing glacial dynamics, this system would be proactive in protecting the most vulnerable populations against the rising threat of GLOFs, thus supporting sustainable disaster risk reduction efforts. In general, DEWS the CIIRC structure is very robust and likely to be with us for a long time. This assurance originates from its launching and rigid testing under the extreme conditions of Antarctica's polar region for nearly three months.

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