Early Warning Systems for Glacier Lake Outburst Floods and Debris Flows Case Studies from China and Georgia

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Abstract: Climate change affects the cryosphere in a strong way. In 2012 the IPCC (IPCC, 2012) concluded that there is high confidence that changes in heat waves, glacial retreat and/or permafrost degradation will have a strong on high mountain phenomena such as slope instabilities, mass movements and glacial lake outburst floods (GLOF). The overall frequency of debris flows may decrease in absolute terms, but the magnitude of events may increase. This was concluded from an analysis of debris flow events in the past 150 years and using this information for future projections on climate change. Two case studies from China and Georgia demonstrate the evidence of ongoing climate change. In both situation early warning systems and glacier monitoring are the key for a) detailed hazard assessment, b) a longterm observation of the system development and c) the warning and alarming of a major damage potential (settlements, main touristic roads, gas pipline). While the early warning system in the Yarkant River at Kyagar glacier (Chinese Karakoram Mountains) has already been tested in a real GLOF event in 2015, the system in Georgia for huge debris flows induced by glacier collapses in the on top of Mt. Kazbeg will be installed in spring 2016. In both project GEOTEST AG and GEOPREAVENT AG build a successful joint venture; while the experienced geologists and glaciologists of Geotest assess the hazard potential and evaluate mitigation measures, Geopraevent's engineers develop, install and run the early warning system. Both systems are based on modern technologies and devices.

Keywords: early warning system, risk management, glacial lake outburst flood (GLOF), debris flow

1. Introduction

Early warning is the provision of timely and effective information, through identified institutions, that allows individuals exposed to a hazard to take action to avoid or reduce their risk and prepare for effective response. In other words, early warning can be defined as the set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a hazard to prepare and to act appropriately and in sufficient time to reduce the possibility of harm or loss (UNISDR, 2010). The definition does not include a reference to the time scale on which a warning is given. Early Warning Systems (EWS) include a chain of concerns, namely: understanding and mapping the hazard; monitoring and forecasting impending events; processing and disseminating understandable warnings to political authorities and the population, and undertaking appropriate and timely actions in response to the warnings.

A complete and effective EWS comprises four elements, spanning knowledge of the risks faced through to preparedness to act on early warning. Failure in any one part can mean failure of the whole system. The "four elements of effective early warning systems", the early warning chain, include the development and operation of early warning systems in regard to: (a) knowledge of risks; (b) monitoring and warning services; (c) warning dissemination and communication; and (d) emergency response (CCES 2013; Sättele & Bründl, 2015). These four elements imply that early warning is based on the assessment of risk and vulnerability. Moreover, early warning should be communicated appropriately and ensure response capability of the people at risk, taking into account short and long-term measures.

Mountain systems are particularly sensitive to climate change. It is important to stress that climate change will not only adversely affect the resilience of communities, environment, urban infrastructures, transportation, energy suppliers and other sectors but also EWS. It is a common opinion that beyond the need for mitigation, adaptation to climate change is an important task. It should be highlighted here that in this context not only the exemplary listed sector above will have to adapt to climate change but also existing and planned early warning concepts need to be climate checked. The need for adapting EWS may reveal for all parts of the early warning chain.

The following two case studies from China and Georgia demonstrate the evidence of ongoing climate change. In both situation early warning systems and glacier monitoring are the key for a) detailed hazard assessment, b) a longterm observation of the system development and c) the warning and alarming of a major damage potential (settlements, main touristic roads, gas pipline).

2. Case Study China – Glacier Lake Outburst Flood

2.1 Intruduction

The hazard assessment of glacier lakes at remote and high-elevation sites of the Himalaya, Karakoram and Tien Shan is difficult due to restricted field site accessibility. Yarkant river in the Chinese Karakoram (Fig. 2.1) drains an area of 50’248 km2 and ranks as number one in terms of flood frequency and damage in Xinjiang. Its glacial outburst floods, with peak discharges of up to 6’000 m3 s–1, originate from a remote ice-dammed glacier lake at 4’750 m a.s.l. in the Shaksgam valley, approx. 560 km upstream of the floodplains. The hazardous lake is impounded behind the snout of the Kyagar Glacier which blocks the riverbed of Shaksgam valley. In the past the maximum lake volume was 230 million m^3. Based on the hazard assessment of Kyagar Lake and newly gained knowledge about the glacier dynamics, a sophisticated monitoring and EWS for GLOFs was successfully implemented (Fig. 2.2). The system is operational since 2012.

The project is designed to significantly reduce human and material losses through adaptation in vulnerable communities in the floodplains of glacier-fed river system, by considering long-term development of the flood hazard situation in the catchment of Yarkant River. Practical approaches to climate change adaptation have been developed: (1) establishment of an early warning system (EWS) for GLOFs, (2) risk management in the floodplain, (3) glacier and climate change monitoring.

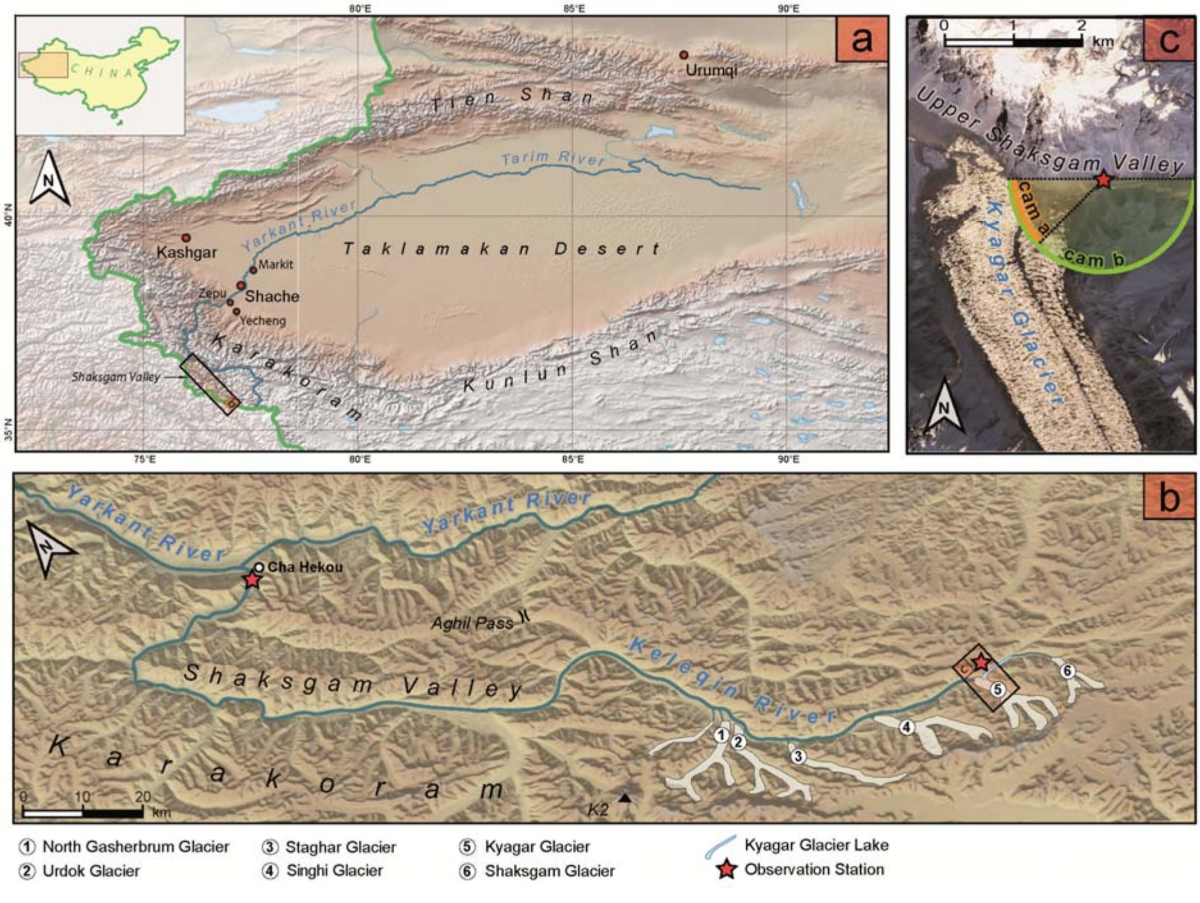

Fig. 2.1: Situation of (a) Yarkant river in the Tarim basin, (b) Shaksgam valley and (c) Kyagar Glacier tongue with the location of the observation station and the indicated camera view directions of the automatic camera.

2.2 The Early Warning System

Because the lake is situated in a remote area, the EWS utilized a combination of satellite remote-sensing and automatic terrestrial measurements (Fig. 2.3). Based on the DEM of the empty lake basin and periodically acquired SAR images, the evolving morphology of both lake and glacier can be observed within a time interval of 11 days. The lake volume was then calculated, and the hazard level determined and transmitted to the Chinese decision-makers. In addition to remote-sensing techniques, terrestrial solar-powered, fully automatic observation stations were installed directly at the lake and further downstream along Keleqin and Yarkant rivers at Cha Hekou and Kuluklangan (Fig. 2.1 and 2.3). The observation station close to the ice dam (Fig. 2.2) was able to take daily photographic images from different viewing angles (Fig. 2.1) and to record the local meteorological conditions (air temperature, solid and liquid precipitation, humidity, global radiation). At the two stations downstream radar sensors continuously log the water level of the rivers, and pictures of the riverbed are taken. Several times a day, all data are automatically transmitted via satellite link to a specific data portal.

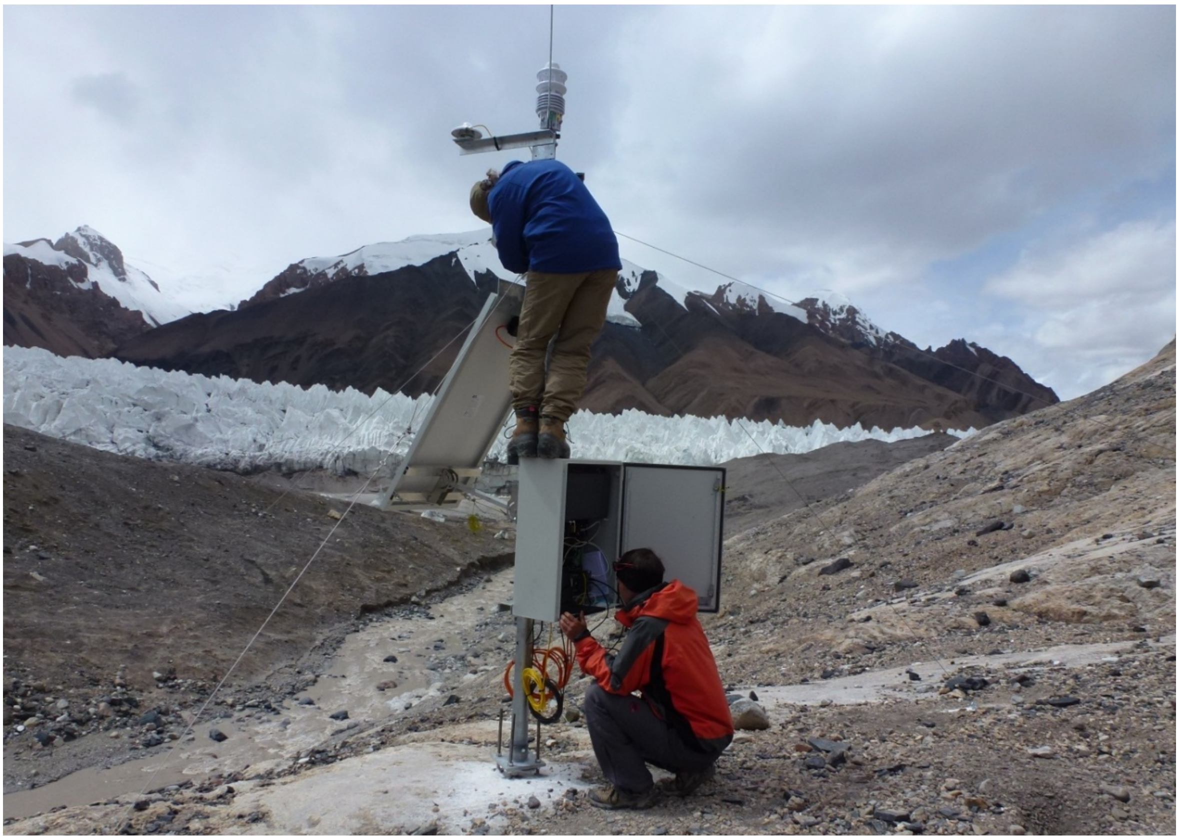

Fig. 2.2: Installation work on the observation station. The Kyagar Glacier is visible in the background.

With the glacier observation station a possible outburst can be recognized at an early stage. The lead time of an outburst observation till the impact of the flood wave at the floodplain is from the glacier station appox. 34 – 36 hours, the one from Cha Hekou 22 h and from Kuluklangan 7.5 h. GLOFs typically show an obvious peak with rapidly rising and declining discharge. If a GLOF is detected, an automatically generated alarm-signal will immediately be sent to mobile phones of the Chinese authorities. Thus, emergency actions can be initiated. The station at Kuluklangan covers a large catchment area and is therefore suitable to monitor GLOFs, meltwater and rainfall floods. In case of a GLOF it serves as a redundant alarm station of the one at Cha Hekou.

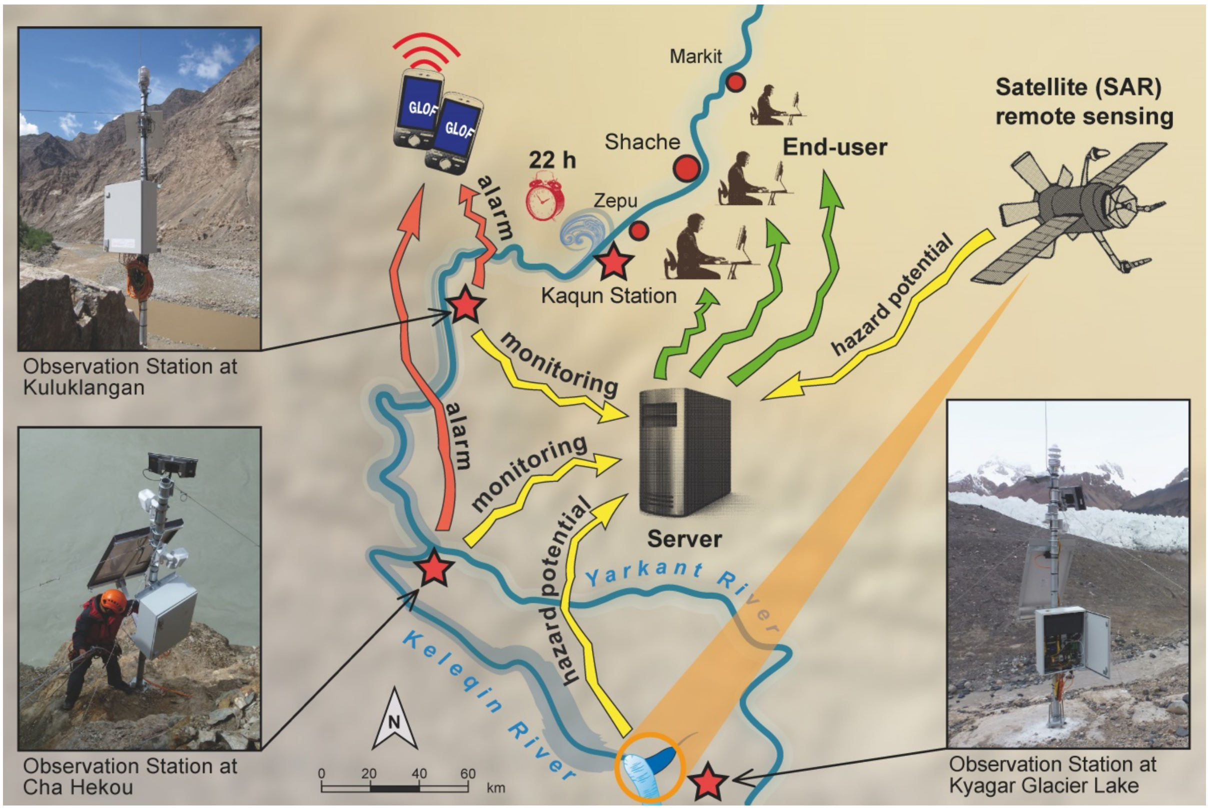

Fig. 2.3: Concept of the early warning system, combining satellite remote sensing and automatic terrestrial observation stations.

2.3 Observation of Glacier Surge

The daily images from the automatic camera installed at Kyagar Lake in September 2012 provide an exceptional possibility to assess geometrical changes close to the glacier terminus in a qualitative way at high temporal resolution.

The repeated observations of glacier flow speed show that ice flow was very slow (10-30 m yr-1) on the glacier tongue until 2010. Over the last years, however, a considerable speed-up of the glacier was observed, first in the upper reaches of Kyagar Glacier, later extending towards the glacier terminus. In some places the speed has nearly doubled between 2011 and 2012 (Haemmig et al. 2014). The changes in surface velocity have been interpreted as the result of a glacier surge. In fact, the surge activity announced by a DEM comparison and by the analysis of surface velocities has arrived in the region of the ice dam in 2014/2015. It has been leading to a dramatic acceleration of flow speed and a considerable thickening of the glacier (Fig. 2.4).

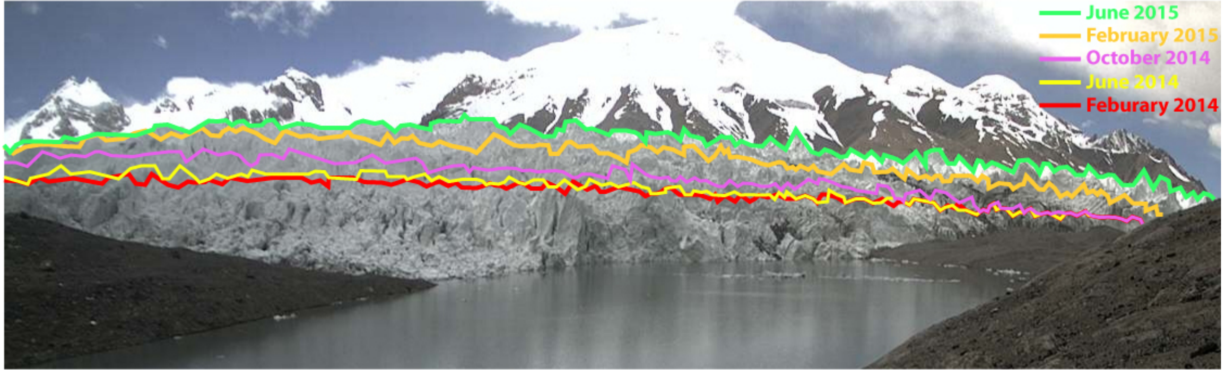

Fig. 2.4: Direct comparison of the glacier surface between February 2014 and June 2015. The thickening is most pronounced in the upstream region and propagates towards the glacier terminus. The ice-dam at the lake thickened by about 1/3 within one year, which corresponds to an elevation increase of the ice surface of approx. 30 – 50 meters (Haemmig et al. 2014).

2.4 GLOF Event July 2015

Since 2014 a dangerous lake has been impounding behind the ice-dam (Fig. 2.5). Based on camera images acquired by the Kyagar observation station, the lake volume has been estimated using terrestrial markers on the mountain flanks. Hence, it was possible to directly identify the hazard potential on photographs taken by the automatic camera.

An accurate forecast of an outburst event is extremely complex due to the continuous processes at the ice-dam (i.e. surge-activity, ablation, availability of subglacial discharge channels) and the highly variable water-influx into the lake basin. Sophisticated monitoring technologies, such as terrestrial observation stations and satellite remote sensing are the base of a robust GLOF hazard assessment. The GLOF hazard level was periodically estimated based on terrestrial and satellite images.

In summer 2015, due to the thickening of the ice-dam, the onset of the flotation equilibrium was estimated at a lake level of approx. 4’840 m a.s.l. with a corresponding lake volume of approx. 40 million m^3 (see Fig. 2.6). On June 29th 2015, the lake reached a volume of approx. 17.2 million m^3.

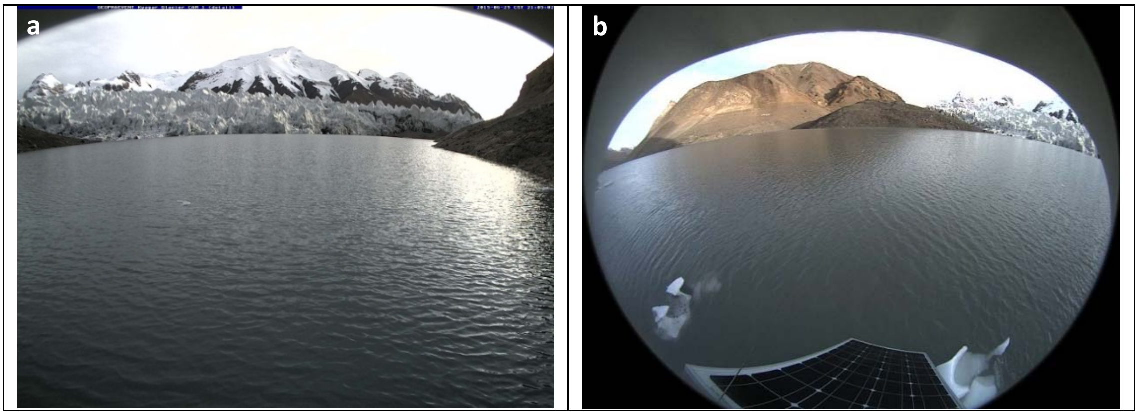

Fig. 2.5: Glacial lake, observed by automatic observation station at Kyagar Glacier (June 29th, 2015).

Since June 30th, 2015, after almost three years of successful monitoring, the automatic observation station at Kyagar Glacier Lake has been out of operation. The station was submerged due to the rapid impoundment of the glacial lake, triggered by the surge-activity of the glacier tongue.

Afterwards the ongoing rise of the lake level and the hazard potential have been estimated based on very high-resolution SAR data of the TerraSAR-X satellites. Based on SAR backscatter, lake surfaces for every image could be delineated. Lake volumes were calculated using lake shorelines and the detailed reference DEM of the lake basin established in 2011. Hazard levels were estimated as a result of the lake size.

The glacial lake with an estimated volume of approx. 50 million m^3 drained completely at the end of July 2015.
Based on satellite remote sensing, the timing and volume of the outburst could be reliably predicted.
The implemented fully automatic GLOF early warning system successfully warned the Chinese decision-makers.

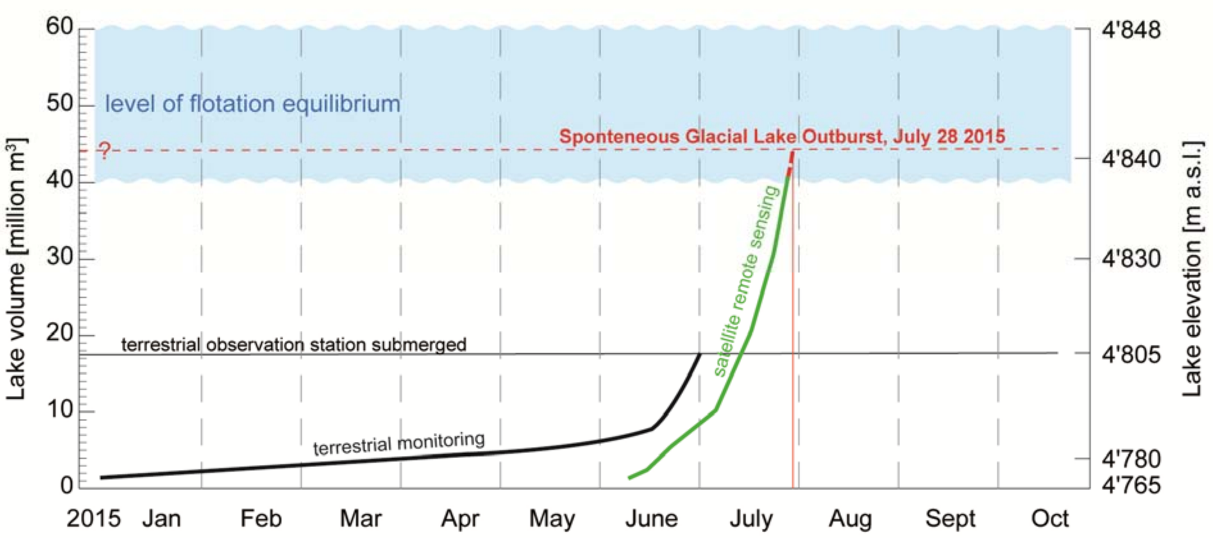

Fig. 2.6: Based on terrestrial and satellite based monitoring techniques an accurate forecast of the GLOF was possible. Terrestrial monitoring was based on the original DEM 2011, whereas volume estimates by satellite remote sensing (sentinel-1) is based on a modified DEM 2011.

3. Case study Georgia

3.1 Intruduction

The Greater Caucasus is a large mountain range between Georgia and Russia with Mt. Elbrus as its highest peak. The main road connecting Georgia with Russia runs along Mt. Kazbek, a 5’048 m high volcano and one of the highest summits of the Caucasus range (Fig. 3.1).

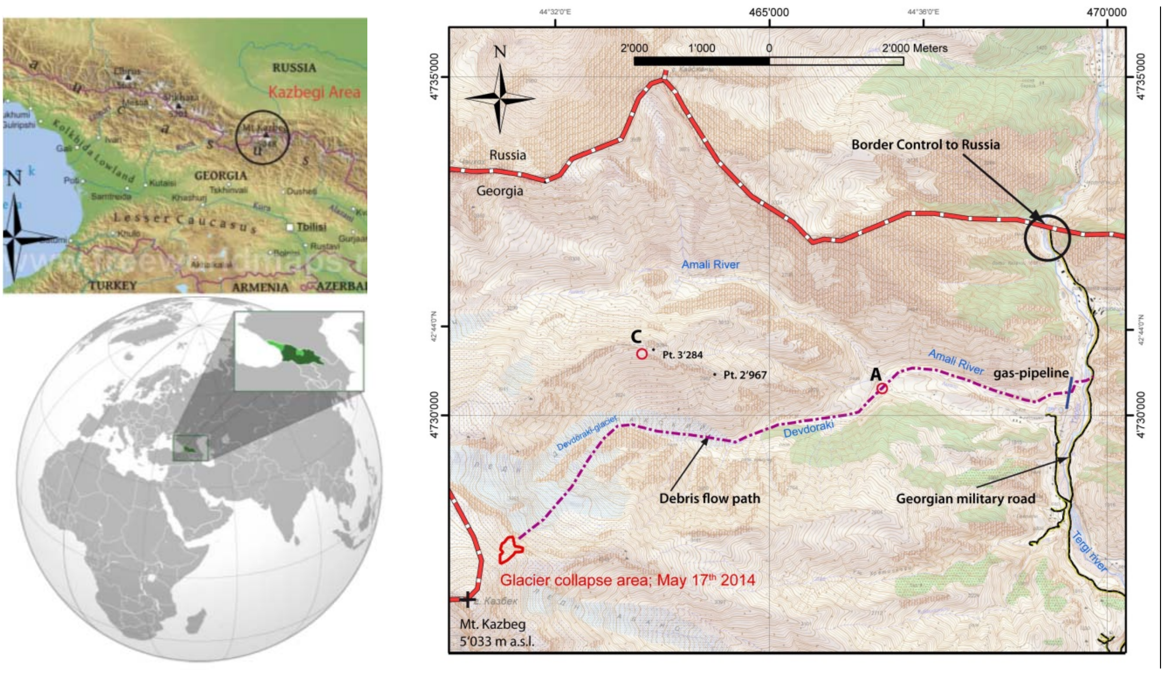

Fig. 3.1: Situation of Devdoraki area within the Mt.Kazbeg region in Georgia.

In May 2014 a huge debris flow consisting of rock and ice blocked the main road just south of the Russian border (Fig. 3.2). The source of the debris flow was high up at the headwall of Mt. Kazbeg, where part of the glacier had collapsed (Fig. 3.3). The debris slid down the Devdoraki glacier, covering the road as well as damaging an important gas pipeline in the main valley. Further events in August 2014 affected the infrastructure of the border control, the customs service and a hydro power plant.

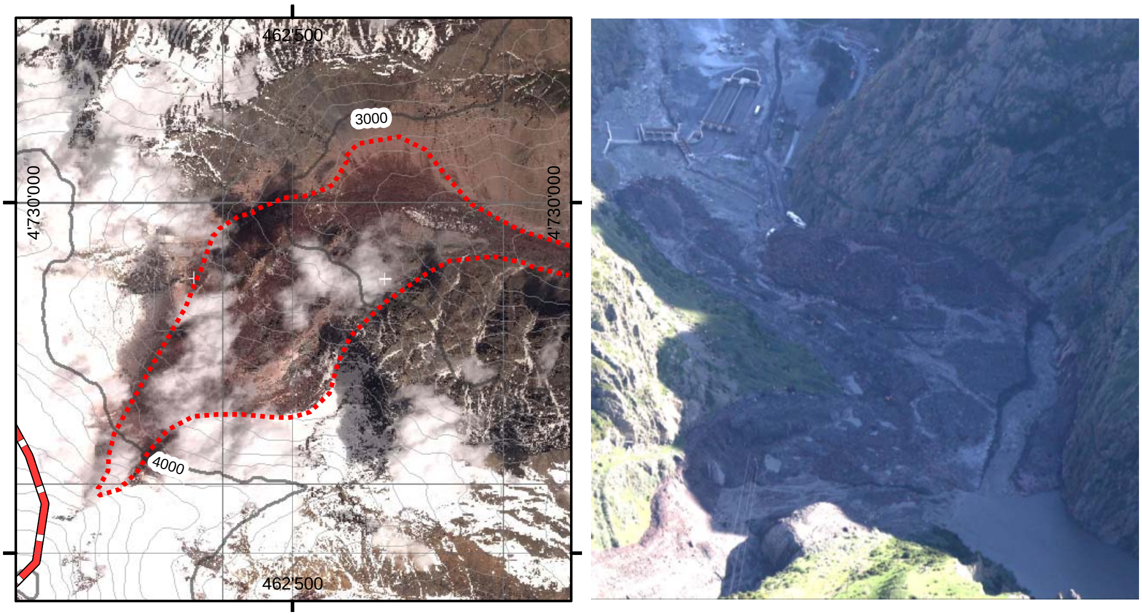

Fig. 3.2: Pleiades satellite image; acquired on May 18th 2014 with outlined process area of the May 17th 2014 event (red dotted line, left) and debris flow deposition in the main valley (right).

Based on a detailed hazard assessment local authorities decided to implement an early warning system for a) monitoring the glacier activities in the upper part of Mt. Kazbeg and b) alarming affected people and infrastructures in the valley from devastating debris flow processes. The concept of the EWS is identical with the one implemented in China (monitoring and alarm stations, data transfer and processing). It is foreseen to install the whole system in April 2016.

3.2 Hazard Assessment – Scenarios

The reason of the event in May 2014 was a combination of a gravitational slope failure along pre-existing discontinuities, longterm degradation of permafrost and glacier melting and probably also volcanic activity expressed in low seismicity and thermal activities. The seismic institute of Illia Stat University, Tbilisi, registered a small tremor prior to the May 17th 2014 event. Volcanic activity (tremor / temperature) may eventually also have a negative impact on the slope stability situation on a very short term and trigger catastrophic events depending on the intensity of the activity.

Fig. 3.3: Main scarp of the glacier collapse in the summit area of Mt. Kazbeg (left) and silent witnesses of the debris flow event in the Devdoraki valley (right).

Rising mean annual air temperatures are causing enduring progressive permafrost degradation (Noetzli and Gruber, 2009) while percolation of melted water can advectively penetrate into bedrock along joints and therefore lead to thermal perturbation and fast modification of the mechanical conditions at depth. Such observations give evidence that the observed increase in frequency and magnitude of mass movements in glacial environments have a relation to climate change (Huggel et al., 2010). The global permafrost zonation index map shows that the glaciated part of Mt. Kazbeg lies within a zone of highly probable permafrost occurrence.

In the lower part of the eastern slope of Mt. Kazbeg the main Devdoraki glacier divides into several glacier tongues. One of the tributary glaciers just ends on a steep slope several dozens of meters above the main glacier. The tongue is mainly detached from the main glacier by huge cracks. Signs of strain and deformation along the limits of the tongue (lose rock material, silent witnesses of actual icefall events, flowing water) have been detected in autumn 2015.

Fig. 3.4: Global permafrost zonation index map (Noetzli and Gruber, 2009) on Google Earth showing the detachment area of the ice collapse within the main permafrost area (left). View of Mt. Kazbeg from the east with active tributary glacier tongue in the lower part of the picture.

According to the hazard assessment in the detachment zone and along the Devdoraki valley, the general structural setting as well as the rough glacier stability analysis the scenarios for future events have been defined:

- Rock-ice slope failures similar to the May 17th 2014 event, with volumes of several millions m^3, can happen again in the next 10 – 30 years. Such big slope failures are often preceded by smaller events in the detachment area possibly announcing an imminent bigger event.
- At the tongue of the tributary glacier, signs of strong stress have been detected in the ice. Experiences from hanging glacier collapses in the Alps indicate that a complete detachment of this part of the tributary glacier cannot be excluded. The instable glacier mass has a volume of approx. 1 Mio. m^3

Evens and Claque (1988) stated that glacial environments can significantly enhance the runout distance of rapid mass movements by travelling on low-friction surfaces such as on glaciers, by melting of ice and snow due to frictional heating that causes pore pressure effects at the base of the moving mass or fluidizes the entire flow body, and by channeling or air-launching the debris by moraines. Schneider et al. (2011) as well as Bottino et al. (2002) quantified by means of numerical simulations the observed runout distances of rock-ice avalanches in glacial environments to exceed predicted ones for pure rock avalanches by up to 30%. The event of May 2014 confirms these conclusions. Thus we know that both scenarios end in huge debris flows reaching down to the main valley endangering the main road, a hydropower plant, a gas pipeline, border police as well as all people using the road. In order to predict the flow velocity of the different events as well as flow heights numerical simulations for the event itself and the defined scenarios have been carried out with the model RAMMS (Christen et al., 2012, Fig. 3.5). According to the simulations the warning time for a debris flow detection system installed at location A (Fig. 3.1 and Fig. 3.6) will be around 5 minutes, which is an absolute minimum to evacuate the whole traffic on the critical road section.

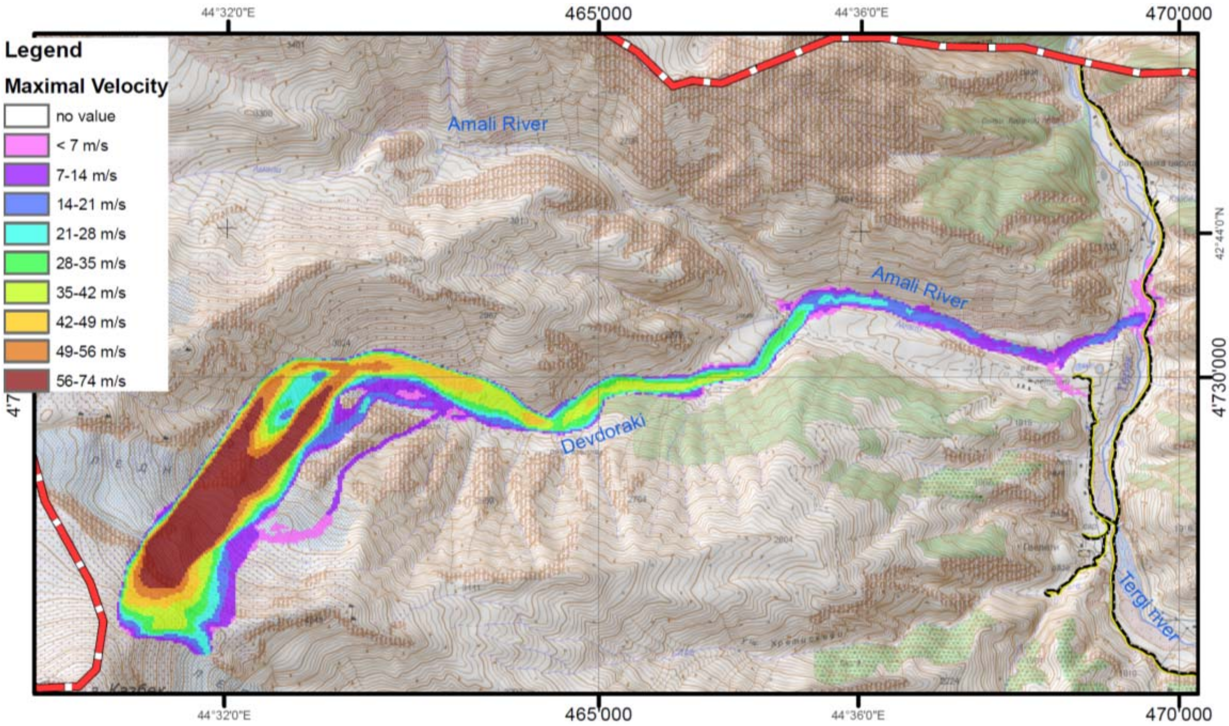

Fig. 3.5: Debris flow simulation with RAMMS to define flow velocities of the main event in 2014. The maximum warning time interval with an early warning system positioned at location A (fig. 3.1 and fig 3.7) can be deviated from the velocities.

3.3 The Early Warning System

The early warning system consists of a glacier observation station and a debris flow alarm system. While the glacier observation point is situated on the eastern ridge of Mt. Kazbeg at 3000 m a. s. l., the debris flow detection is located along the main channel down in the valley (Fig. 3.1).

Glacier monitoring cameras

Glaciers terminating in steep terrain are potentially hazardous. This has been shown in different historical events, where devastating rock-ice avalanches have buried towns or entire cities (e.g. Mattmark, Switzerland 1965 (McCall et al. 1992) or Huascaran, Peru 1962 and 1970 (Evans et al., 2009)). In order to detect such an ice collapse in the topmost area of Mt. Kazbek as well as on the tongue of the tributary glacier a monitoring station will be implemented (Fig. 3.6).

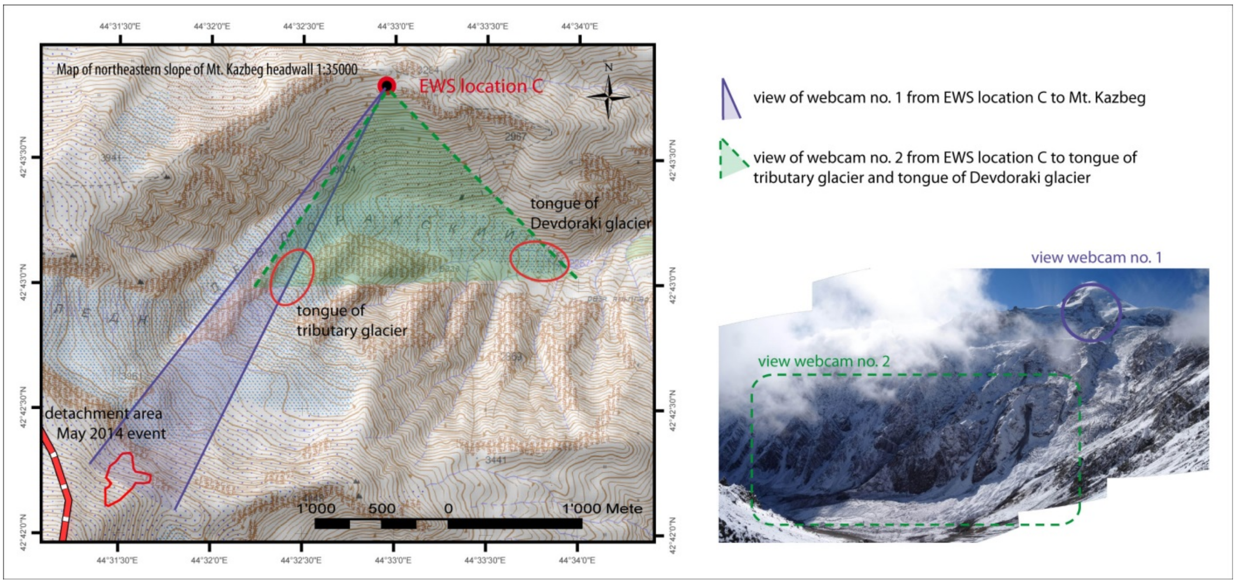

Fig. 3.6: Situation of the glacier monitoring station at location C on 3000 m a.s.l. The critical ice masses will be monitored by two automatic cameras transmitting the taken pictures directly on a password protected data portal.

Two webcams will shoot images of the critical glacier areas at regular intervals, allowing local authorities to determine the glacier movement based on feature tracking within the images (example see fig. 3.7). All webcam images can be accessed on a password protected data portal, providing additional information of all implemented devices.

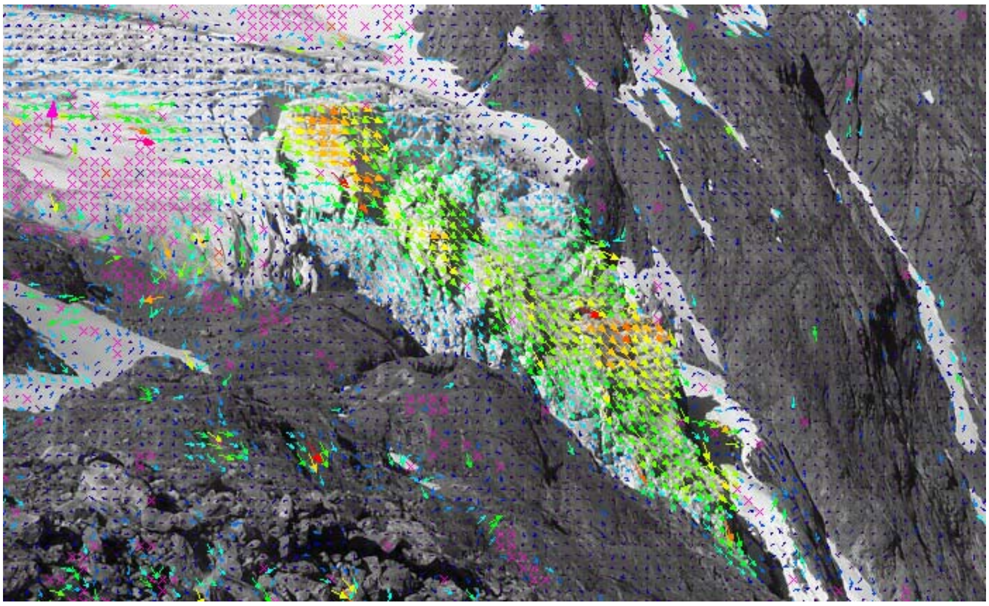

Figure 3.7: Displacement monitoring based on image analysis (example from Trift glacier, Switzerland). Green: small displacement, red: large displacement, purple crosses: stable

Alarm installations for debris flow

For the automated closure of the road and the alerting of local authorities, a large scale monitoring system will be installed in the lower part of the debris channel approximately 3 km away from the damage potential (Fig. 3.8). The alarm system is equipped with the following components:

- three gauge radars hanging on lines spanned across the channel to estimate flow height and debris flow magnitude (Fig. 3.8, right).
- Two webcams with live-access and infrared floodlights allow day and night alarm verification.
- One geophone positioned at the channel border to record seismic data for a better understanding the physical processes of the debris flows

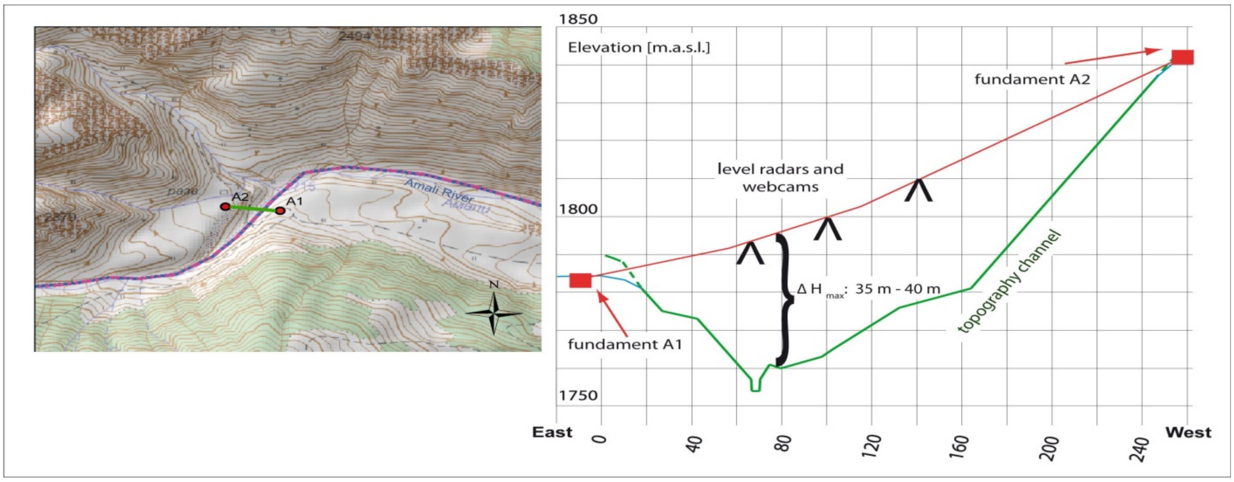

Figure 3.8: Debris flow detection installation at position A with level radars and cameras. The channel width of 250 to 270 m is a challenge for system.

The dimensions of the channel as well as the rough climate during winter time will be the major challenges for the system. At the installation point the channel is about 40 m deep and 250 m wide. Influence of wind and ice-building on the cables can hardly be calculated in a proper way.

Figure 3.9: Location A (left) where gauge radars for the alarm system will be positioned on wire ropes (right).

Local authorities developed an action plan in case of an alarm (debris flow) as well as an upcoming glacier collapse. Today this document is still under construction and strictly confidential.

4. Conclusions

As mountainous countries China, Georgia and Switzerland are affected by more frequent extreme flood events and increased glacier melt due to climate change. Switzerland has a lot of experience and knowledge regarding natural hazards and risks. In both project the main target is to improve international knowledge in the assessment of climate impacts and risks, and to develop practical approaches to climate change adaptation and emergency response.

In remote areas, a continuous glacier monitoring proved to be important for the hazard assessment. Early warning system based on satellite data and terrestrial stations is a reliable and efficient tool for local communities / authorities. Expert know-how and human resources on local level are limited. Pragmatic planning and proactive support is necessary. Cooperation and know-how exchange on local level with a strong governmental backing/support is helpful.

The strategy to avoid the unmanageable (mitigation – land-use planning) and to manage the unavoidable (adaptation to climate change – early warning system) is valid around the globe. The implemented methodology in the Karakoram Mountains as well as in the Caukasus (monitoring, early warning system, risk management) can be transferred to other regions.

The working partnership between specialized private companies, authorities and universities is the backbone of a sustainable project management. Adaptation strategies in those projects mean anticipating the effects of climate change and taking appropriate actions to reduce the damage they can cause.

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