

Monitoring and early warning system of Cirenmaco glacial lake in the central Himalayas

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ABSTRACT

The Himalayas are home to many high-risk glacial lakes. Effective prevention of glacial lake outburst floods (GLOFs) in this region has recently become an urgent priority. As a major element of an integrated risk management strategy, the GLOF early warning system is a viable and promising tool for mitigating climate change-related risks. It prevents loss of life and reduces the economic and societal impacts of disasters. Within the framework of the Second Tibetan Plateau Scientific Expedition and Research program, we developed and implemented a monitoring and early warning system (EWS) for Cirenmaco, a transboundary high-risk glacial lake located in the central Himalayas. The EWS consists of monitoring lake-level change, end-moraine displacement, ice collapse, and downstream runoff. The monitoring data can be transmitted via the Beidou and Inmarsat satellites and a mobile network to the data center. The in-situ and real-time monitoring guarantee captures the precursors of ice collapse and glacial lake outburst and raises alarms in advance for downstream communities. In terms of data transmission, monitoring elements, and warning thresholds, the Cirenmaco EWS scheme is one of the most advanced among all similar GLOF early warning systems. Implementing an early warning system is the most practical strategy for mitigating potential threats to Himalayan high-risk glacial lakes. The EWS system is less expensive than lake dam immobilization and artificial drainage projects, and it provides more valuable environmental monitoring data in high mountain areas. The Cirenmaco EWS serves an effective demonstration for the construction of similar projects to prevent and mitigate GLOFs in the Himalayas.

1. Introduction

Due to climate warming and ongoing glacier recession, glacial lakes in the Tibetan Plateau and its surroundings (TPS) are in a state of rapid expansion [1–3], and numerous potential glacial lakes buried within the glacier beds are projected to be exposed in the future [4–7]. Over the past few decades, the number and area of glacial lakes on the plateau have increased by ~10.7% and ~15.2%, respectively [2]. The Himalayas have the highest concentration of contemporary glacial lakes among all subregions of the TPS [8]. Because of its longitudinal length, over 2000 km from east to west, and an altitude difference of up to 5000 m, great spatial heterogeneity is manifested across many aspects, such as climate composition, geographic resources, and ecological environment [9,10], prompting it to become one of the main study areas in cryospheric science, geology, and social humanities. To date, research on glacial

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lakes has focused on the distribution characteristics of contemporary or potential glacial lakes, and their accompanying hazards and/or risks [4,11–15], inventory of regional glacial lake outburst floods (GLOFs) [16–20], reconstruction of previous GLOFs and projection of GLOFs from high outburst potential lakes [21–26]. However, research on prevention and mitigation measures for GLOFs from high-hazard/risk glacial lakes remains lacking [27–29].

Previous studies on identifying potentially dangerous glacial lakes selected the central Himalayas as subjects, including a large number of high-hazard/risk glacial lakes, over the other subregions of the TPS [12,15,30,31]. Zheng et al. [7] conducted a risk assessment for glacial lakes in the TPS, and another study focused on future changes in glacial lakes, as well as the accompanying enhanced hazards and risks. The results revealed that approximately 3200 potential glacial lakes are buried in the Himalayan glacier beds, accounting for 23.4% of the total number across the TPS. Approximately 32.1% of the Himalayan potential glacial lakes will be exposed by 2050 and 54.4% by 2100, at RCP8.5 scenario. The results of the risk assessment indicated that future GLOF susceptibility in this region will be at least 10 times higher than the current level. There have been several studies on glacial lake hazard/risk assessment for the entire Himalayan area, and some typical regional areas [32–35]. It is noteworthy that, although the evaluation schemes are varied among different studies, assessments of high-hazard/risk glacial lakes have comparatively high consistency and consensus [15]. Therefore, an in-depth understanding of glacial lakes with high outburst potential in this region provides a reliable basis for further studies.

TPS regions have seen more than 100 GLOFs originating from glacial lakes (Fig. 1a) [18–20,36–38]. The Himalayas are a global hotspot of GLOFs in the TPS. Since the 1980s, the GLOF frequency has been ~ 1.3 times per year [39], and there remains a distinctively steady trend of outbursts compared to other glaciated areas of the world where the GLOF frequency is decreasing or remain constant [40]. Recent studies have suggested that the frequency of future GLOFs in some areas will not increase. One such area is the Peruvian Andes. These tropical glaciers have already retreated quite close to steep headwalls [41,42], and numerous posterior bedrock-dammed lakes have become exposed. A decrease in GLOF susceptibility has been observed, the potential for future glacial lake development is not high, as lakes will become progressively distant from their mother glacier, which is the main source of triggers. Additionally, several remedial studies have been conducted to prevent GLOFs.

Unexpected Himalayan glacial lake outburst floods have caused thousands of deaths and enormous socio-economic losses [16]. For

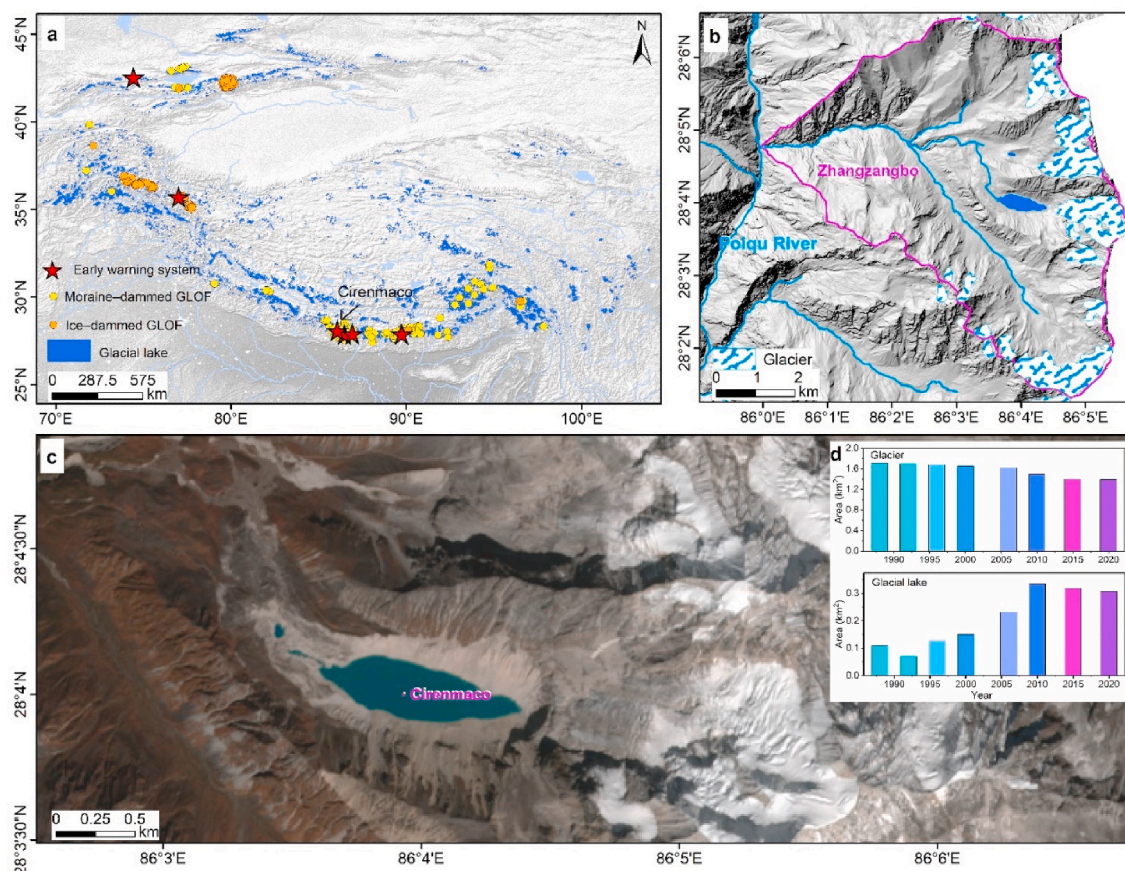


Fig. 1. Location of Cirenmaco in the TPS. (a) Since the 1980s, there have been many GLOFs originating from moraine and ice-dammed lakes in the TPS. Meanwhile, several EWS have been established in this region. (b, c) Cirenmaco is located in the Zhangzangbo Valley, central Himalaya. (d) The area changes of the lake and its parent glacier from 1988 to 2020.

instance, a catastrophic GLOF originating from Luggye Tsho, Eastern Himalaya, on October 7, 1994, was triggered by the melting of buried ice beneath the moraine dam, and the resulting flood killed 21 people and destroyed local infrastructure [43,44]. The largest GLOF event recorded in the region occurred on June 16, 2013. Chorabari, a moraine-dammed lake in the central Himalayas, suddenly drained, and the outburst flood, accompanied by rainfall floods, washed away settlements downstream, causing more than 6000 deaths [45,46]. Therefore, determining how to prevent and mitigate these outburst flood disasters is urgent. It is necessary to assess potential GLOF hazards and risks and simulate possible outburst floods. Moreover, it is crucial to meaningfully implement a variety of remedial works, such as lake dam immobilization, artificial drainage, and construction of monitoring and early warning systems (EWS).

Such engineering measures have been applied sporadically worldwide, even though numerous high-risk glacial lakes have been identified. The danger, high-altitude, and inaccessibility of high mountain areas make engineering measures several times more expensive than in densely populated plains. In the Himalayas, there are currently fewer than 10 engineering measures in place at present. For instance, Jialongco (Table 1), a moraine-dammed lake in the Himalayas, drained in 2002, resulting in severe downstream damage. Considering the serious threat posed, the local government artificially strengthened the moraine dam in 2020. In contrast, in the Peruvian Andes, at least 38 glacial lakes have been used for various remedial works, including 38 lakes that were artificially drained by open-cut excavation, tunnels, or siphon measures, 15 lake dams that were strengthened; and one lake that established an EWS [27,47]. These measures were taken mainly because many villages, towns, and cities are situated downstream of the high-risk glacial lakes in the surrounding region. An EWS generally consists of monitoring the glacial lake, its parent glaciers, and/or the downstream river, formulating a disaster mitigation plan, and training for evacuation. The latter two are non-engineering measures. However, they should be conducted based on an in-depth understanding of the original GLOF hazards. The difficulty lies in fostering strong support from local governments and residents [21,28].

It is vital for the implementation of remedial work that high-risk glacial lakes, adequate economic and engineering reserves, and long-term development plans are prepared in advance. Cirenmaco is located in the Poiqu River Basin, central Himalaya, close to the China–Nepal border (Fig. 1a and b). Three GLOFs from this lake have occurred in 1964, 1981, and 1983, respectively. In the past few decades, the high outburst susceptibility of Cirenmaco and the accompanied transboundary threat of its GLOF have plagued residents in both regions [7,12,48,49]. An EWS was installed near Zhangmu Port in 2001 unilaterally by the Nepalese government, to protect downstream hydropower projects [50]. However, the absence of a glacial lake monitoring system caused the EWS to lose a considerable part of its effective functions, as the upper Poiqu River Basin is home to many high-risk glacial lakes located in China. Therefore, supported by the Second Tibetan Plateau Scientific Expedition and Research (STEP) Program, we have established an EWS for Cirenmaco to monitor dynamic changes in the lake and its parent glacier, lake and downstream river water-level, meteorology, etc., to provide a timely warning signal to the downstream area.

Table 1

The categories of remedial work for glacial lakes with high risk, and corresponding measures. A typical case is given for the specific measure.

Remedial works	Measures	Typical cases			Reference
		Location	Name	Explanation	
Artificial drainage	Open cut	Cordillera Blanca, Peru	Palcacocha	This moraine-dammed lake failed in 1941, and then an open cut was excavated in 1974, lowering the lake to a level of 3 m.	[27]
	Tunnel	Cordillera Blanca, Peru	Parón	The tunnel became functional in 1984 and the lake level could be lowered by 52 m.	[27]
	Siphon	Cordillera Blanca, Peru	Lake 513	This bedrock-dammed lake failed in 1991 and 2010, but a siphon was already installed in 1989, lowering the lake level of 8 m. Subsequently, a combination of tunnels was used to lower the lake level by 20 m in 1993.	[51]
Lake dam immobilization	Earth dam	Central Himalaya	Jialongco	This moraine-dammed lake had been drained in 2002 causing severe damage downstream, the lake is still a high risk. Thus, in 2020 the local government immobilized its dam.	This study
	Arch dam	Alps, Swiss	Trift glacier lake	The dam, built primarily to generate electricity, was completed by 2007, but undoubtedly reduced the incidence of glacier-related hazards.	[52]
Monitoring and Early warning system	Monitoring and/or warning system	Central Caucasus, Russia	Bashkara Glacier lakes	The two sister lakes failed in 1958 and 1959. To protect the infrastructure and settlements downstream, an early warning and monitoring system was installed in 2008.	[53]
	Disaster mitigation plan	Cordillera Blanca, Peru	Lake 513	When information of the GLOF arrived, alarm will be issued to evacuate. At the same time, sirens were installed in all important communities and major transportation routes.	[28]
	Evacuation drills	Cordillera Blanca, Peru	Palcacocha, Tullparaju, Cuchillacocha	Detailed evacuation plans and evacuation briefs were developed by relevant staff to protect the downstream city of Huaraz, and were given extensive publicity.	[21]

2. Previous studies on Cirenmaco

Cirenmaco ($86^{\circ}03'56''\text{E}$, $28^{\circ}04'02''\text{N}$) glacial lake is located at 4612 m above sea level. Since the 1990s, the region in which it is situated (south slope of the central Himalayas) has been designated as a region of intensively developed of glacial lakes [2,8]. Cirenmaco's perennial mean annual precipitation can be estimated at ~ 1000 mm and the relevant mean annual temperature at approximately 0°C by interpolating the nearest meteorological stations [24]. The lake, which was drained in 1981, had reached a disastrous and alarming level. Based on a post-disaster investigation conducted by Xu [54], approximately $19 \times 10^6 \text{ m}^3$ of water was released, with a peak discharge of $15,920 \text{ m}^3/\text{s}$ at the breach and a total flood duration of 1 h. Because of the GLOF, substantial erosion was observed throughout the downstream valley, transporting approximately $4 \times 10^6 \text{ m}^3$ of solid material. There was a possibility of debris flow within the flood spreading in the Zhangzangbo Valley. The GLOF, which moved over 50 km along the downstream Poi-qu/Sun Koshi River, destroyed two bridges (at the mouth of Zhangzangbo Valley and Zhangmu Port), 6 km of China-Nepal roads and buildings on both sides, and one hydropower facility, resulting in 200 fatalities [48,54].

Cirenmaco has been identified as a high-hazard/risk glacial lake in recent studies [12,15,55] due to its steep surroundings, buried ice in the moraine dam, and the high exposure of downstream communities and infrastructure. Although the area of Cirenmaco underwent a rapid increase from 0.11 to 0.33 km^2 beginning in the 1980s, a stable trend in lake area has been maintained since 2010 (Fig. 1c and d). On the surface, the development potential of this lake has reached its limits. However, the dead ice in the lake bottom may continuously melt to increase the lake volume, and the buried ice melting in the moraine dam may continuously affect dam stability and trigger outburst floods [24]. A bathymetric survey of Cirenmaco was conducted in 2012. The results showed that approximately $18 \times 10^6 \text{ m}^3$ of water was held by this lake, with a maximum depth of 115 m [24]. Subsequently, Zhang et al. [25] simulated outburst floods at different drainage percentages and assessed the hazards and potential impacts of Cirenmaco GLOFs (Fig. 2a–c). Although their scheme for the outburst flood hydrograph as an input for the HEC-RAS model was proposed using an ideal drainage curve process, it has been demonstrated to be feasible in many other studies also [56,57]. In contrast, predicted GLOF propagation is transported entirely within a narrow valley. Because of DEM accuracy and simulation uncertainties, precisely identifying potentially damaged buildings, roads, etc., in such gullies is difficult. Therefore, prior simulation results for the Cirenmaco GLOF depth, velocity, and arrival time provide suitable reference points. The distance between Cirenmaco and the Zhangmu ports were found to be 23 km. The estimated travel time of the flood indicated that, if Cirenmaco released 100% of its volume, the GLOF would have at least 50 min to reach Zhangmu Port [25]. Moreover, studies of the 1981 GLOF reconstruction revealed that the flood time was more than an hour when it crossed this route [24]. However, we deduced that the actual flood migration time for this period may be

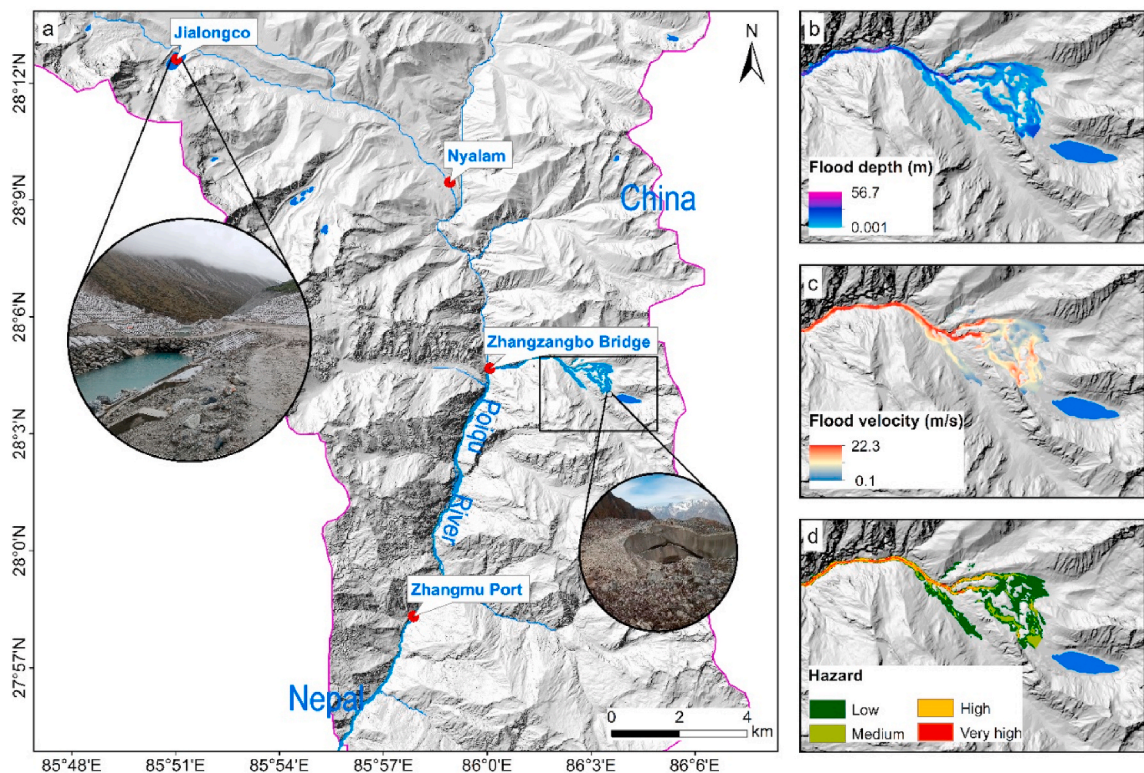


Fig. 2. Simulation of the Cirenmaco GLOF. (a) The outburst floods will cross the Zhangzangbo Bridge to Zhangmu Port and then enter Nepal at the largest drainage scenario (100%). (b) The Cirenmaco GLOF depth and (c) velocity are used to composite the (d) hazard map. All data in this figure were provided by Zhang et al. [25]. The picture in the circle on the left shows the strengthened moraine dam of Jialongcuo, and on the right shows the melting of buried ice in the moraine dam of Cirenmaco.

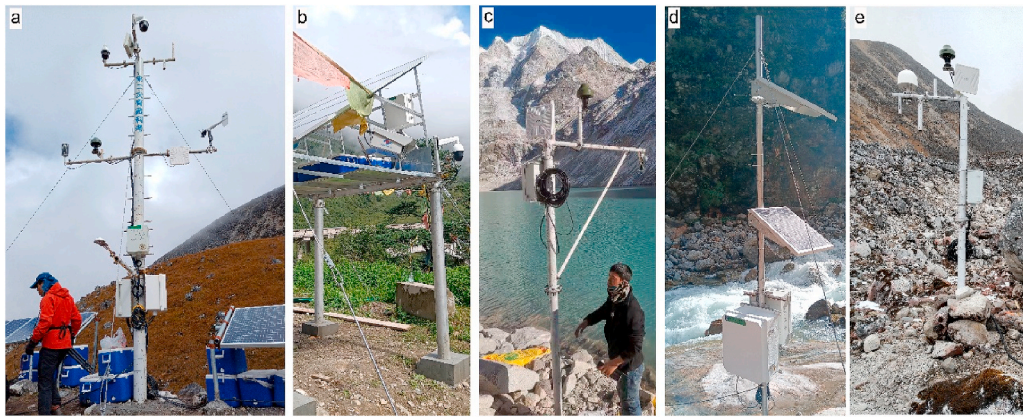


Fig. 3. Early warning system installed at Cirenmaco. A total of nine different services are contained in this project. These include (a) monitoring of the lake and its parent glacier, (b) monitoring of the environment of the downstream river, (c) water level monitoring of the glacial lake, (d) water level monitoring of the downstream river and (e) moraine dam dynamic monitoring.

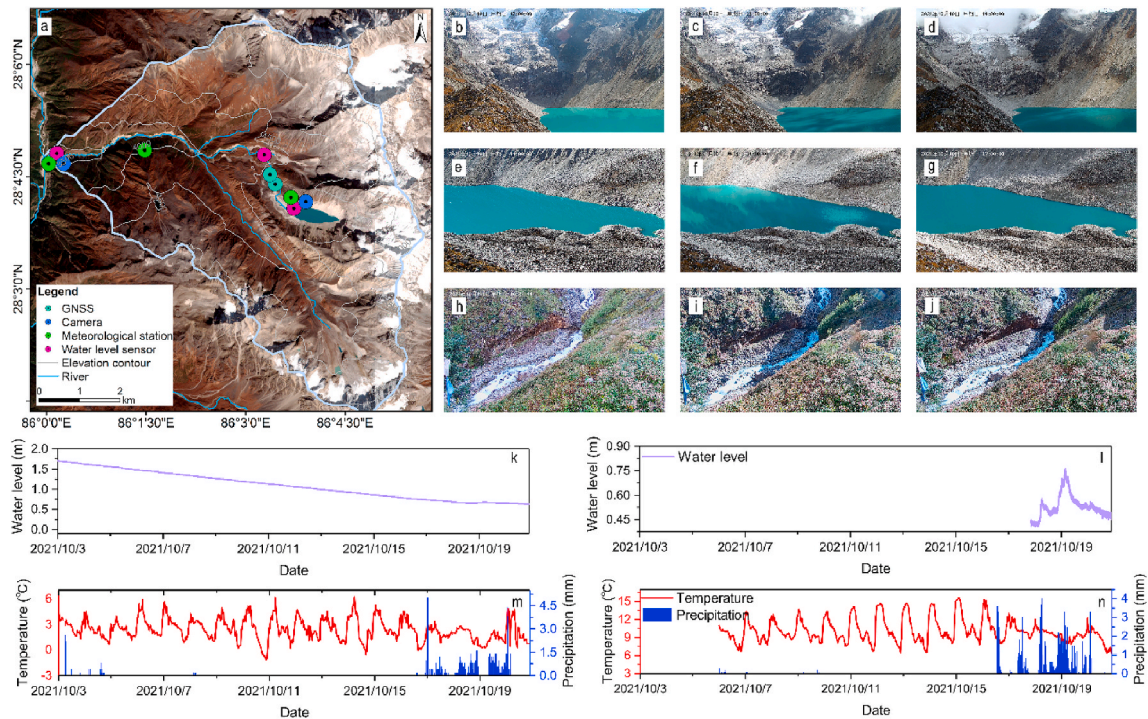


Fig. 4. Real-time monitoring data transmission via satellite and mobile networks. (a) Distribution of the main monitoring points in the Zhangzangbo Valley, and the monitoring data currently available, such as photographs taken by three visible light cameras, which are aligned (b–d) with the Cirenmaco inlet area and the snout of its parent glacier and (e–g) its outlet area, and (h–j) the terminus of the Zhangzangbo Valley. (k, l) Water level data and (m, n) meteorological data from the glacial lake and the mouth of the valley.

~40 min, according to the observed average flow velocity (9.8 m/s) of the 1981 GLOF in Nepal [54]. These data suggest that approximately 40–60 min may be required to send a warning signal.

In addition, the hazard map was composited by flood depth and velocity and translated into four intensity levels: low, medium, high, and very high (Fig. 2d). In the future, more refined and accurate simulation results can be relied upon to establish this hazard map, which has implications for determining evacuation locations in downstream areas, constructing GLOF prevention and mitigation facilities, and implementation of economic development measures. These studies provide an understanding of the possible flood damage from Cirenmaco and are the basis of this EWS construction [21,28,58].

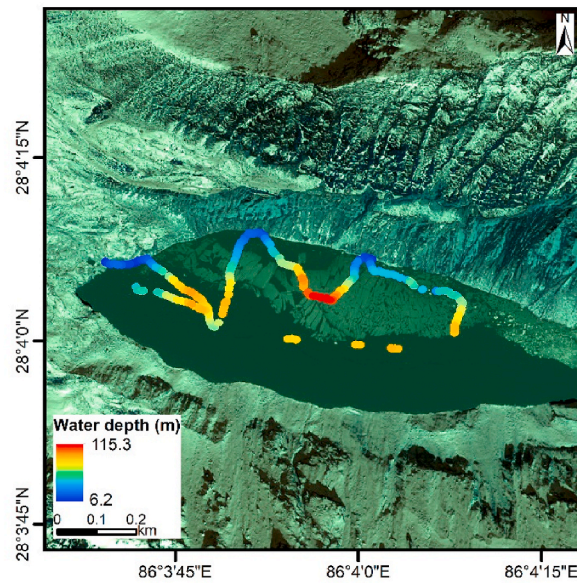


Fig. 5. In 2012, Wang et al. [24] measured the water depth and estimated the volume of Cirenmaco using an unmanned boat.

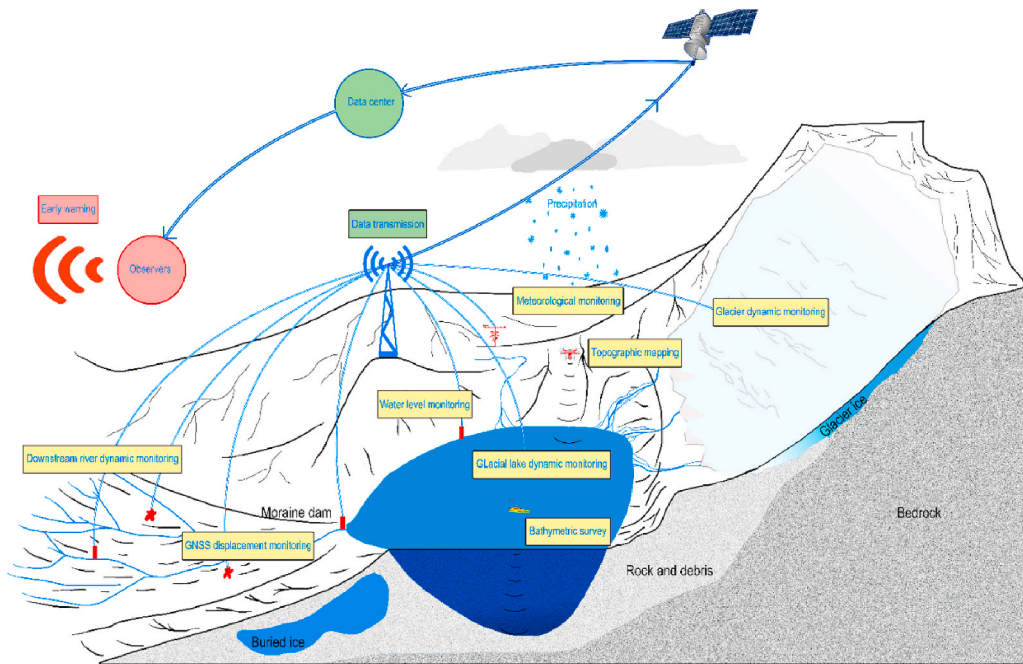


Fig. 6. Schematic diagram illustrating major components of the Cirenmaco EWS, including the lake and its parent glacier monitoring, downstream river monitoring, water-level monitoring, moraine dam dynamic monitoring, meteorological monitoring, bathymetric survey, topographic mapping, data transmission, and transferring the early warning signal.

3. Characteristics of EWS

3.1. A typical case: an EWS established for 513 Lake, Cordillera Blanca, Peru, in 2012

Two drainage events occurred in the Peruvian glacial Lake 513, in 1994 and 2010. An ice avalanche triggered the 1994 GLOF. However, because of the prior artificial drainage of the lake, the GLOF magnitude was comparatively low, so no damage was caused to the downstream area [51,59]. The 2010 GLOF was a catastrophic event, also triggered by an ice avalanche, that severely damaged the downstream city of Carhuaz, destroying 22 buildings and 100 km of roads, and causing 100 casualties [59]. In response to the serious threat posed by Lake 513, the local government implemented an EWS in 2011–2012 to prevent potential disaster [28]. Notably, the

EWS of Lake 513 is the first glacial lake early warning system worldwide with a fully functional service system. It includes risk knowledge (hazard and risk assessment), monitoring and warning services (monitoring and warning of hazard occurrence), dissemination and communication (dissemination of warning signals), and response capability (disaster mitigation plans and evacuation drills) [60].

Risk knowledge requires field investigation and analytical work to make a hazard and risk assessment of glacial lakes to clarify lake outburst probability and downstream exposure within the GLOF path. Monitoring and warning services consist of five components [28, 61]. The first is a glacier and lake monitoring station at the lake shore, which consists of four geophones and two cameras that record ground shaking during ice avalanches and flooding, as well as glacier–glacial lake dynamics. The second component is a hydrometeorological monitoring station, which is installed downstream of the lake outlet. The third component is the repeater station, whose main function is to transmit the monitored data to the data center. The fourth component is the data center in the city of Carhuaz, which is responsible for data evaluation and storage. The fifth component is the warning station, which is primarily responsible for the warning signal. The functionality of the dissemination and communication components, as well as the response capability, largely depends on active coordination with local authorities and residents to maximize the full functionality of the EWS and reduce potential losses. The EWS of Lake 513 provides a good reference for the construction of an EWS for Cirenmaco.

3.2. EWSs on the TPS

The early warning system essentially differs in predicting GLOFs versus rainfall-type floods. The EWS for GLOFs focuses on monitoring various elements and issuing timely warnings rather than providing specific flood features. This is due to GLOFs' high magnitude, short duration, and destructive properties. Forecasting rainfall-type floods, on the other hand, concentrates primarily on real-time hydrological processes based on dynamic courses of flow regime, streambed roughness, fluid density, etc., to establish effective standard curves to predict and warn of floods downstream with metrics generally on peak discharge, maximum water level, and arrival time [62].

Five EWSs have been established over the past few decades in the TPS region, to prevent GLOFs (Fig. 1a, Table 2). EWSs can be divided into two categories, based on their technical structures. The first is a semi-automatic system that relies on staff assistance. For example, a manual EWS in Bhutan was installed, with six water-level sensors and two automatic weather stations, and included a control room with two workers in a village downstream of the glacial lakes. The workers are equipped with satellite phones for information transmission [63,64]. The second was a fully automatic EWS. These services generally consist of real-time monitoring of the glacial lake and its parent glacier, hydrometeorological monitoring, data transmission and storage, and early warning [28,61]. For example, in 2014, an EWS was installed in Kyagar, an ice-dammed lake in Karakoram, China. It consists of three observation stations situated the lakeshore, estuary, and far downstream. The parameters, including the water-level of the lake and river, monitored by automatic sensors and photographs of the lake and riverbed taken by automatic time-lapse cameras, are all transferred through a satellite link to a data center [29]. If a GLOF was identified, warning signals were sent to authorities. In addition, fully automatic EWSs require an indispensable threshold to determine GLOFs, which may be real-time dynamic warning indicators such as lake and river water levels, deformation of the lake and glacier, or meteorological data [65]. The water-level threshold is frequently used in EWSs [28]. The main difference between a semi-automatic EWS and a fully automatic EWS is data transmission. Due to the remote and inaccessible environment in high-altitude mountainous regions, data transmission is very difficult and expensive. However, long-term observations using satellite for data transmission incur high costs. The frequency and cost of equipment maintenance are also higher than those of semi-automatic systems.

Overall, the quality of the current EWS applied to high-risk glacial lakes varies greatly around the world. In theory, a simple prediction scheme would require only the installation of water-level sensors for real-time analysis. Some activities in the Hindu Kush-Karakorum range rely on primitive beaconing methods to provide early warning [66]. If the purpose is not to investigate the mechanism of GLOF, but rather to provide early warning, it is a success as long as the effective alarm signal can reduce downstream exposure damage. Due to the limited data transmission scheme, fully automated and multidimensional monitoring of EWS is rare. Under the

Table 2

The GLOF early warning systems widely established in the TPS region, including the Tian Shan Mountains, Karakoram, and Himalayas.

ID	Lake name	Lake type	Location	Longitude°	Latitude°	Explanation	References
1	Teztor lake	Moraine-dammed	Tien Shan, Kyrgyzstan	42.54	74.43	The EWS was installed in 2011, and successfully predicted the Teztor lake GLOF in 2012.	[67]
2	Kyagar lake	Ice-dammed	Karakoram, China	35.71	77.01	The EWS combined three automatic terrestrial observation stations, and successfully predicted Kyagar GLOFs from 2015 to 2018.	[29,38]
3	Ropal Tsho	Moraine-dammed	Central Himalaya, Nepal	27.86	86.47	A manual EWS was set up in 1997, and evolved into a fully automatic system in 1998.	[50]
4	Imja Tsho	Moraine-dammed	Central Himalaya, Nepal	27.9	86.93	The EWS combined two monitoring stations and two relay stations.	[63]
5	Raphstreng Tsho; Luggye Tsho; Thorthormi Tsho; Besta lake	Moraine-dammed	Eastern Himalaya, Bhutan	27.88	89.74	The EWS was installed with six water level sensors and two weather stations, and successfully predicted Lemthang Tsho GLOF in 2015.	[63,64]

premise of ensuring effective early warning efforts, a comprehensive monitoring system is crucial and valuable for understanding the GLOF generation mechanism, propagation process, and flow regime transformation. This is particularly true regarding the action of photo or video monitoring of glaciers and glacial lakes, which not only eliminates many false alarm signals but also motivates us to understand the potential glacier–glacial lake–moraine dam linkage process when GLOF occurs.

4. Construction of the Cirenmaco EWS

The Cirenmaco EWS project, which was established in 2020 and validated in 2021, is the first use of a comprehensive EWS application in a moraine-dammed lake in China. It is a fully automatic system that applies several new technologies and methods. The entire system complies with the current two basic mechanisms of moraine-dammed lake outbursts: overtopping and piping. Both mechanisms are likely to emerge in Cirenmaco drainage. Overtopping triggers mainly consist of the ice avalanche from its mother glacier, which has been detecting by photo and video monitoring and satellite remote sensing image analysis. A water-level sensor located at Cirenmaco Lake will record the potential wave displacement. This is the main surface dynamic process that we considered, because the Cirenmaco GLOF generated in 1981 was determined to have been caused by an ice avalanche based on field investigations. Piping is generally induced by the melting of buried ice; thus, surface displacement monitoring was employed to record the activity status of the Cirenmaco moraine dam. We also deployed three water-level sensors and two meteorological stations along the flood route in Zhangzangbo Valley to observe the response of the lake and river after the GLOF occurred, as well as the meteorological context of the disaster (see Table 3). We elaborate on this advanced EWS in terms of four major categories and 10 specific components.

4.1. Monitoring system

- (i). Glacial lake, related parent glacier, and downstream river monitoring. A 6 m observation tower was built on the right bank of the lake to equip various apparatuses (Fig. 3a). Three 360° rotatable high-definition dome cameras were mounted on the tower, to capture daytime video surveillance and high-frequency timing photographs (Fig. 4a). The first camera was pointed at the lake's inlet area and the snout of its parent glacier (filming every hour from 8 a.m. to 8 p.m.) (Fig. 4b–d). The second camera was pointed at the middle of Cirenmaco Lake (filming every 3 h from 8 a.m. to 8 p.m.), and the third was pointed at the outlet area of Cirenmaco (filming every 3 h from 8 a.m. to 8 p.m.) (Fig. 4e–g) and also monitors the status of the moraine dam. A thermal imaging dome camera (infrared night vision device) was installed at the same angle as the first camera to monitor the lake and glacier (filming every hour from 8 p.m. to 8 a.m.). The thermal camera has low power consumption and a fog-penetration function and can provide video and timed photos under nighttime or foggy conditions. We also installed a group of infrared and visible light cameras at the intersection of Zhangzangbo Valley and the Poiqu River to record the state of the downstream river environment (Figs. 3b and 4h–j). The filming frequency of both cameras was one frame per hour.
- (ii). Water-level monitoring of glacial lakes and downstream rivers. This service consisted of three automatic water-level sensors that also monitored additional parameters, including water temperature and pressure. One was installed on the lake shore of Cirenmaco (Fig. 3c), recording the possible wave displacement induced by an ice avalanche. One was installed at the lake outlet, and the other was installed at the terminal of the Zhangzangbo Valley (Fig. 3d), near the location of the cameras. The recordings of these sensors were collected every 30 s (Fig. 4k and l).
- (iii). Dynamic monitoring of moraine dam. This element includes thickness, displacement, and temperature monitoring of the moraine dam. The Cirenmaco moraine dam has accumulated an enormous quantity of rocks, debris, and buried dead ice (Fig. 2a). The stability of the moraine dam impacts the frequency and magnitude of outburst floods. Two global navigation satellite systems (GNSS) were used to detect the elements of the moraine dam (Fig. 3e). This technology was applied here for the first time to observe the moraine dam in a glacial lake. The main potential variations were the settlement of the moraine dam caused by the melting of buried ice, and the movement effect of the moraine dam when the GLOF occurred. Ground penetrating radar was used to detect the moraine dam and analyze its thickness.
- (iv). Meteorological monitoring. Meteorological stations measured more than a dozen meteorological parameters, including wind speed, wind direction, precipitation, air temperature, air humidity, radiation, soil temperature, soil moisture, and atmospheric pressure (Figs. 3a and 4m–n). We selected three automatic meteorological stations at different altitudes in Zhangzangbo Valley. These were located at the lake shore of Cirenmaco, the middle altitude of the valley, and the intersection of the valley and the Poiqu River to monitor the three-dimensional and horizontal meteorological background of disasters within the study area. The total elevation difference between the three automatic meteorological stations was nearly 2500 m.
- (v). Satellite Remote Sensing Image Monitoring. To trace the historical state of the entire sequence of Cirenmaco disasters, a series of satellite images, such as Landsat, Sentinel, and SPOT, were selected to illustrate the lake–glacier dynamics. Useful information such as glacier boundary, glacier velocity, and ice crevasse development should be extracted as much as possible. Regular updates and database maintenance are required to provide a broad contextual awareness for high-frequency water-level, meteorology, and displacement monitoring.
- (vi). Bathymetric survey for the lake and topographic mapping for the lake and its surroundings. Lake volume is a critical metric in identifying potentially dangerous glacial lakes. Following the Cirenmaco bathymetric survey in 2012 (Fig. 5) [24], we conducted a more detailed bathymetric survey in 2020 to understand the lake's evolution. We also utilized drone images to create high-resolution topographic mapping around the lake.

Table 3

Primary equipment for the early warning system of Cirenmaco, as well as the involved monitoring elements, data acquisition intervals and accuracy.

Equipment	Number	Locations	Primarily monitored elements	Accuracy	Acquisition interval
Pressure type water level sensor	3	lake, downstream river	Water-level	0.1%FS	30 s
Automatic meteorological station	3	lake, Zhangzangbo Valley	air temperature; precipitation; wind speed and direction; air humidity; radiation; soil temperature; soil moisture; atmospheric pressure	$\pm 0.2\text{ }^{\circ}\text{C}$; $\pm 0.4\text{ mm}$; $\pm 0.3\text{ m/s}$; $\pm 5\%$; $\pm 3\%$; $\pm 5\text{ W/m}^2$; $\pm 0.5\text{ }^{\circ}\text{C}$; $\pm 3\%$; $\pm 0.3\text{ hPa}$	30 min
Camera	6	glacier, glacial lake, moraine dam, river	dynamic processes	\	1–3 h
GNSS	2	moraine dam	surface displacement	<1 m	0.25 s

4.2. Data-processing system

- (vii). Data transmission. The data measured in this ESW were transmitted via the Beidou and Inmarsat satellites and a mobile network to a data center (Fig. 6). The devices situated around Cirenmaco need to employ satellites to transmit data due to the lack of mobile signal coverage. The water-level and meteorological and imaging data at the mouth (middle) of Zhangzangbo Valley can be transmitted through the mobile network. Furthermore, all these devices are powered by solar panels.
- (viii). Data Center. It is located at the Institute of Tibetan Plateau Research Chinese Academy of Sciences, China. The center is responsible mainly for data storage, real-time surveillance, and transferring early warning signals. All data were moved or directly transferred to the Tibet Autonomous Region Disaster Cloud Platform (<http://holo-earth.cn:9022/>), established by the Institute of Tibetan Plateau Research, Chinese Academy of Sciences. There is a delay of approximately 2 min when data transmitted via satellite and mobile networks are loaded into the platform. Subsequently, the data can be immediately used for real-time alarm analysis. In addition, all the data measured from this EWS will be shared with Nepalese authorities, which is an important measure to increase cooperation and protect lives, livelihoods, and property on both sides downstream.

4.3. Early warning system

- (ix). Warning system. In this study, a compound warning threshold was used. Those already successfully operated included the water-level and meteorological thresholds. In subsequent field investigations and indoor technical implementation studies, the deformation of the lake and glacier, moraine dam displacement threshold, and seismic threshold will be incorporated. It should be emphasized that we still lack experience with alarm techniques, and many novel strategies and thresholds are constantly being investigated and developed. The water-level threshold is a critical component of our early warning system, and the three water-level sensors scattered around Zhangzangbo Valley will be integrated. The warning level was separated into three grades, with the first level being the highest and the third being the lowest. The difference between the most recent measurement and the lowest value of the water-level over the past 10 min was used to calculate water-level variation. Eventually, three water levels with thresholds of 30, 25, and 20 cm were selected (Table 4), obtained based on the analysis of our monthly acquired monitoring data. The meteorological thresholds have an auxiliary role in this system and are simply intended to remind the observer to keep a closer eye on the Cirenmaco condition over time. A warning signal was automatically issued to the observer whenever the monitoring element exceeded a specified threshold. Subsequently, the observer checks the real time photos or video of the glacial lake and its parent glacier to determine the lake situation and informs the decision makers and authorities. Since the travel time of a GLOF from Cirenmaco to the cross-border is ~ 40 min, it was very important to make the warning process easy and efficient. Despite the EWS with a time delay of ~ 2 min for monitoring data transmitted to the data center, the data can be used for real-time warning analysis at the platform. This could benefit our valuable basic warning time.

4.4. Response capacity development

Disaster mitigation plans and evacuation drills for GLOFs are also critical in ensuring that potentially influenced people can be evacuated to a safe area and that their belongings are secured in a timely manner. This study examines the ability of authorities, who require a considerable degree of general awareness of the present and future challenges facing high mountain regions, specific knowledge of GLOF susceptibility, risks, and warning time, as well as considerable vigor and foresight. Prior to the establishment of the

Table 4

Constructed and in-process designs of early warning indicators and their threshold settings.

Equipment	Thresholds	Status
Water level sensor at lake shore	I:30 cm; II:25 cm; III: 20 cm	Run
Water level sensor at lake outlet	I:30 cm; II:25 cm; III: 20 cm	Run
Water level sensor at valley mouth	I:30 cm; II:25 cm; III: 20 cm	Run
Precipitation at lake shore	I:16 mm/h; II:10 mm/h; III: 8 mm/h	Run
Deformation of the lake and glacier	\	To be built
Moraine dam displacement	\	To be built
Seismic	\	To be built

Cirenmaco EWS, the relevant glacial lake research group, made up of researchers, had been working continuously in the area for five years and had played a key role in improving the knowledge of the local population and government regarding the glacial lake and its accompanying hazard/risk. Therefore, when the EWS was ready to be established, we gained strong support from the local government. This also facilitated many of our communication efforts for specific actions of GLOF prevention, and later maintenance of the EWS devices, and avoided some of the human damage caused by differences in perceptions, such as religious beliefs.

Formulating disaster mitigation plans, implementing relief measures, and reserving relief supplies in advance are critical steps for minimizing casualties and losses [59]. Disseminating disaster prevention knowledge to residents, and allowing them to participate fully are also necessary. At present, relevant functionaries have been cooperating with the Disaster Emergency Management Department of the Tibet Autonomous Region and Nepal to fully utilize its function and help it become an effective, timeless, and representative EWS.

5. Summary and perspectives

In the Himalayas, where numerous high-risk glacial lakes are distributed, the ability to prevent and mitigate GLOFs remains insufficient, especially for transboundary threats. There are no reports that mention methods to effectively solve this problem. The construction cost of the Cirenmaco EWS was kept under 0.5 million dollars, which is much less than the cost used to strengthen the moraine dam of Jialongco (>\$10 million) in the same basin. Therefore, the EWS is relatively inexpensive to establish compared to other engineering measures on glacial lakes, and the availability of valuable field observations is important for furthering scientific research and development, making it suitable for large-scale replication in the Himalayas. The cost of the satellite transmission is also affordable. The pros and cons of each scenario must be weighed by the staff of each party, and any plan put in place must match the strength of regional social and economic development.

The Cirenmaco EWS is advanced and applies many new technologies such as real-time video transmission. One of the main objectives of applying this feature is to record the entire process of a glacial lake outburst, from the initial triggering event to the flood breaking through the dam and causing damage downstream; as the dynamics of a GLOF, as it occurs, are yet directly observed. We describe in detail the Cirenmaco EWS implemented in our project in four main categories: monitoring systems, data-processing systems, early warning systems, and response capacity development. All monitoring data have been successfully transmitted in real-time, and the EWS has been functional since October 2021. Both China and Nepal could benefit from the EWS project. Our study is of great significance in adapting to the increasing disaster risks in high-altitude mountainous areas and in providing a demonstration for the prevention and mitigation of GLOFs in the Himalayas and TPS.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this study.

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