Early warning system for ice collapses and river blockages in the Sedongpu Valley, southeastern Tibetan Plateau

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Abstract: The Tibetan Plateau and its surroundings have recently experienced several catastrophic glacier-related disasters. It is of great scientific and practical significance to establish ground-based early warning systems (EWS) to understand the processes and mechanisms of glacial disasters and warn against potential threats to downstream settlements and infrastructure. However, there are few sophisticated EWSs on the Tibetan Plateau. With the support of the Second Tibetan Plateau Scientific Expedition and Research Program, an EWS was developed and implemented in the Sedongpu Valley, southeastern Tibetan Plateau, where repeated river blockages have occurred due to ice/rock collapse debris flow. The EWS collected datasets of optical/thermal videos/photos, geophone waveforms, water levels, and meteorological variables in this sparsely populated zone. It has successfully warned against three ice-rock collapse - debris flow - river blockage chain events, and seven small-scale ice-rock collapse- debris flow events. Meanwhile, it was found that the low-cost geophone can effectively indicate the occurrence and magnitude of ice/rock collapses by local thresholds, and water level observation is an efficient way to warn of river blockages. Our observations showed that several factors, such as the volume and location of the collapses and the percentage of ice content involved, influence the velocities of debris flows and the magnitude of river blockages. There are still two possible glaciers in the study area that are at risk of ice collapse. It is worth monitoring their dynamic changes using high-resolution satellite data and the ground-based EWS to safeguard the surrounding hydrological projects and infrastructure in this transboundary region.

1. Introduction

The rate of air temperature warming in the Tibetan Plateau and surrounding regions is approximately twice the global average (Yao et al., 2022). As a result, glaciers on the Tibetan Plateau have experienced accelerated mass loss (Bhattacharya et

al., 2021; Hugonnet et al., 2021), thermal changes (Gilbert et al., 2020), and dynamic changes (Dehecq et al., 2019),

30 contributing to glacier instability that triggered ice collapses and glacier surges (Evans et al., 2021). Glacier-related disasters have been reported in the last decade, such as the Karayaylak glacier surge in the eastern Pamir (Zhang et al., 2022), the collapse of the Aru Co twin giant glaciers in the western Tibetan Plateau (Kääb et al., 2018; Tian et al., 2017), glacier detachments and ice-rock collapse in the Petra Pervogo range in Tajikistan (Leinss et al., 2021), repeated ice collapses and surges at Mt. Amney Machen in the northeastern Tibetan Plateau (Paul, 2019), massive ice-rock collapses at Chamoli in the

35 Indian Himalayas (Shugar et al., 2021), and the massive glacier detachment and repeated ice-rock collapses in the Sedongpu valley in the southeastern Tibetan Plateau (Zhao et al., 2022; Li et al., 2022b; Kääb et al., 2021).

In high-altitude alpine regimes, ice-rock masses have high potential energy, and the ice-rock collapses typically cause cascading hazards, such as debris flows (Peng et al., 2022), river blockages (Chen et al., 2020), and glacier lake outburst floods (Allen et al., 2022), threatening downstream settlements and infrastructure. For example, the detachment of the

40 Sedongpu Glacier in October 2018 blocked the Yarlung Tsangpo River for ~60 h, damaging or threatening roads and hydropower plants and leading to the relocation of more than 6000 local residents (Chen et al., 2020). The Chamoli rock-ice collapse and the associated debris flow in 2021 resulted in more than 200 deaths and destroyed two hydropower plants downstream (Shugar et al., 2021).

Some precursory signs, such as abnormal changes in surface velocity, surface crevasses and glacier ice relocation, can be

45 captured before glacier collapse using remote sensing methods (Kääb et al., 2018). However, satellite data sometimes suffers from weather conditions and revisit cycles. Given the short duration of glacier collapse, it is difficult to provide timely warnings of glacier catastrophes and assess their impacts. Ground-based early warning systems (EWS) provide a real-time monitoring dataset for warning against catastrophes. Some ground-based EWSs for glacial lake outburst floods have been implemented on the Tibetan Plateau and at high-elevation regimes (Wang et al., 2022; Huggel et al., 2020). However, few

50 successful warnings have been reported, and it is difficult to assess the reliability and transferability of such EWSs (Petrakov et al., 2012). In addition, there is still a lack of EWSs which was designed for ice collapse on the Tibetan Plateau.

The repeated ice-rock collapses and the induced river blockages in the Sedongpu Valley in the southeastern Tibetan Plateau (An et al., 2022; Chen et al., 2020; Kääb et al., 2021; Li et al., 2022b; Tong et al., 2019; Zhao et al., 2022) motivated us to establish the ground-based EWS. Supported by the Second Tibetan Plateau Scientific Expedition and Research Program,

55 the EWS was implemented to provide real-time warning signals to the downstream areas and to study the process and mechanism of the catastrophe from the Sedongpu Valley. The aim of this study is to introduce the structure and performance of the EWSs and analyse the process of different types of ice-rock collapses. Such pioneering work on EWS is not only helpful for understanding the process and mechanism of glacier-related disasters but also paves the way for establishing similar EWSs in other high-risk regions of the Tibetan Plateau.

2.   Study region

The study region is located in the Namcha Barwa-Gyala Peri massif on the southeastern Tibetan Plateau (Fig. 1a). This region is characterized by high tectonic activity, wide topographic variations, a deepened incision by the Yarlung Tsangpo River, influence of the Indian summer monsoon, the concentration of temperate glaciers and deposition of thick Quaternary glacial till.

The Namcha Barwa-Gyala Peri massif has experienced the fastest uplift rate and highest denudation rate in the world (Enkelmann et al., 2011; King et al., 2016) , and is, therefore, an earthquake-prone area that produced the 1950 Tibet-Assam earthquake (Mw 8.6). There were two peaks over 7000 m above sea level (m asl): Mt. Namcha Barwa (7782 m asl) and Mt. Gyala Peri (7294 m asl). The Yarlung Tsangpo River carves a deep gorge with a vertical elevation difference of more than 5000m. The Indian summer monsoon intrudes via the Yarlung Tsangpo Canyon, resulting in the longest annual rainy season on the Tibetan Plateau (Yang et al., 2013). The combination of high relief and abundant monsoonal precipitation results in 141 modern temperate glaciers, with a total glaciated area of 263 km^2 around these two peaks (Arendt et al., 2017). The competition between rapid uplift and glacial erosion around the Namcha Barwa-Gyala Peri massif contributed to the formation of thick Quaternary glacial deposits (Hu et al., 2020; Montgomery et al., 2004). These specific tectonic, climatic and topographic conditions have led to massive prehistoric and modern catastrophes and river blockages (Zhang, 1992; Chen et al., 2020; Cook et al., 2018).

The Sedongpu basin covers an area of 66.9 km^2 and has a length of ~11 km, with elevations ranging from the Mt. Gyala Peri at 7294 m asl to the valley outlet at 2700 m asl (Fig. 1b). According to the Randolph Glacier Inventory (RGI) 6.0 (Arendt et al., 2017), there are five major glaciers in the valley. The largest glacier is the Sedongpu Glacier (RGI60-13.01428) with an area of 5.0 km^2, most of which was detached in October 2018 (Kääb et al., 2021). The glacier surface is covered with a thick layer of debris. The bedrock consists mainly of Proterozoic marble and gneiss (Chen et al., 2020).

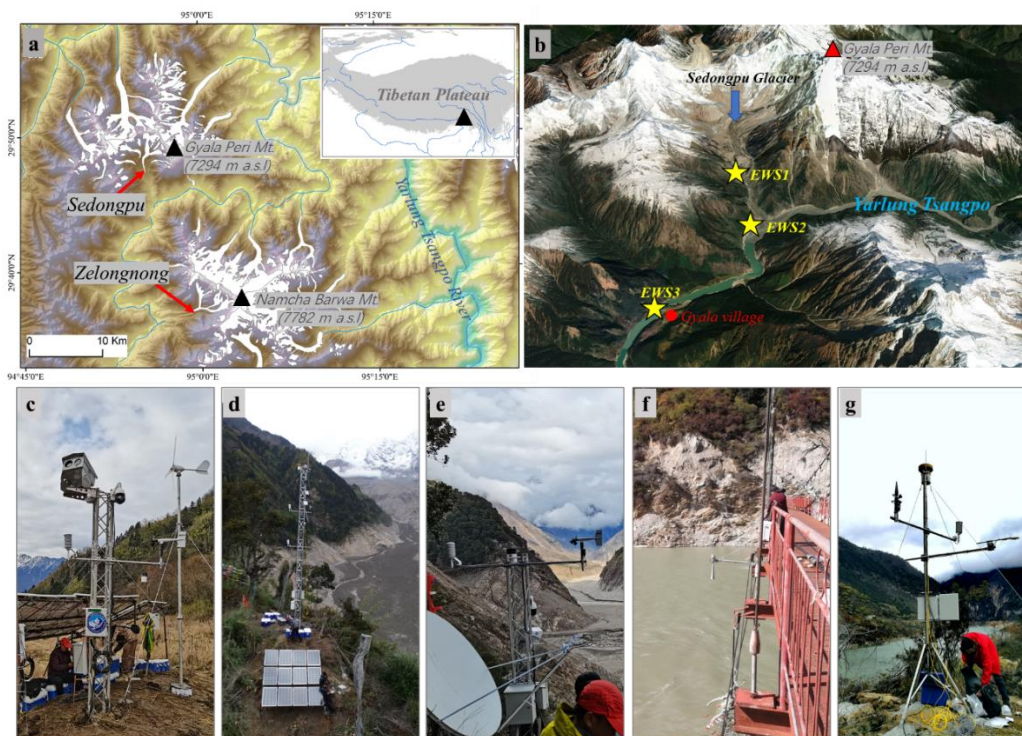



Figure 1: Study region and early warning systems. (a) Glacier distribution around the Mt. Namcha Barwa and the Mt. Gyala Peri in the southeastern Tibetan Plateau with the Sedongpu Glacier and Zelongnong Glacier; (b) © Google Earth image showing the 3D topography of the Sedongpu Valley and the locations of three early warning systems: EWS1-3 (yellow stars); (c) the EWS1 inside the Sedongpu Valley for ice collapse observations; (d) the EWS2 of the 10 m observation tower, which was installed near the Sedongpu Valley outlet but was destroyed by the massive ice-rock collapse on 22 March 2022; (e) the rebuilt EWS2 near the Sedongpu Valley outlet to warn the blockage of the Yarlung Tsangpo River; (f, g) the EWS3 of the radar water level sensor and the automatic weather station (AWS) with pressure water level sensor near the Gyala village.

3. Historical ice-rock collapses around the Mt. Gyala Peri and the Mt. Namcha Barwa

3.1 Historical ice-rock collapses in the Sedongpu Valley near Mt. Gyala Peri

Both the well-developed vegetation inside the Sedongpu Valley and the vegetation-covered dam near the outlet of the Sedongpu Valley during the period from the 1970s to the 2010s indicated that no massive ice collapse-induced debris flows had occurred during the past 40 years (Li et al., 2022b).

Since 2014, ice-rock collapses have occurred frequently in the Sedongpu Valley. Satellite images show that a debris flow destroyed the valley floor forest and vegetation-covered dam between June 2014 and October 2014 (Tong et al., 2019; Li et al., 2022b). The height difference between the two digital elevation models (DEMs) between 2013 and 2015 showed

that the total collapse volume from the northern ridge of Mt. Gyala Peri was ~4 Mm^3 (Li et al., 2022b). From October 2017 to October 2018, repeated ice-rock collapse-induced debris flows occurred in October 2017, November 2017, December 2017, January 2018 and July 2018 (Tong et al., 2019). Among these debris flows, the event on 22 October 2017 was the

100   most severe, destroying a large area of vegetation in the valley. Based on the differences in DEMs in 2015 and in 2018, the total volume of these collapses was more than 50 Mm^3 on the northern ridge of Mt. Gyala Peri (Kääb et al., 2021).

On 16 October 2018, a total of 130 Mm^3 of low-angle debris-covered glacier detached from the Sedongpu Valley (Kääb et al., 2021; Li et al., 2022b), blocking the Yarlung Tsangpo River for ~60 h (Chen et al., 2020). On 22 March 2021, massive ice-rock collapses totaling 50 Mm^3 occurred in the Sedongpu Valley, producing a mobile debris flow that temporarily

105   blocked the Yarlung Tsangpo River (Zhao et al., 2022).

3.2 Historical ice-rock collapses in the Zelongnong valley near the Mt Namcha Barwa

The Zelongnong Glacier (RGI60-13.01428), 20 km south of the Sedongpu Glacier, is located near Mt. Namcha Barwa and has a total glacier area of 9.5 km^2, ranging from 3819 to 6931 m asl (Fig. 1a). Both glacial and fluvial deposits near the outlet of the Zelongnong Valley indicated that this glacier has repeatedly advanced or collapsed since the last glacial

110   maximum (Hu et al., 2020; Montgomery et al., 2004). Four modern glacier catastrophes have been reported on the Zelongnong Glacier. River blockages have been reported to have occurred in 1950, 1968 and 1984 (Zhang, 1992). In 2020, a total of 1.14 Mm^3 of ice-debris mixture produced a high-speed debris flow and partially blocked the Yarlung Tsangpo River (Peng et al., 2022).

4.   The ground-based EWSs near the Sedongpu Valley

115   Since 2019, the EWSs have been built around the Sedongpu Valley. The EWSs consist of three parts (EWS 1-3) with different monitoring instruments and scientific functions (Fig. 1c-g and Table 1).

4.1 EWS1 inside the Sedongpu Valley

In May 2022, a 4 m observation tower with various monitoring sensors was constructed on the right bank of the glacial terraces at 3308 m asl in the Sedongpu Valley (Fig. 1b and c). Owing to logistical inaccessibility, all instruments were

120   transported by helicopters. The objective of EWS1 is to monitor the location, magnitude and process of the ice-rock collapse inside the Sedongpu Valley. The overall monitoring system consists of the following five parts:

i)   Panoramic surveillance of the Sedongpu Valley. A 360° rotatable high-definition dome camera was mounted on the tower and aimed at the Sedongpu Valley to provide daytime video surveillance and high-frequency timing photographs. Because of the limited capability of satellite transmission, the video of the disaster process was stored locally on the

125   hard disk and only retrieved remotely by command. Photographs taken hourly from 8 a.m. to 8 p.m. were regularly

transmitted to the server of the National Tibetan Plateau Data Centre (https://data.tpdc.ac.cn/home). Such panoramic monitoring is used to monitor the process of the ice and rock collapse along the Sedongpu Valley.

ii) Targeted monitoring of the collapsed area. Optical and thermal cameras were used to monitor the dynamic changes in rocks and glaciers on the northern ridge of Mt. Gyala Peri, where ice and rock collapses have occurred repeatedly over the past five years. The video of the disaster process is retrieved remotely. Hourly photographs were transmitted to the server via satellite. This targeted monitoring was designed to identify the location and magnitude of the recurrent collapses.

iii) Surface vibration from repeated collapses. Ice-rock collapses and highly mobile debris flows generally produce significant surface vibrations. A 5 Hz three-component (XYZ vector) SmartSolo geophone was used to record the surface vibrations from collapses and debris flows. Owing to a large amount of useless waveform data and the limited capability of satellite transmission, a threshold for data transmission was adopted in the field. During the installation of EWS1, several small-scale collapses were observed at midnight. The corresponding amplitude of the three-component waveform was generally greater than three. Therefore, if any XYZ vector was greater than three, the 200-second waveform data before and after the threshold were transmitted automatically to the server.

iv) Meteorological records inside the valley. With regard to possible triggers of extreme weather conditions for ice-rock collapses, meteorological variables were recorded using the Campbell datalogger and were transmitted to the server. Air temperature (T_{air}) and relative humidity (RH) were measured using the temperature and relative humidity probe (Vaisala HMP155A). Precipitation was measured using a rain gauge (Texas TE525MM). Wind speed and direction were recorded using a wind monitor (RM Young 05106).

v) Data transmission and power supply. All datasets were transmitted via the Asia-Pacific satellite (Asiasat 7). Owing to the heavy monsoon cloud cover and less efficient solar power generation in this region, power is supplied by both solar panels and wind (Fig. 1c).

4.2 EWS2 near the Sedongpu Valley outlet

Ice-rock collapses generally produce debris flows that are deposited near the Sedongpu Valley outlet and then block the Yarlung Tsangpo River (Chen et al., 2020; Tong et al., 2019). The EWS2 was installed near the valley outlet to monitor the river blockage. In fact, a 10 m integrated observation tower, equipped with time-lapse optical and thermal cameras and various meteorological variables, was installed 150 m above the valley floor at the valley outlet in October 2019 (Fig. 1d). However, this EWS2 was destroyed by the collapse-induced mass flow on 22 March 2021, which had overtopped the 200 m high hill at the basin outlet and stripped the surrounding slope of vegetation (Zhao et al., 2022).

In May 2021, the EWS2 in the upstream region was re-established to avoid possible destruction by debris flows of similar magnitude as in March 2021 (Fig. 1e). Similar to the monitoring equipment at EWS1, EWS2 was equipped with optical and thermal cameras to monitor the status of the Sedongpu Valley outlet, a three-component SmartSolo geophone

with a transmission threshold of 10 to indicate the power of debris flows and various meteorological sensors (Table. 1). The video was stored locally on the hard disk, and hourly photos were transmitted to the service via satellite.

4.3 EWS3 at the Gyala village

The main objective of EWS3 was to provide real-time early warning information of river blockage through changes in the water level at Gyala village, which is located ~6 km upstream of the Sedongpu Basin. The water level will soon rise when the Yarlung Tsangpo River is partially or completely blocked by debris flow from the Sedongpu Valley. Therefore, the water level is a very important early warning indicator. Two different types of water level sensors were used to provide sufficient redundancy and to avoid possible sensor failures. A Campbell CS477 radar water-level sensor (10-minute interval) and a Campbell CS451 pressure transducer (5-minute interval) were installed separately in October 2019 and May 2021 to provide real-time records of the water level in case of river blockages (Fig. 1f).

Considering the relatively open topography near Gyala village, an automatic weather station was also installed (Fig. 1g) for long-term monitoring of the regional background of climate change by measuring air temperature, relative humidity, precipitation, and four components of radiation including incoming shortwave radiation (S_{in}), reflected shortwave radiation (S_{out}), incoming longwave radiation (L_{in}), outgoing longwave radiation (L_{out}) using a CNR4 net radiometer, and air pressure using a Vaisala PTB110 barometer (Table. 1).

5. Performance of the EWS

The warning signals were automatically sent to the mobile phones of all responsible persons whenever any geophone waveform or water level exceeded the specified thresholds (Section 5.4). Subsequently, the observers checked the real-time photos or videos to determine the glacier and river status and informed the local government. Since the establishment of the EWS, the system has successfully detected three ice-rock collapse-debris flow-river blockage chain disasters and alerted the local government of early disaster management. In addition, the system monitored seven small-scale ice-rock collapse-debris flow events that did not result in river blockage, but the debris mass flow approached the Yarlung Tsangpo River. Here, the performance of the EWS has been briefly described and the effectiveness of early warning indicators is discussed, such as the geophone waveform and water level.

5.1 Massive ice-rock collapse and river blockage on 22 March 2021

On 22 March 2021, a massive ice-rock collapse occurred from the northern ridge of Mt. Gyala Peri, and the resulting mass flow temporarily dammed the Yarlung Tsangpo River. Based on a comparison of pre- and post-event DEMs, the total collapse volume was estimated to be ~50 Mm^3 (Zhao et al., 2022).The water level sensor at EWS3 sent an automatic warning message due to a sudden 2.2 m rise in the river level between 23:50 on 22 March and 00:00 on 23 March (Fig. 2). The water

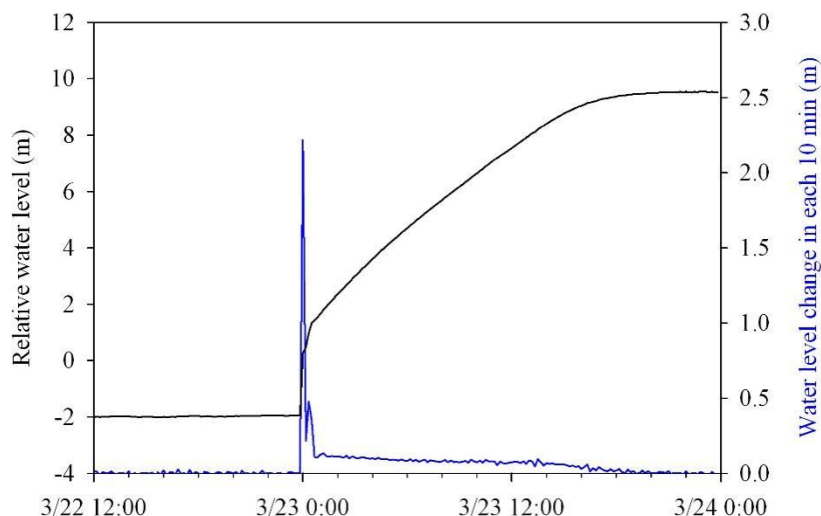
level continued to rise at a rate of 0.6 - 0.8 m/hour, rising by a total of 11 m before stabilising at approximately 18:00 on 23 March 2021. This collapse turned into a highly mobile mass flow which completely destroyed the EWS2 installed near the Sedongpu Valley outlet (Fig. 1d). Unfortunately, the process of this chain catastrophe was not recorded.

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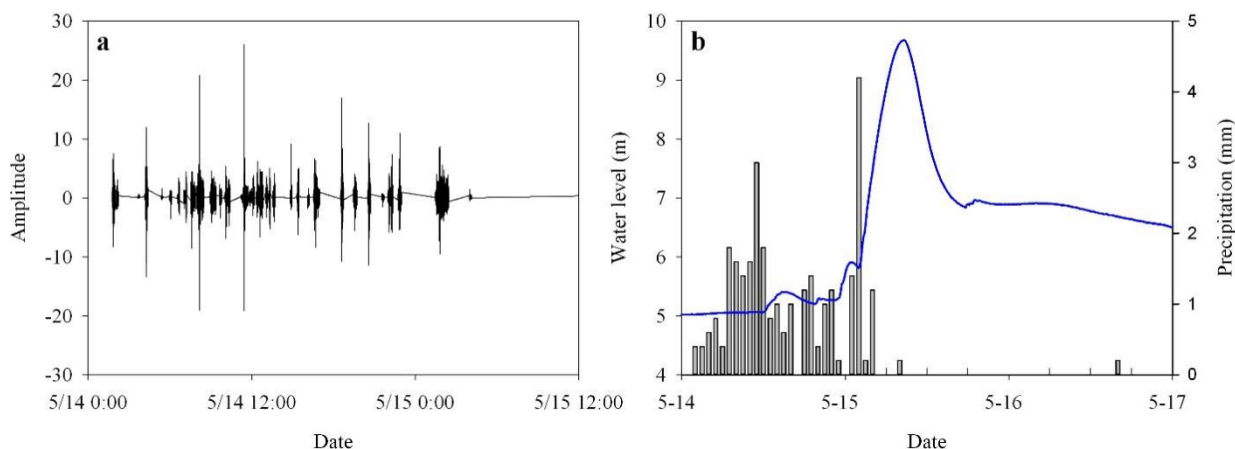
Figure 2: A total water level rise of 11 m (black line) caused by the damming of the Yarlung Tsangpo River on 22 March 2021, with the rate of water level rise every 10 minutes (blue line)

5.2 Ice-rock collapses and river blockage on 14 May 2022

On 14 May 2022, the geophone at EWS1 warned that repeated collapses occurred in the Sedongpu Valley (Fig. 3a). The
195 most pronounced shaking occurred at approximately 10:00 and 12:00, with both waveform amplitudes exceeding 20. However, both EWS2 near the Sedongpu Valley outlet and EWS3 near Gyala village did not send a warning message before midnight on 14 May 2022. Between 23:50 on 14 May and 00:00 on 15 May, the water level sensor at EWS3 sent a warning message, and the water level rose by a total of 4 m before stabilising at around 20:00 on 15 May 2022 (Fig. 3b). Infrared imagery at EWS2 showed that the Yarlung Tsangpo River was temporarily completely dammed and then released, consistent
200 with the rapid rise and fall in the water level (Fig. 4ab). The AWS at EWS1 recorded a total rainfall of 31.6 mm on 14 May with intensive rainfall (7mm) occurring between 01:00 and 04:00 on 15 May. Overall, the ice-rock collapse and intensive rainfall provided favorable conditions for the formation of a diluted debris flow, resulting in the temporary blockage of the Yarlung Tsangpo River (Fig. 4a, b).

205 **Figure 3:** The recorded geophone waveform at EWS1 due to frequent ice-rock collapses on 14 May 2022 (a), and the rising water level of the Yarlung Tsangpo River due to the blockage on 15 May 2022 along with the hourly precipitation (b)

A comparison of both optical and infrared photographs before and after the ice collapse showed that repeated collapses occurred on the northern ridge of Mt Gyala Peri (Fig. 4c-f), which is close to the locations of previous massive ice-rock

210 collapses in 2017 (Kääb et al., 2021) and 2021 (Zhao et al., 2022). In fact, the ridge was heavily glaciated, so these repeated events were mixed ice-rock collapses. The delayed formation of debris flows after ice-rock collapses suggests that it takes some time for the collapsed ice to melt, which agrees well with the delay between the observed ice collapse in October 2019 and its delayed debris flow (Zhao et al., 2022).

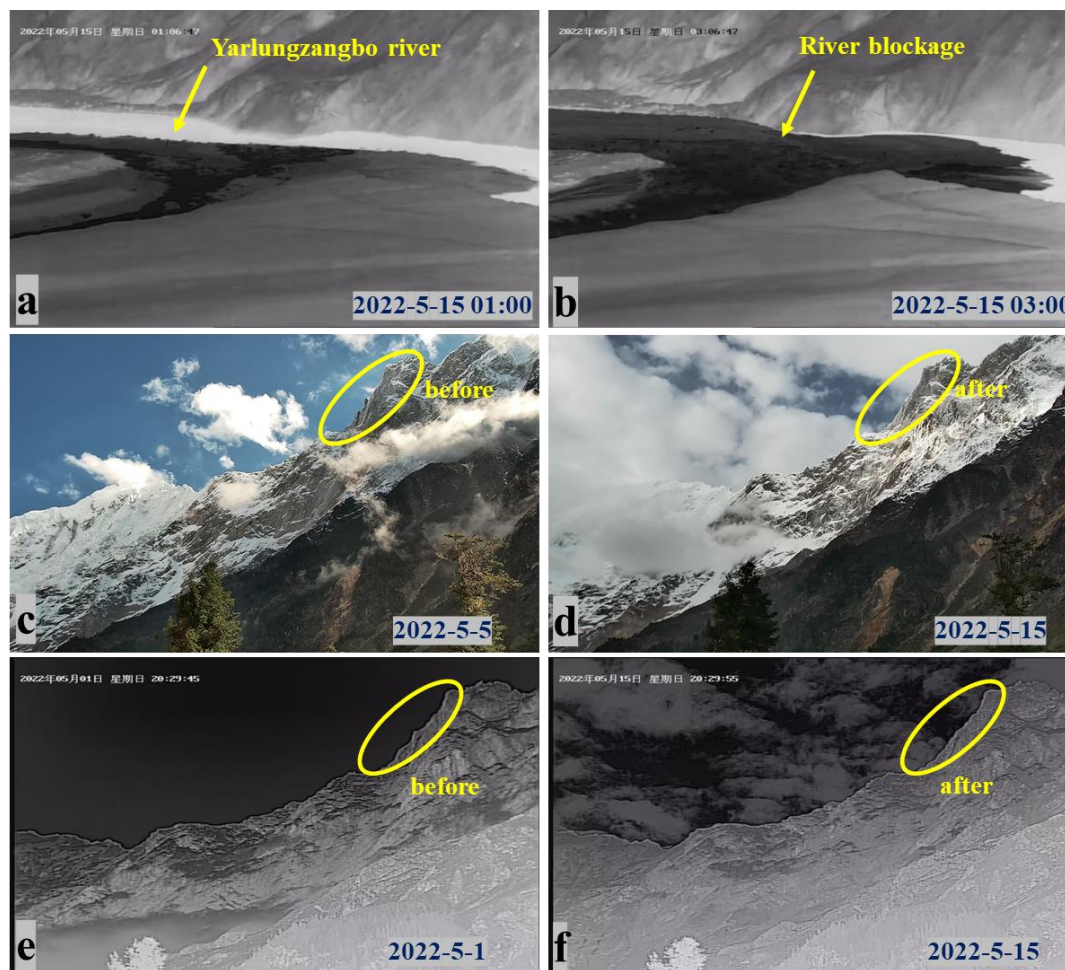



Figure 4: The debris-induced blockage of the Yarlung Tsangpo River (a, b) and the optical (a, b) and thermal (c, d) images showing the topographic changes before and after the repeated ice-rock collapses on 14 May 2022.

5.3 Repeated ice-rock collapses on 11 August 2022

On 11 August 2022, the geophone at EWS1 again warned of repeated collapses in the Sedongpu Valley (Fig. 5a). The first collapse occurred at 16:26, with a waveform amplitude greater than 20, and lasted approximately 5-7 minutes. The following six repeated collapses occurred within the next eight hours. Among these seven repeated collapses, the waveform showed that the greatest energy was released by the second collapse, with a maximum amplitude greater than 28, and the longest collapse process lasted approximately 84 mins during the third event (Fig. 5a).

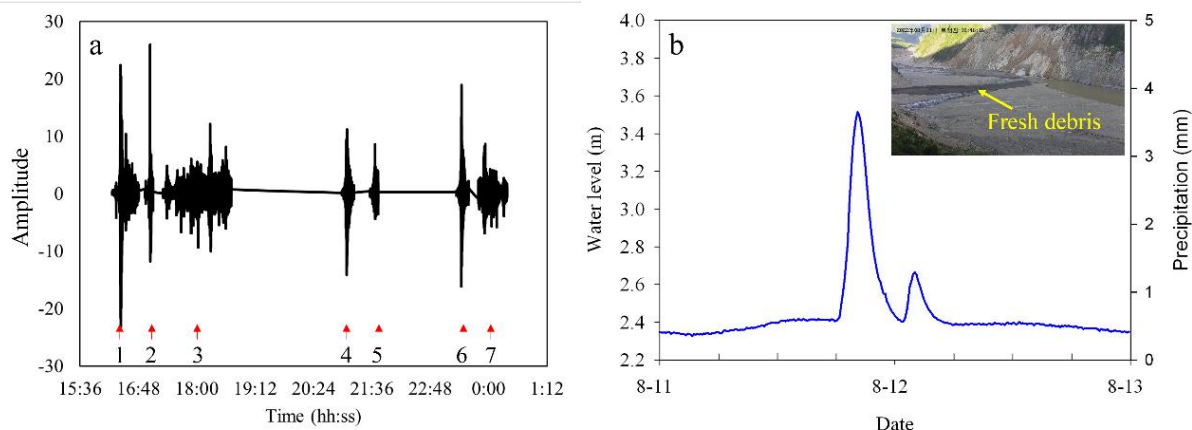



Figure 5: The recorded waveform of seven collapses on 11 August 2022 (a) and the small-scale fresh debris flow into the Yarlung Tsangpo River and the corresponding water level rise (b).

Owing to the sunny weather conditions, the optical video system at EMS1 successfully captured the entire process of the two collapses that occurred during the daytime (Fig. 6a and b). Both videos of the two collapses showed that the highly mobile collapsed material resulted in dark yellow dust in the Sedongpu Valley. The colours of both collapses differed from the observed ice collapse recorded in October 2019 (Zhao et al., 2022). This indicates that the majority of the collapsed material on 11 August 2022 was composed of rock. Second, the combination of the video and geophone waveform showed that the size of the collapses was impressive when the amplitude of the geophone waveform at EWS1 was greater than 20. In addition, the video showed that the magnitude of the second collapse was significantly larger than that of the first collapse, and the onset and duration of the collapse recorded by the geophone were in agreement with the video recordings. These matches demonstrate that the geophone waveform at EWS1 can be used to reflect the onset and magnitude of repeated collapses in the Sedongpu Valley.

Photographs of EWS2 show that small-scale fresh debris flowed into the Yarlung Tsangpo River, causing partial river blockage (Fig. 5b). The warning system at EWS3 indicated that the water level began to rise at around 18:30 and rose by 1.1 m at around 20:00, and then started to fall back rapidly (Fig. 5b). Comparison between the post- and pre-event optical and infrared imagery at EWS1 showed that the collapsed sources were different from previous ice-rock collapses (Fig. 4). Two visible collapsed regions are mainly concentrated a few hundred meters below the mountain ridge, with a few glacier distributions (Fig. 6c-f). This evidence suggests that lower ice content within collapsed materials prevent the formation of highly mobile debris flows and thus limit the magnitude of river blockage.

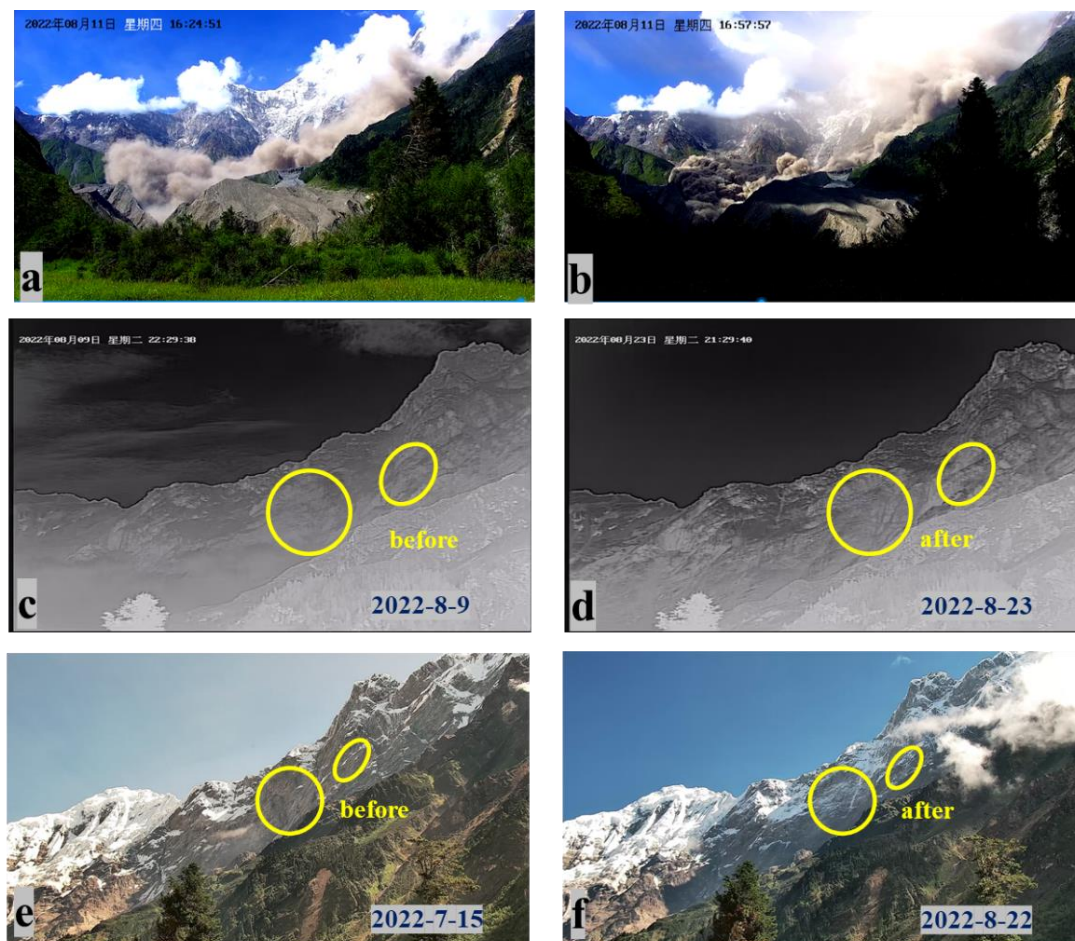



Figure 6: Video screenshots of two rock collapses at 16:24 and 16:57 on 11 August 2022 (a, b), and the thermal (c, d) and optical (e, f) photos before and after the collapses showing the collapsed sources.

5.4 Warning indicators and their implications

As shown by the above-mentioned ice-rock-debris flow-river blockage events, water level monitoring proved to be an effective means of warning against river blockage. The water level monitoring intervals were 5 mins and 10 mins at EWS1. Based on the analysis of our monitoring data and three blockage events, water levels rising at three-level thresholds of 20, 25, and 30 cm per 5 or 10 mins were selected. Meanwhile, the real-time camera and hourly photos at EWS2 were also used as complementary data to confirm river blockages.

Previous retrospective studies have shown that seismic observations are helpful in reconstructing the processes of both glacial lake outburst floods (Maurer et al., 2020) and ice-rock collapses (Bai et al., 2023). The above-mentioned ice-rock collapses in the Sedongpu Valley further demonstrated that the in-situ geophone waveform can be effectively used to warn

against the occurrence and magnitude of ice-rock collapses. When the amplitude of the geophone waveform at EWS1 was approximately 20, the magnitude of the ice-rock collapse was similar to that of the 11 August 2022 event (Fig. 6a and b). The geophone records at EWS1 show that there are a total of 12 events with waveform amplitudes greater than 20 from May 2022 to December 2022. Combined with the infrared and optical photographs at the Sedongpu Valley outlet, nine of the
260 twelve events were confirmed to correspond to the occurrence of debris flows that arrived at the Sedongpu Valley outlet but did not significantly block the river (Fig. 7 and Supplementary Figures). Only three events, including the Mw 5.6 earthquake centred at Modog on 10 November 2022, did not correspond to the debris flow near the valley outlet. Therefore, when the geophone amplitude exceeds 20 in EWS1, there is a high probability that collapse-induced debris flow will occur in the Sedongpu Valley. In practice, the EWS in this study provides a three-level warning system by selecting thresholds of 20, 40
265 and 60, respectively.

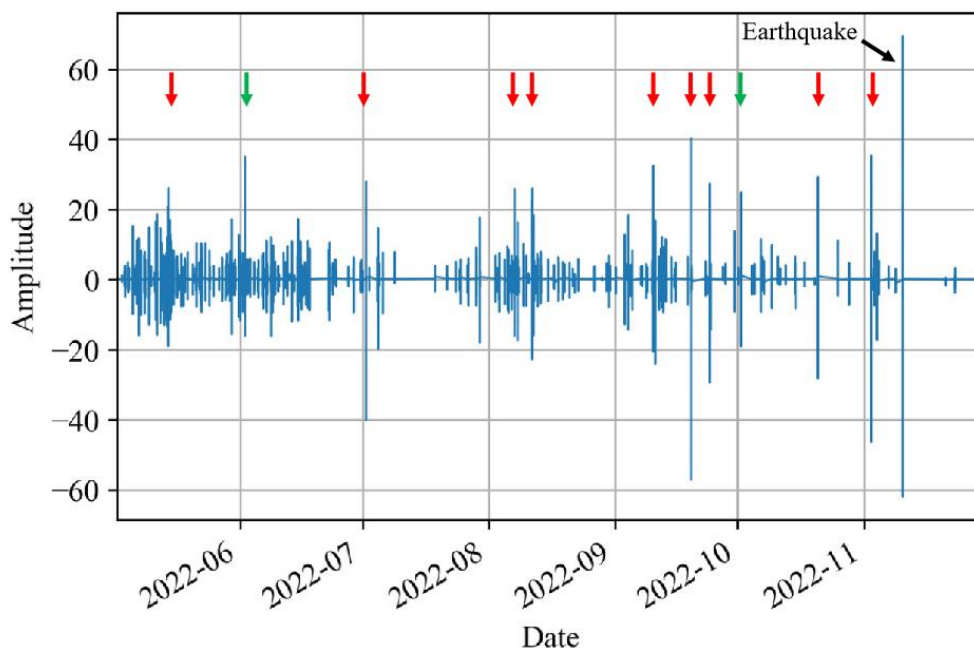



Figure 7: Geophone waveform inside the Sedongpu Valley during the period from May to December with 12 events of waveform amplitude greater than 20. The red arrow indicates the confirmed collapses and induced debris flows, the black arrow indicates the Mw 5.6 earthquake on 10 November 2022, and the green arrow indicates two abnormal waveform.

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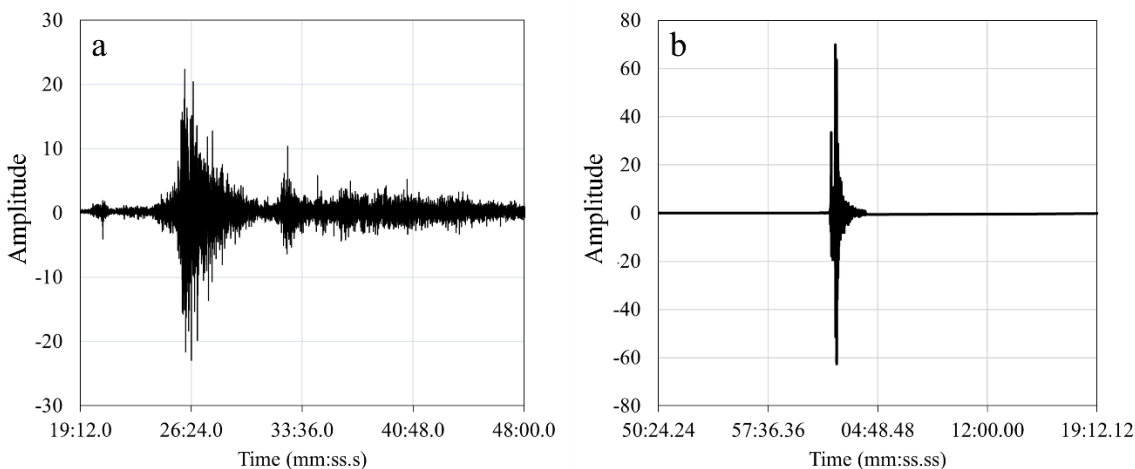
The study region is located in an active crustal zone that experiences frequent earthquakes (Li et al., 2022b). A mixed waveform of collapses and earthquakes may result in false warning signals. In fact, the waveforms of ice collapses and earthquakes differ because of different physical processes. Figure 8 shows a comparison of the waveform triggered by a rock collapse recorded on 10 August 2022 and the Mw 5.6 earthquake on 10 November 2022. The collapse typically lasted for

275   several minutes and produced a continuous waveform. In contrast, the waveform from an earthquake is usually short-lived owing to the rapid release of rupture energy, e.g., approximately one minute for a Mw 5.6 earthquake (Fig. 8b). Therefore, in addition to the threshold of the maximum amplitude, the duration of the waveform was also used as additional information for the ice-rock collapse warning in the Sedongpu Valley.

280   **Figure 8:** Comparison of the waveforms generated by the rock collapse on 11 August 2022 and the seismic waveforms by the earthquake on 10 November 2022.

6. Discussions

6.1 Glaciers with potential risks near the Gyala Peri-Namcha Barwa Massif

285   Repeated ice-rock collapses in the Sedongpu Valley near Mt. Gyala Peri (An et al., 2022; Chen et al., 2020; Kääb et al., 2021; Li et al., 2022b; Tong et al., 2019; Zhao et al., 2022) and the Zelongnong valley near Mt. Namcha Barwa (Peng et al., 2022; Hu et al., 2020; Montgomery et al., 2004; Zhang, 1992) showed high disaster risks in this high mountain region. Based on previous glacier-related disaster studies, some precursors of abnormal glacier dynamics, such as accelerated surface velocity, widening surface crevasse and glacier thickening at the glacier terminus, could be captured prior to glacier collapse

290   using repeated high-resolution remote sensing data (Kääb et al., 2018; Jacquemart et al., 2020; An et al., 2022; Shugar et al., 2021), thus providing first-order discrimination of glaciers at risk.

    Based on the published datasets, including glacier elevation change during the period 2010-2020 (Hugonnet et al., 2021) and glacier surface velocity during the period 2017–2018 (Millan et al., 2022), it was found that apart from the detached Sedongpu Glacier, there are still two glaciers (Zelongnong Glacier and the glacier numbered RGI60-13.01430) with possible

295   collapse risks in the study region (Fig. 9). As shown in Figure 9a, the ablation zone of the Sedongpu Glacier has experienced

an anomalous glacier thickening (~2.0 m/yr) over the past decade, which facilitated massive low-angle glacier detachment in October 2018 (Kääb et al., 2021). A similar anomalous ice thickening near the ablation zone was also found at the Zelongnong Glacier (~+0.35 m/yr) and RGI60-13.01430 Glacier (~+0.37 m/yr). In addition, the spatial distribution of the surface velocity also indicated a high glacier displacement in the ablation zone with possible sliding risks on these glaciers

300   (Fig. 9b).

It is therefore worth paying special attention to the dynamic changes of these glaciers by using high-resolution satellite data and ground-based EWS. Enhanced monitoring is particularly critical for the Zelongnong Glacier, which is very close to the town of Pai with a population of more than 3000, and for the proposed large-scale hydropower project (Fig.9b). In the event of massive ice-rock collapses or glacier detachment, the potential hazards will be more severe than those from the

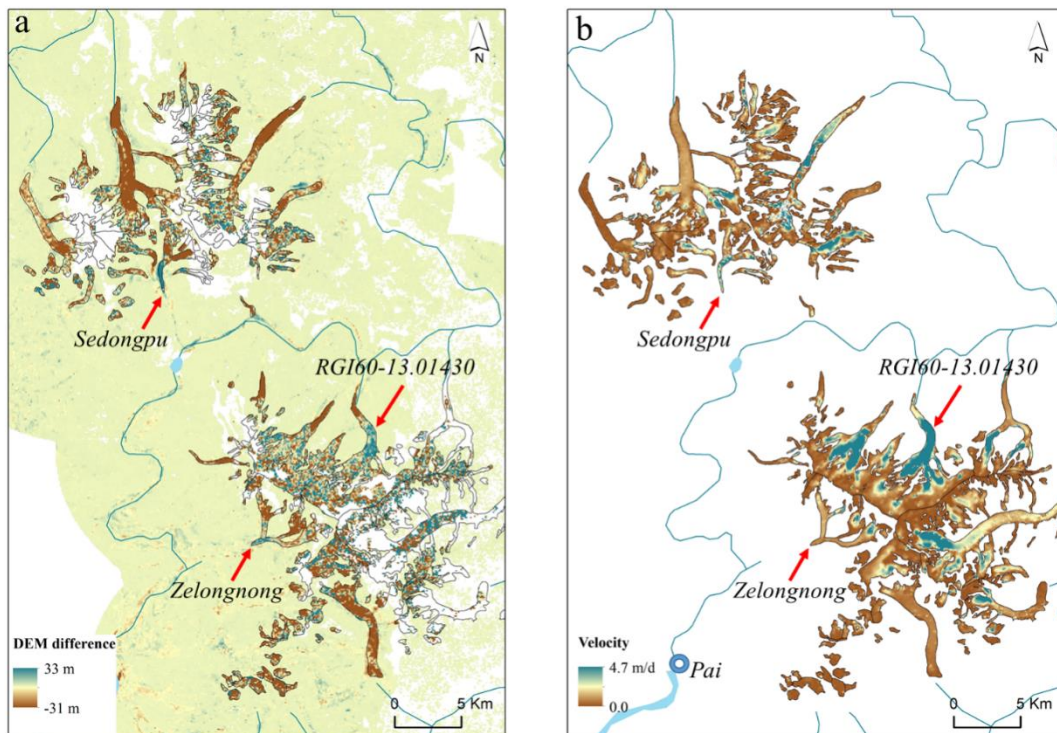
305   Sedongpu Glacier and RGI60-13.01430 Glacier because of the limited elevation difference (~70m) and linear distance (~11 km) between Pai town (2920 m asl) and the Zelongnong Valley outlet (2850 m asl). Therefore, similar to the EWS in the Sedongpu Valley, it is necessary to conduct continuous ground-based monitoring on/near the Zelongnong Glacier to provide early warning for the protection of the surrounding and downstream hydrological projects and infrastructure in this transboundary region.

310

Figure 9: Spatial distribution of mean surface elevation change (m) during 2010-2020 and annual surface velocity (m/day) in 2017, and the locations of the two glaciers with possible collapse risks and the tower of Pai.

6.2 The monitoring priority for ice-rock disasters near the Gyala Peri-Namcha Barwa massif

The EWS in this study provides valuable datasets, including optical/thermal video/photographic, seismic,
315 meteorological, and water level data, for monitoring the occurrence of ice-rock collapses and river blockages near the Sedongpu Valley. However, both in-situ and satellite observations have revealed that the collapsed source is generally concentrated at extremely high elevations above 6000 m asl (Kääb et al., 2021; Zhao et al., 2022). Abundant monsoonal moisture and cloud formation at high elevations have prevented the availability of real-time, cloud-free video/imagery to determine the location and magnitude of the ice-rock collapses.
320 As shown in Figures 4c-f and Figure 6c-f, the selected cloud-free photos were taken several days before and after the collapse, delaying the real-time assessment of the collapse. Therefore, new weather-independent monitoring instruments (e.g. all-weather avalanche radar) should be considered for real-time monitoring and for accessing the location and volume of ice-rock collapses for the next updated ground-based EWS in the Sedongpu Valley. Although satellite data sometimes suffer from weather conditions and revisit intervals, repeated comparisons of high-resolution remote sensing data and weather-
325 independent SAR data are recommended to provide preliminary information on the deformation and instability of rock and ice in high-altitude glaciated regions.

Special attention should be paid to the tectonic-climatic interactions near the Gyala Peri-Namcha Barwa massif. The Namcha Barwa-Gyala Peri has experienced the highest uplift and denudation rates worldwide (Enkelmann et al., 2011; King et al., 2016). The competition between rapid uplift and glacial erosion around the Namcha Barwa-Gyala Peri massif
330 contributed to the formation of thick Quaternary glacial deposits (Hu et al., 2020; Zhu et al., 2012). With extreme climate events, temperate glaciers in this region become unstable, leading to repeated ice-rock collapses. The combination of excess meltwater from glacier collapse and the thick, unconsolidated glacial deposits is therefore likely to contribute to anomalous glaciofluvial erosion. Most of the debris flows and eroded glacial sediments from the high elevations were eventually transported down by the Yarlung Tsangpo River. Thus, the instability of high-elevation glaciers near the Gyala Peri-Namcha
335 Barwa massif could potentially affect the safety of downstream hydropower dams as well as the ecological systems by changing sediment loads along the transboundary river (Li et al., 2022a).

7.   Conclusions

An EWS has been established to monitor ice-rock collapses and river blockages in the Sedongpu Valley in the southeastern Tibetan Plateau. It consists of three parts with different monitoring sensors and scientific functions: EWS1 for
340 ice-rock collapse warning and EWS2 and EWS3 for river blockage warning. The EWSs provide valuable information on

optical/thermal video/photo, seismic, meteorological and water level data transmitted mainly via satellites in this sparsely populated region. The systems successfully detected three ice-rock collapse-debris flow-river blockage chain events and at least seven ice-rock collapse -debris flow events, providing alarming information to the local government.

Based on these monitoring efforts, we found that the geophone waveform plays a critical role in warning of collapses in
345 the Sedongpu Valley. When the geophone waveform amplitude is greater than 20 at EWS1, there is a high probability that a collapse-induced debris flow will be generated from the Sedongpu Valley, and the magnitude of the collapses is impressive as shown by the events videotaped on 11 August 2022. The river blockage at the Sedongpu Valley outlet can be warned in time by a water level monitoring system. Based on the analysis of these observed disaster events, it was found that several key factors, including the volume/location of the collapses, percentage of ice content in the collapsed material and
350 meteorological conditions, could contribute to the different velocities of the debris flows and different magnitudes of the river blockages.

Based on the previous studies on the precursors of glacier collapse and the published datasets, it was found that, apart from the detached Sedongpu Glacier, there are still two glaciers (Zelongnong Glacier and the RGI60-13.01430 Glacier) with possible collapse risks in the study region. It is worth paying special attention to these dynamic changes using high-
355 resolution satellite data and ground-based EWSs. In addition, this pioneering work on EWS paves the way for the establishment of similar EWSs in other potential collapse regions on the Tibetan Plateau for early detection of hazards and for effectively reducing risks.

360 **Author contributions.** W.Y., B.A, T.Y, Y.C was responsible for the framework design of the EWS. Z.W., W.Y. and B.A. installed the EWS. W.Y. analysed the data and write the manuscript. G.W., L.B., F.Z., C.Z., C.L, W.W., and J.L. assisted in collecting all data and discussion. Funding acquisition, T.Y. All authors have read and agreed to the published version of the manuscript.

365 **Declaration of competing interest**

The authors declare that they have no conflict of interests.

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Table 1. Detailed information on the ground-based early warning system installed near the Sedongpu Valley in the southeastern Tibetan Plateau

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Locations	Lat/Lon	Elevation (m)	Instruments	Monitoring elements and purpose	Frequency	Manufacture	Transfer
Inside the valley	29.77° 94.92°	3308	Optical camera1	real-time video、daytime photo for the whole valley	Hourly photo from 08:00-20:00	Hikvision DS	Asiasat 7 satellites
			Optical camera2	real-time video、daytime photo for the collapse region	Hourly photo from 08:00-20:00	IR8000	
			Thermal camera	real-time video、night-time photo for the collapse region	Hourly photo from 20:00-08:00		
			Geophone	X,Y,Z three- component waveform	5 HZ	SmartSolo DT-SOLO	
			AWS	T_{air}, RH, rainfall, wind	10 min	Compbell	
Valley outlet	29.75° 94.93°	2930	Optical camera	real-time video、daytime photo for river blockage	Hourly photo from 08:00-20:00	Hikvision DS	Asiasat 7 satellites
			Thermal camera	real-time video、night-time photo for river blockage	Hourly photo from 20:00-08:00	STZ100X5	
			Geophone	X,Y,Z three- component waveform	5 HZ	SmartSolo DT-SOLO	
			AWS	T_{air}, RH, rainfall, wind	10 min	Compbell	
Gyala village	29.71° 94.90°	2780	Radar water level	water level of Yarlung Tsangpo River	10 min	Campbell CS477	2G cellular network
			Pressure water level	water level of Yarlung Tsangpo River	5 min	Campbell CS451	
			AWS	T_{air}, RH, S_{in}, S_{out}, L_{in}, L_{out}, rainfall, wind, air pressure	10 min	Compbell	Beidou satellites

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