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Research Paper

Catastrophic Debris Flows in Kazbegi Mountain Area, Georgia – Use of Available Free Internet Information as a Source to Generate Conceptual Engineering Geological Model

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ABSTRACT

This paper presents how much valuable data is freely available from the Internet to be efficiently used together with the interpretation of internet maps and 3D visualizations to analyse geological hazard of some areas in the sense of conceptual engineering geological model generation. The example presented here is of the Kazbegi Mountain area in Georgia near the border with Russia. The area in question is famous for abundant debris flows with some of them being very catastrophic and associated with melting glaciers. There were two tragic events in the recent past in the Dariali Gorge east of the Mkinvartsveri (Kazbegi) peak in 2014. Using the internet information together with geological experience it can be easily anticipated what may happen in the future within the area due to slope movement hazards. Dangerous areas possibly to be affected by debris flow (mud flow) in the future may be defined and thus cost-effectively provide the first step to avoid constructions in these areas to eliminate the loss of human lives and destruction of property.

1. Introduction

Internet and web map applications currently provide high quality geological information for various parts of the world. Professional publications from the Internet are available and these publications provide a 3D spatial view with the fourth axis being time with the use of map servers allowing spatial visualization. Using these resources, the information about the long-term activity of geodynamical processes in some areas and their spatial distribution can be easily investigated. This is very useful to generate successful conceptual engineering geological models to anticipate what may happen in the future in areas in question (Parry et al., 2014, Parry et al., 2018). The conceptual engineering geological model is based on understanding the relationships between engineering geological units, their likely geometry, and anticipated distribution. The concept is formulated from geological knowledge and experience using existing geological data of the area in question. Evaluation of surface and sub-surface processes and their activity is a part of the model. These models provide a powerful tool for presenting what

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is known about a site, what is conjectured, and were significant uncertainties may remain (Parry et al., 2014; Parry et al., 2018).

This paper discusses how much valuable information for the generation of conceptual engineering geological model is freely available from the Internet with respect to debris flow / mud flow hazards using the Kazbegi Mountain area in Georgia (**Fig. 1**) as an example.

2. Debris flow / mud flow hazard in high mountain areas

Debris flows or mud flows are common phenomena on steep slopes in high mountainous areas. The English term debris flow (or mud flow) (Coates, 1977; Varnes, 1978) has an equivalent term in the Russian literature as "sel" (Statkowsky, 1859 in Chernomorets, 2007), in Spanish they are referred to as "flujos detríticos" and "flujos de lodo".

The main initiating factor for debris (mud) flow generation is sudden increase of water content in loose sediments, most often it is caused by high intensity rainfalls or longer intense rain. In mountainous areas in alpine zones, however, an increase in water content also occurs by melting of large amount of ice and snow from melting glaciers and by dam outburst of natural or artificial lakes. Melting glaciers can be related to global climate change, which has long been seen in all mountain ranges around the world. Ice free areas from the melting of glaciers are often filled with mountain glacial lakes that are dammed by glacial till. In the case of moraine dam collapse, catastrophic debris flow occurs. As an example of it can serve Lake Palcacocha in the Peruvian Andes, whose nearly 100 m high moraine dam broke and debris flow generated in this way destroyed a large part of Huaraz city, located more than twenty kilometres down the slope (Klimeš et al., 2016). The outburst flood occurred here early in the morning of December 13, 1941, when a huge piece of the adjacent glacier fell into the Palcacocha Lake. Within 15 minutes the debris flow reached Huaraz, burying parts of the town by debris and killing several thousands of inhabitants (http:// Wikipedia®). Rybar (in Ondrášik and Rybar, 1991) reports the rupture of the dam of Iszyk Lake in Tien Shan, which occurred due to debris flow entering into the lake that resulted in a catastrophic valley-type debris flow.

The fall of the glacier can cause a debris flow even if the glacial masses fall on loose sediments (colluvium, glacial till, etc.). Due to the impact of the falling glacier block it results in the conversion of ice into water and, if favourable conditions exist, the initiation of a debris flow occurs.

The fall of the glacier can be caused purely by gravitational forces or in connection with seismic activity. The fall of huge block of glacier caused well-known debris flow that occurred in the 1970 in Peru on the slopes of Huascaran. This event resulted in the destruction of the city of Yungay and the village of Ranrahirca (Lliboutry et al., 1977) being buried. A partial debris flow buried Czechoslovakian climbing camp resulting in the deaths of all the climbers.

Instead of the collapse of the glacier, debris flow in appropriate hydrogeological and hydrological conditions can be initiated also by rock fall of masses of the mountain massifs. Other causes of debris flow generation include the sudden melting of mountain glaciers related to volcanic activity. As an example at Kazbegi Mountain, may serve the collapse of Kolka and Devdoraki Glaciers (Drobyshev, 2006; Kotlyakov et al., 2014).

Debris flows and mud flows are very dangerous slope movements. It results from their high velocity, usually tens of kilometres per hour, sometimes even higher speeds occur (Drobyshev, 2006). In addition, high hazard results from the large distances that the entrained rock material can travel, that often destroys all in its path. The distance between the source area and the accumulation area is often in the range of kilometres, sometimes even tens of kilometres. Particularly in the less developed parts of the world with the lack of engineering geologists, the hazard of these phenomena lies in their lack of understanding the potential risk associated with urbanization of the area in hazard zones. There are many cases of inappropriate urbanization, where a new settlement is developed on a flat debris flow accumulation that had previously buried a village; the new settlement is at high risk of a similar fate. The reason for underestimation of risk may also be the exchange of the population, where the new population does not know the natural hazards of the area that the original inhabitants were experienced.

3. Kazbegi Mountain – debris flow / mud flow hazard - desk study

The following section presents information obtained through the use of the Internet for the Kazbegi Mountain area (**Fig. 1**) in relation to debris flow / mud flow hazards.

3.1 Settings, stratigraphy, structure

The area of interest is located in the central part of the Great Caucasus at an elevation of more than five thousands meters above sea level (m a.s.l.) that was uplifted during the Tertiary Alpine orogeny. It is a megaanticlinal core of Precambrian crystalline schists with a gravitational–tectonic structure. This zone consists mainly of metamorphic and intensely folded schists, quartzites and quartz sandstones.

Fig. 1. Location of the area of interest Sources:DEM – USGS 2019, glaciers – GLIMS 2019

The core is enveloped by Palaeozoic to Jurassic sedimentary rocks (mainly schists and sandstone), on which the younger series of Jurassic, Cretaceous and Tertiary age (mainly limestone, marlstone, and sandstone) are thrusted from the north onto the basement. The area of interest was volcanically active during the Quaternary. The activity of the Kazbek Neovolcanic Centre is divided into several phases; the current phase began about 50 thousand years ago and is still ongoing. Volcanic activity continued in the Quaternary, as evidenced by a number of lava flows and pyroclastics on moraine accumulations. The central peak is currently not active. It was formed about 185 thousand years ago, followed by eruptions from satellite peaks (Lebedev, 2018). The last confirmed eruption (6 thousand years ago) formed the peak of Small Tkarshet (Chernyshev, et al., 2002).

The former volcanic processes are evidenced by a number of hydrothermal springs rising along tectonic faults, mostly on mountain slopes of about 3 km above sea level. The movement of morphostructural blocks separated by tectonic faults caused increased seismic activity. The earthquake intensity (MM) ranged from 7 to 8 and was reported in the Kazbegi area in 1878, 1915, 1947, 1951, 1992 (Gaprindashvili, 2015).

There is volcanic, gravitationally erosive and glacial Alpine relief dominated here with recent glacial and firn cover and corresponding permafrost zone.

During the last 54 years, the number of glaciers in the Tergi River basin has decreased by approximately 40%, at the ice-cover area has decreased by almost 50% (Tielidze, 2017). This type of environment represents a zone of frost and mechanical weathering processes, gravitational collapse, snow avalanches, and glacial and rock creep. There are many erosional gorges, diverging radially from the Kazbek-Dzhimara Massif (Khokhi Range). The depth of these erosive valleys reaches from 800 to 1,200 meters, typically with very steep slopes. This type of relief encourages debris flows generation. They take place in valleys and gorges between mountain ridges and also in the valleys of the main streams. Debris flow and/or mud flow associated with the instability of slopes near the glaciers or the total melting of the glaciers are the main relief processes in the valleys and therefore this paper focuses on these processes.

3.2 Debris flow / mud flow phenomena and their activity

The first debris flow / mud flow phenomenon was documented in the Kazbegi area in 1752 (Berger, 2007). These include the Devdoraki Glacier with the Devdoraki-Amali River flowing into the Tergi River in the Dariali Gorge, the Kolka Glacier with the Genaldon River, and the Abano Glacier with the Blot and Chkheri Rivers draining into the Tergi River in town of Stepantsminda. The formation of debris flows / mud flows as a result of the separation of the mountain glacier can also occur with other mountain glaciers in the area such as Gergeti, Denkara, Mna, Suatisi, Midagrabin, Zeigalan, Arcy, Shau, Maili and Chach. The most important examples are described below.

Due to Kazbegi’s on-going geothermal activity, glacial outburst floods (jökulhlaup) can be expected as a potential triggering factor for debris flows / mud flows.

Glacial surge is another geodynamic process connected with the area in question which may also cause debris flows / mud flows activation, in this case without the climatic influence. Subsequent breaking of the glacier into blocks may sometimes initiate dangerous movements of 10x – 100x higher velocity than the normal speed of glacier movement (Kotlyakov, 2014). In Kazbegi area, Zeigalan, Kolka, Chachi, Devdoraki, Abano and Mna Glaciers are known for such activity (Rototaeva, 2006).

In some cases, debris flow hazard increases when the debris flow accumulation blocks the flow of the river at the valley floor and following collapse of this natural dam generates a subsequent flood-wave that can reach an area even very far from the source area. An example is the blockage of the Tergi River in Georgia and the expansion of the flood-wave into Russia in 1776 and 1832 (Zaporozhchenko and Chernomorets, 2004).

The above mentioned processes, together with global climatic change initiating deglaciation, results in a reduction of permafrost and together with the relief of the valley previously burdened by glacier are the reasons for increase of susceptibility of the area to slope movements on slopes covered by large amount of unconsolidated glacial and colluvial sediments.

3.3 Dariali debris flow(s) – Devdoraki Glacier

On May 17, 2014, during an unusually strong storm, part of the Devdoraki Glacier broke loose. This caused the formation of a debris flow in the Devdoraki-Amali Valley. The sediments blocked the Dariali Gorge and the Tergi River. On August 20, 2014 the movements of the hillside were reactivated, when unusually strong torrential rains caused the water saturation of the previously settled material and resulted in their failure. The gully was re-buried and floods were generated.

Calculations and geodynamic characteristics of the phenomenon from 2014 are discussed in Drobyshev (2018). The scarp area of the glacier is at an altitude of approximately 4,000–4,550 m a.s.l, with the glacier toe descending to 2,550 m a.s.l. Massive dacite rock and ice block of about dimension of 550 m x 350 m x 40 m and up to 5 million m^3 (**Fig. 3**) travelled along the rock surface on a slope >40°.

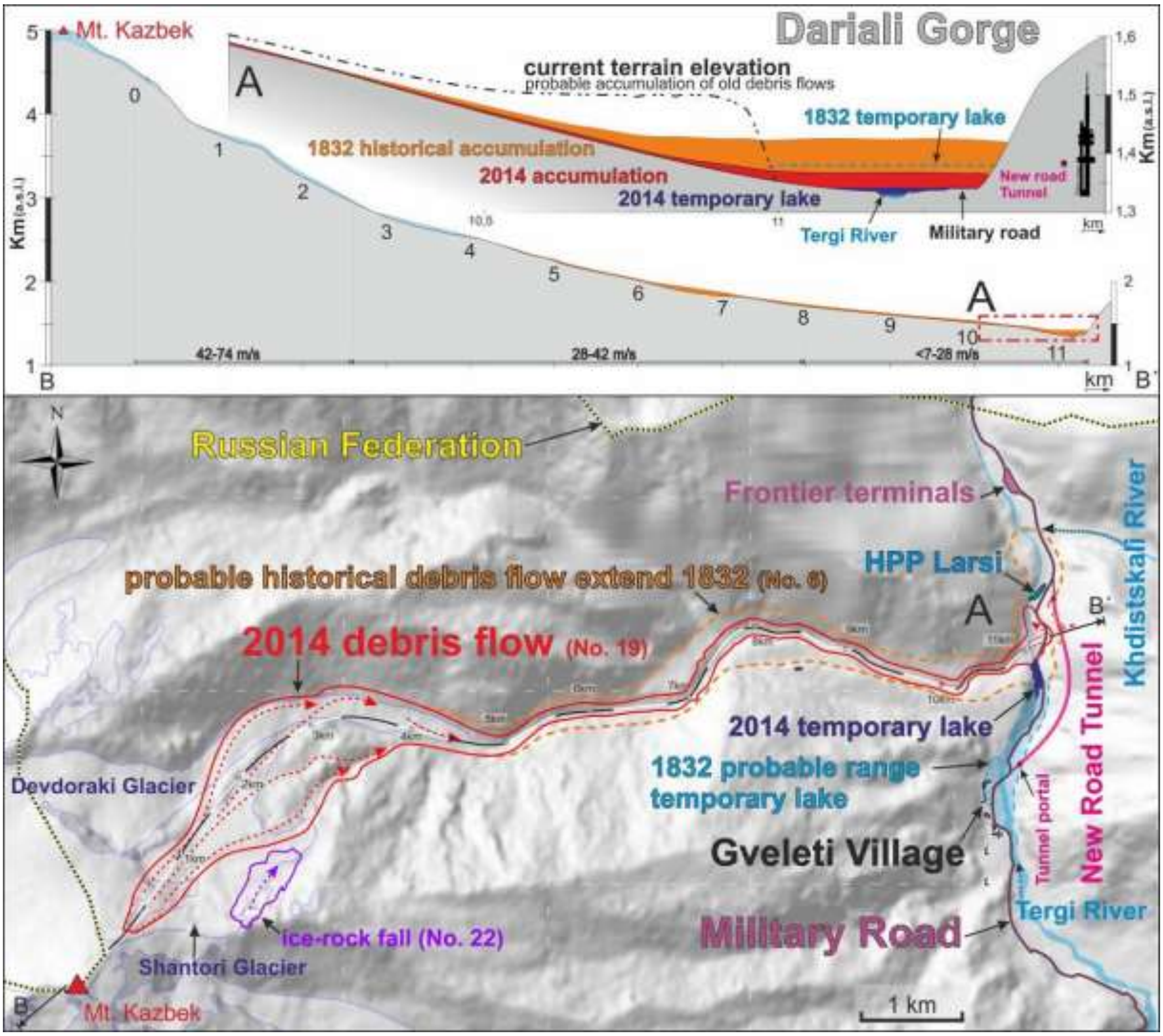

Fig. 2. Upper part: Schematic cross section of the 2014 Dariali debris flow with estimated velocity in each part of the flow. Inset: Detailed cross section of debris flows accumulation area (A). Lower part: Map of the 2014 Dariali debris flow (Hydroelectric Power Plant Larsi is within the hazard area, in extreme events new road tunnel portals can be also endangered). Source of DEM: USGS 2019, Source of glacier: GLIMS 2019

The speed of debris flow (May 17, 2014) was estimated up to 200 km / h (Drobyshev, 2018). After falling on the mountain glacier, the mass of ice and rock disintegrated, energy was transferred to the loose sediments that were saturated by melted water and the flow started to move. The moving masses encountered an opposite slope and changed flow direction after 2.5 km of transport. The slope was undercut and new loose volcanic material was added into the current debris flow. The resulting semi-viscous mixture of rock – red volcanic ash, andesite, dacite, glacier till, ice and water moved through the Devdoraki-Amali Valley at a speed of 80–150 km / h. According to Drobyshev (2018), the flow accelerated up to 150 km / h in straight sections of the valley, when passing through sharp corners, the flow velocity decreased to 80 km / h. The flow stopped completely after travelling 11.7 km at an altitude of 1336 m a.s.l. after nearly 8 minutes of total movement. This length of the runout was estimated from a digital elevation model (USGS 2019) and it is different from the distance indicated on the geologic map (i.e., 10.7 km).

From the altitude of about 2,500 m a.s.l., transported material gradually settled, with the most significant accumulations located at the confluence of the Devdoraki and Amali Rivers. Only about 1.16 million m^3 of the total volume of material was transported to the Dariali Gorge at an altitude of 1,336 m a.s.l. This volume formed up to 600 m wide dam with a height up to 35 m and a natural lake with an area 0.1 km^2 on the Tergi River. After Drobyshev (2018), it is estimated that 50% of the accumulation was formed by ice. The lake was 300 m long, 80 m wide, situated on the upstream direction of the dam. The water from the lake was drained by a drainage tunnel of the Larsi Hydroelectric Power Plant. The removal the road took almost one month. The traffic was restored on June 14, 2014.

Floods are regularly (seasonally) repeated in these high mountain conditions and are one of the chief factors stimulating the geodynamic processes in the valley floor that are documented in **Fig. 8** (river bank erosion, landslides, rock falls, debris flows). The time-lapse image (**Fig. 4**) demonstrates the destructive activity of the Tergi River in the Dariali Gorge at approximately one-year intervals. It is clear from **Fig. 4** how changes of debris flow accumulation represent additional geological hazard by reorganizing non-consolidated clastic sediments, which may be further transported downstream during floods. Currently, a new road tunnel bypassing this risky gorge is in the operation (**Fig. 2**).

Two consecutive natural disasters in May and August 2014 took the life of ten people, destruction of two gas pipelines, the border crossing, as well as the destruction of the Larsi Hydroelectric Power Plant. The strategic transit road, the so-called “military road”, which is a continuation of the E117 and runs from Georgia to Russia, was closed for one month in May–June 2014 and for 10 days in August 2014.

The Larsi Hydroelectric Power Plant was destroyed in August 20, 2014. One debris flow event also occurred in 2007 at the construction site, but in this case, was not connected with glacier fall but induced by a climatic trigger. There was one victim and no destruction of the military road at this time, but high debris flow / mud flow hazard of the area was clearly demonstrated by this event. Regardless of the known hazard, the Larsi HPP was launched in the area.

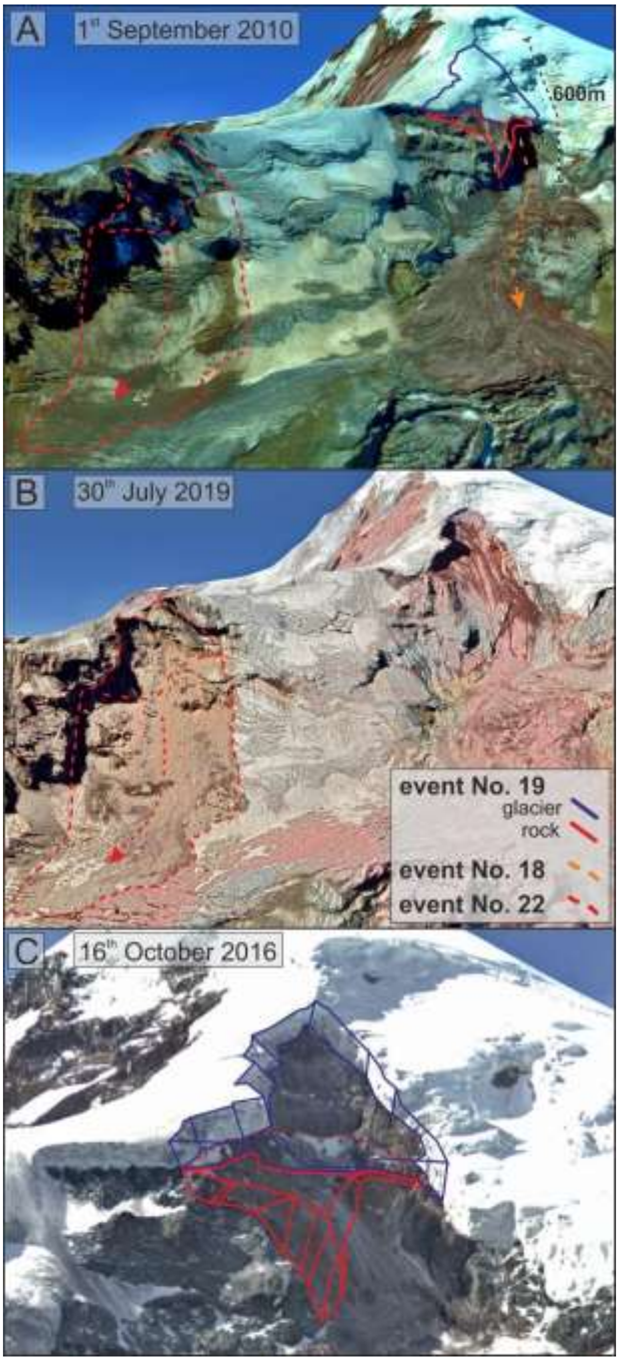

Fig. 3. Ice-rock fall area on the northwest slope of the Kazbek Mountain. 3A: 2010 Satellite image from Google Earth with drawing of collapse area from 2010 and 2014 (phenomenon No. 19, in Fig. 8 and Table 1). 3B: 2019 Satellite image from Google Earth with drawing of collapse area No. 22 in Fig. 2 and Table 1. 3C: Image from monitoring camera from 2016 with visualization of the glacier and rock block which fell down in 2014 (https://www.geopraevent.ch)

The construction of the Larsi HPP (Hydroelectric Power Plant) at cost of US $ 20 million was launched in 2011 due to the hydroenergetic potential of the Tergi River Basin to solve electricity problems in the region. Once operational, the hydroelectric plant produced 1 million kW / year beginning on January 24, 2014. The

Larsi HPP was situated to be able to connect to the Dariali HPP, which is situated upstream in Stepantsminda at the confluence of the Chkheri and Tergi Rivers, also in the area with high debris flow / mud flow hazard (the area was affected by debris flow / mud flow originating from Abano Glacier in 1909 / 1910).

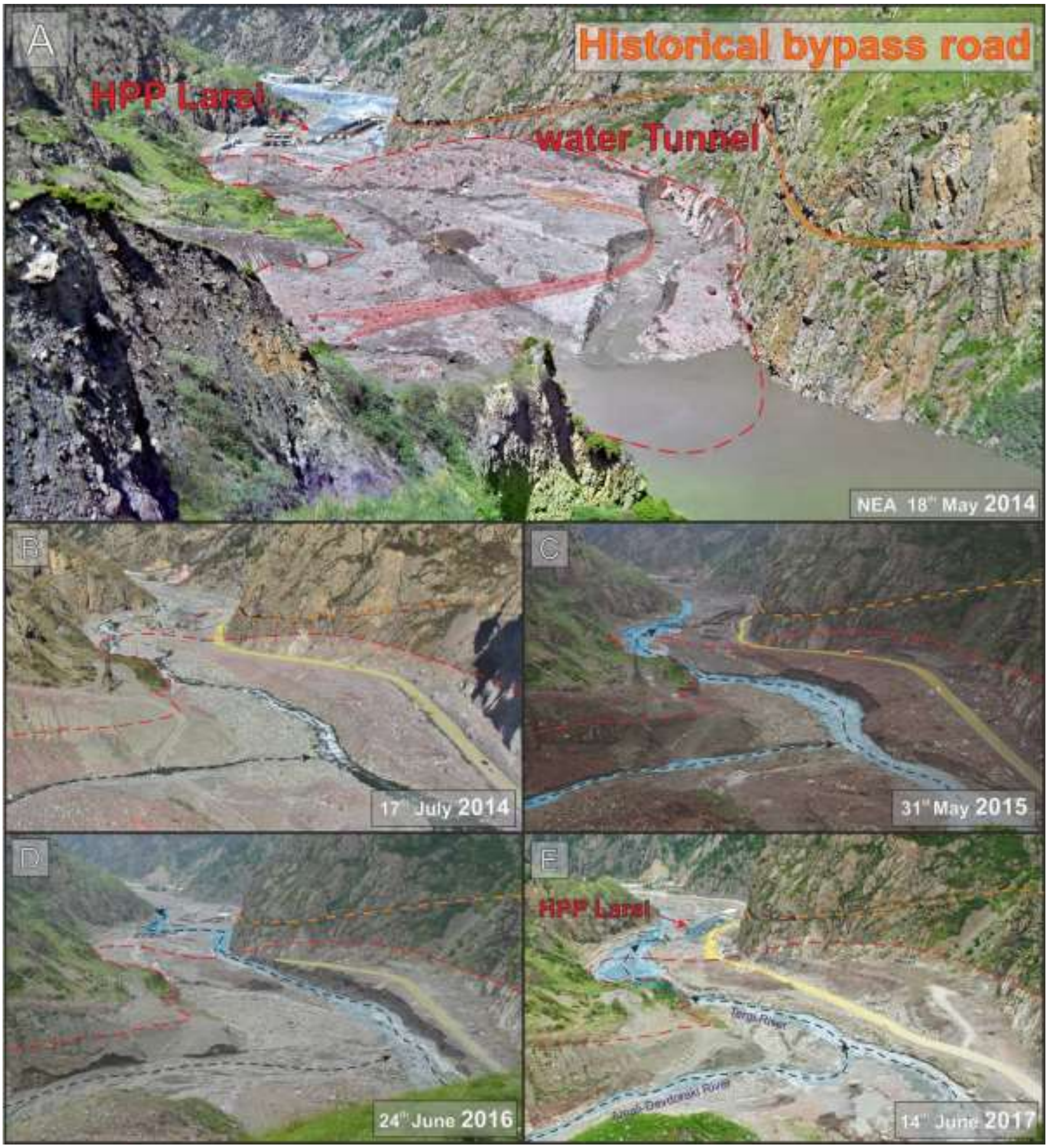

Fig. 4. Time-lapse images of accumulation area of the debris flow in Dariali Gorge in approximately year intervals (red line is distribution of the accumulation from 2014, orange line is bypass road created after debris flow 1832 – probable distribution of the accumulation). 4A: Dariali Gorge day after the event 2014 (NEA), 4B: new road (Vit Baldik), 4C: advancing river bank erosion (Petr Kycl), 4D: new road was destroyed by river bank erosion and HPP Larsi was damaged again (Vit Baldik). 4E: new road and HPP Larsi in operation (Martin Dostalik)

The ice–rock fall at the very similar source area of debris flow from 2014 at an altitude of 4,180 m a.s.l. occurred in 2010. The block covered approximately 730 thousand m^2 at a distance of 2.6 km (Dokukin, 2015). The assumed scarp area is indicated in **Fig. 3**. By comparing satellite images of January 9, 2010 and July 30, 2019 (Image CNES / Airbus from Google Earth in **Fig. 3**), a head scarp area of rock / glacier blocks fall at the altitude of 4,090–3,860 m was identified with dimensions approximately of 270 m x 250 m. The run-out area is 1.1 km long with an average slope inclination of 47°, covering the eastern edge of the Shantori Glacier and reaching up to 3,550 m a.s.l. This phenomenon is marked by number 22 in **Fig. 2** and **Table 1** and is visible on **Fig. 3**.

All recorded events in the Devdoraki-Amali Valley are presented in **Table 1**. Destructive geodynamic processes have long been repeated here in Dariali and historically are documented as so called “Kazbegi blockades”. A description of documented events with original sources is provided by Zaporozhchenko and Chermomorets (2004). The most serious blockades are documented in 1776, 1778, 1785, 1808, 1817, and 1832 (Zaporozhchenko and Chernomorets, 2004).

In 1776, the blockage of the Tergi River by debris flow and following collapse of this dam resulted in extensive flood with water wave completely washing down the valley. In 1817, the Dariali Gorge was blocked by 3 km long and over 100 m high accumulation of debris flow sediments. On August 13, 1832, about 90 m high and 2,166 m long accumulation of 22 m^3 of debris flow sediment flowed into the village of Gvileti to the mouth of the Brolistskali (Khdistskali) River (Statkowsky, 1877 in Chernomorets et al., 2007). The accumulation consisted dominantly of ice, melted after 7 years. By this time a bypass road was built by military engineers. Today, there is still a notch in the rock wall above the debris flow of 2014 (orange line on **Fig. 4A**). The immense power of the 1832 flood is illustrated by the so-called “Yermolov’s Stone” (29 m x 15 m x 13 m) that was transported into the Tergi Valley 5.4 km from Dariali Gorge in Verchny Lars.

The activation of slope movements of debris flow type occurred in 1842, 1843, 1855, 1875 and 1891 but the accumulation did not reach the valley of the Tergi River (Statkowsky, 1877 in Chernomorets et al., 2007; Zaporozhchenko and Chernomorets, 2004; Kotlyakov, 2014).

The main causes of the above-mentioned dangerous slope movements are the high dynamic relief, glacier activity, the current and long-term changes in climate (warming with glacial ice melting), and movements of active morphostructural blocks separated by tectonic disturbances with high seismicity of the area (Gaprindashvili, 2015). Water from the melting glacier feeds a large number of valley colluvial, glacial sediments and loose volcanic debris. An important triggering factor for debris flows here is extreme precipitation. In the spring of 2016, a monitoring system was installed in the risky gorge (Tobler et al., 2016) and it is the first fully-fledged monitoring system linked to the Early Warning System in Georgia. Main causes of disasters in the 1800’s and 1900’s were connected to glaciers and their instability; in the 20th century climatic causes predominate.

3.4 Kolka debris flow(s) – Kolka Glacier

The Kolka Glacier is located at 3450–2960 m a.s.l. and was 3.1 km long with an average width of 700 m and a maximum thickness of about 150 m (Nosenko, 2017). The glacier is surrounded by a steep (35–40°) schists rock walls of 1–1.5 km high.

On September 20, 2002, the whole Kolka Glacier separated from its bed and caused an exceptional debris flow that seriously affected the valley of the Genaldon. River and destroyed the Russian village of Karmadon (**Fig. 5A**).

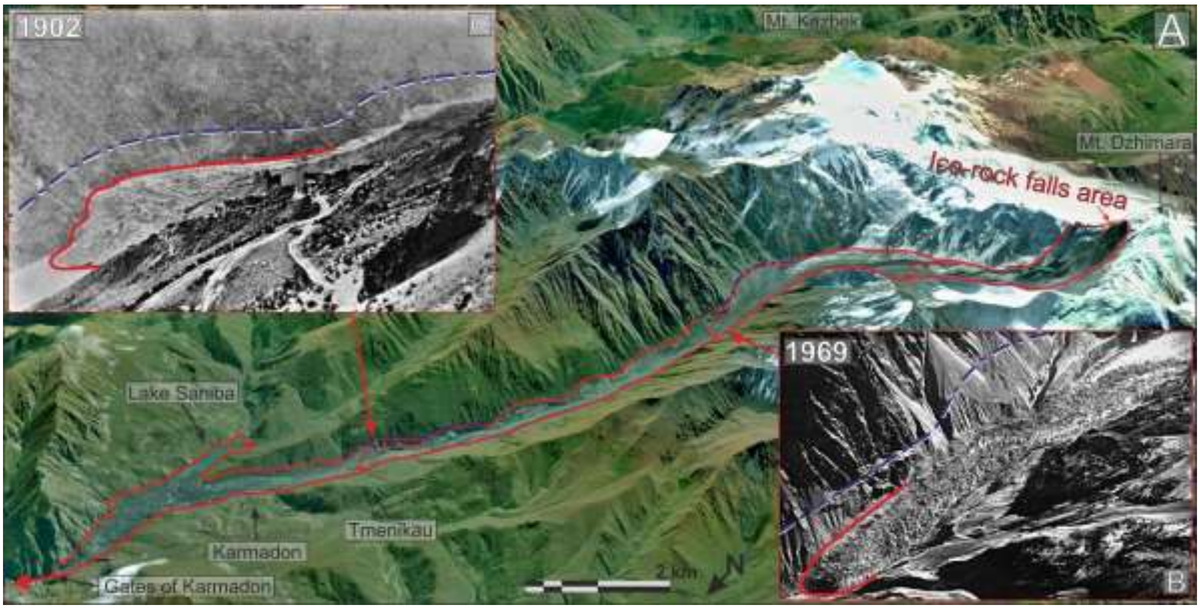

Fig. 5A: Kolka debris flow trace with ice-rock falls zone on the northern slopes of Dzhimara Mountain, transport area with meandering flow character and accumulation area on the Gates of Karmadon, 5B: Historical photo of earlier documented glacier surge on 1969 when glacier extended over 4,600 m in a 6 month (foto O. V. Rototaeva). 5C: Historical photo of earlier documented ice-debris flow 1902 (Photo from archive of North Ossetian Museum of Local Traditions, Rototaev et al., 1983)

The debris flow in the form of a semi-viscous mixture of mostly ice from the glacier, water, and rock material flowed through the valley of the Genaldon River and eroded the bottom and walls of the narrow gorge in a 500 m wide band, at a velocity of up to 250 km / h. After 390 seconds, 19 km of transport, the Karmadon Gate was hit by the debris flow, causing the accumulation of up to 120 million m^3 of material in the Karmadon depression (Chernomorets, 2007). From this point, part of the flow (about 3–5 million m^3) continued and gradually passed into a mud flow, travelling a total distance of 36 km from the source area to almost to the town of Gisel (750 m a.s.l). It is interesting that almost immediately after the glacier clearing in 2002, a new glacier began to form. Studying this emerging glacier is very important for understanding the causes of disasters and determining the recurrence interval.

The catastrophic debris flow caused by the Kolka Glacier in 2002 is one of the most important documented events of its kind in the world. It is the largest catastrophic debris flow documented in the mountain glacial environment in the historic era of the northern slope of the Caucasus Mountains, Russian Federation. This event is exceptional with a volume of material transported up to 130 million m^3 with extreme speeds of up to 250 km / h. The affected area was 12.7 km^2, including the area of the initial rock fall, the narrow transport channel of the Genaldon River, the accumulation area in the Karmadon depression, and the zone of continued movement downstream in the Giseldon Valley. The 3.6 km long accumulation in the Karmadon depression (1,150–1,350 m a.s.l.) was spread over an area of 2.1 km^2 immediately after the disaster (**Fig. 6**). Subsequently, another smaller rock fall in the source area was documented, and on August 12, 2004, a smaller debris flow occurred. The original riverbed was blocked until spring 2007 (Chernomorets, 2007). In the valley, 13 temporary dammed lakes formed, the number of which was later reduced to 4, and their volume are being further reduced. The volume of water in the largest lake Saniba (**Fig. 6**) was artificially reduced by 5% in 3 years (Chernomorets, 2007).

Total damage was estimated at US $ 17.5 million. The reported number of victims varies; the most frequently reported are 125 victims (Chernomorets, 2007). However, in reality, this number could be higher because the refugees from South Ossetia allegedly lived in the affected valley. Eleven residential houses, a three-storey spa building, Karmadon wastewater disposal facilities, a mineral water plant, two recreational settlements, and four bridges were destroyed (Heaberli, 2004).

The mechanism of generation of the Kolka 2002 catastrophic debris flow event is not yet fully understood and is still the subject of ongoing discussions. There are three hypotheses of the origin of catastrophic debris flow:

Kotlyakov (2014) compiled a summary and analysis of the possible causes of the catastrophe published so far.

The first group of hypotheses is related to the initiation factors in the form of ice rock-falls originating from suspended glaciers from the slopes of Mt. Dzhimara. Theses hypotheses explain the initiation of movement by massive rock fall that induced catastrophic glacial movement (Haeberli et al., 2004; Huggel et al., 2005). However this scenario is not supported by satellite images, which show that ice rock-falls occurred gradually since August 19 to September 20 (Evans et al., 2009,), the rugged morphology and slope inclination also do not allow direct and sufficiently aggressive impact (Kotlyakov et al., 2014).

Fig. 6. Accumulation area of the debris flow in Karmadon valley from, October 6, 2002 (by Igor Galushkin In Evans et al., 2009).

The second, so-called conventional shift hypothesis, argues that the collapse of the Kolka Glacier occurred due to the sudden shift of the glacier caused by the accumulation subglacial and interglacial water (Kotlyakov et al., 2004, Huggel et al., 2005).

Evans et al., (2009) introduced a third hypothesis where the separation of the glacier from the rock bed explains by the loss of effective stress due to excess of water pressures within the glacier and/or in the glacier bed without having a major influence on the dynamics of rock fall from the adjacent mountain wall (**Fig. 7B**). This process has been termed as “catastrophic flotation” (Krenke and Kotlyakov, 1985 in Evans and Delaney, 2015).

All hypotheses agree that significant elevated pore fluid pressure was involved in the process (Kotlyakov et al., 2004; Kotlyakov et al., 2014). Some other factors can be discussed, including seismic activity (Drobyshev, 2006), warming of the glacier due to the heat flow from Kazbek Neovolcanic Centre (3.5 km from

Kolka Glacier there are hot springs with the temperature up to 58 °C at 2,250 m a.s.l., 50 m above the river bank), and possibly expanded gases under the glacier (Muravyev, 2005; Berger, 2007; Drobyshev, 2006; Kotlyakov, 2014; Nosenko et al., 2017).

The above mentioned hypotheses are based solely on indirect evidence because the incident that caused the disaster occurred without witnesses, lack of monitoring, and there was not a detailed glaciological study prior to the disaster. A combination of several factors is highly probable.

Fig. 7. Ice-rock fall zone on the northern slopes of Dzhimara Mountain. 7A: Photo of hanging glaciers (red dotted line) (Drobyshev, 2006), 7B: Google Earth satellite image from September 25, 2002 after event and probably active fumaroles (hot exhalations – in violet colour). 7C: Google Earth with satellite image from July 30, 2019 presenting self-regenerating Kolka Glacier (black dotted line)

All recorded historical events in the Genaldon Valley are presented in **Table 2**. There is evidence that similar disasters have occurred in the past, for example in 1752 (Berger, 2007). Years 1834–1835, also mentioned, were connected more with glacial surge then debris flow catastrophe (Kotlyakov, 2014; Chernomorets and Adceev, 2014 in Leonov, Zaalishvili (Eds.), 2014).

The first well-documented catastrophe in the area occurred in 1902 (**Fig. 5C**), when the Kolka Glacier collapsed on July 3 and 6, resulting in 36 casualties in the Genaldon Valley, the destruction of the popular mountain resort, 28 mills, and many farm animals (Steber, 1905; Poggenpol, 1905 in Kotlyakov, 2014, Chenomorets, Adceev, 2014 in Leonov, Zaalishvili (eds.), 2014).

The Kolka Glacier surge occurred at the end of the year 1969, when the glacier moved down slope over 4,600 m in a 6 month (Kotlyakov, 2014; Panov, 1971a, b in Leonov, Zaalishvili (Eds.), 2014). The Karmadon hot springs were buried under a 100m thick layer of ice (Rototaev, 1983 in Kotlyakov, 2014).(**Fig. 5B**)

In the valley of Genaldon River, debris flows were also caused by extreme rainfall in 1877, 1885, 1889, 1907, 1914 and 1937 (Vaskov et al., 2004 in Leonov, Zaalishvili (Eds.) 2014). Extreme precipitation induced debris flow on August 17, 1953 (Yermakov and Loganson, 1957 in Cheronomorets, 2007). On August 5–6 1967, the most catastrophic debris flow transported 1.9 million m^3 of solid material; buildings bridges and roads were destroyed (Rototaev et al., 1983 in Chernomorets, 2007). Damage in Gornaya Saniba village by debris flow occurred on June 21–22, 2002 (Chernomorets, 2007).

3.5 *Abano debris flow(s) - Abano Glacier*

All recorded events in this valley are presented in **Table 3**. At the beginning of July 1909, a massive rock fall from Mt. Bagni to the Abano Glacier was located on the southeast slopes of Mount Kazbek, Georgia. Subsequent loading led to a rapid movement of the glacier and the blocking of glacial channels. The approximate range of the event is shown in polygon 40 (see **Fig. 8**). This provoked the activation of gigantic debris flows on July 6, 1909 which caused the bridges destruction in Chkheri River, a temporary lake on Tergi River formed for two hours, and lose of crops and cattle, and again in the following year on June 14, 27 and 29 and on July 3, 1910 and in 1913 (Dukhovskoy, 1917 in Zaporozhchenko and Chernomorets, 2004; Dukhovskoy, 1917 in Kotlyakov, 2014). The debris flows travelled through the valley of the Blot, then to Chkheri. The Tergi River has also been temporarily blocked. This caused death of a large number of cattle near the Georgian military road and destruction of the harvest. The total volume of transported material is unknown (probably several million m^3). The debris flow length was 7.7 km. Common debris flows also occurred into the Chkheri River from the Gergeti Glacier moraine.

Rain-induced debris flows on Chkheri River on August 8 and 22, 1937 and on August 17, 1953 resulted in temporary dam on the Tergi River built by 5 million m^3

of debris flow sediment (Yermakov and Loganson, 1957 in Chernomorets, 2007).

Between years 1963–1972, there was documented 51 m shift of the Abano glacier terminus by glacier surge (Zaporozhchenko and Chernomorets, 2004).

3.6 Other Glaciers - Mna, Suatisi, Gergeti, Chachi, Zeigalan, Khdistskali River, Tergi River

All recorded events related with glaciers in the title of this section are presented in **Table 3**. On August 18, 1953, a lake outburst at the edge of Mna Glacier occurred and a flow of height of 4–5 m and width 80–100 m went through the Mna village (Grigolia and Tsomaia 2000 in Chernomorets, 2007). The approximate range of the event is shown in polygon 51 (see **Fig. 8**). From the military topographic map (1: 50,000) of 1960, the end of the glacial tip is revealed at this time and it is possible to draw the event exactly onto the map as it shown in **Fig. 8**.

To protect the villages of Shevardeni and Nogkau at the mouth of the Mna River (in Georgian it is Mnaisistskali), a protective wall was built for attenuating flash-floods outside the inhabited area.

The analysis of satellite images from 1989 and 1998 showed a huge rock fall of andesite and dacite at 4300 m a.s.l., which covered 2.7 km^2 of the surface of the Suatisi Glacier within 3.17 km (Dokukin, 2015). This phenomenon has number 54 in **Fig. 8** and **Table 2**.

(Dukhovskoy, 1917 in Zaporozhchenko and Chernomorets, 2004) mentions glacier surge at Gergeti Glacier around 1913. Periodic glacier surges tens to hundreds of meters at the Chach Glacier in 1909–1910 and some movement also occurred in Mna Glacier (Dukhovskoy, 1917 in Kotlyakov, 2014). The last movement - glacier surge and terminus falls to the valley occurred in 1959 at the Zeigalan Glacier (Kovalev, 1961 in Kotlyakov, 2014), which is located in North Ossetia above the Midagrabidon River valley; one of the highest waterfalls in the Euro-Zone with the height approximately 750 m. A devastating debris flow took place 1953 in the valley of the Khdistskali River released from a tributary of the Tergi River (Yermakov and Loganson, 1957 in Chernomorets, 2007).

On the Midagragidon River at the confluence with the Tsatadon River near the village of Dzhimara, there is an accumulation of an approximately 5000-year-old landslide that apparently formed a barrier lake (in **Fig. 8** marked as old landslide accumulation). The landslide age was determined by dating lake sediments using carbon ^{14}C (Rogozhin et al., 2014 in Leonov, Zaalishvili (Eds.), 2014). This is probably the last landslide in the Midagrabidon River valley associated with the Midagrabin Glacier.

In **Fig. 8**, there are orange polygons indicating the position and the extent of the different types of slope deformations. These are landslides with varying degrees of activity, mechanism of movement, and stage of development (Kotlyakov at al., 2008; Rogozhin at al., 2014 in Leonov, Zaalishvili (Eds.), 2014, Mikhailovich, 2017).

4. Conceptual Engineering Geological Model of Kazbegi Mountain Area in terms of debris flow / mud flow events

Information about the occurrence of debris flows / mud flows in the Kazbegi area mentioned in the previous chapters forms a background that can be used with geological knowledge to generate conceptual engineering geological model as a first step to reduce the damage caused by devastating debris flows / mud flows.

For example, the catastrophic debris flows / mud flows in Kazbegi area endanger gas pipelines from Russia to Georgia, the interstate road between Russia and Georgia, and the urbanization of Vladikavkaz. In 2014, this is evidenced by the destruction of Hydroelectric Power Plant Larsi, situated inappropriately in the historically known extent of debris flow accumulations from Devdoraki Glacier.

The available archive information discussed in the previous chapters is presented graphically in **Fig. 8**. From **Fig. 8**, the occurrence of the recorded and described debris flows of Devdoraki, Kolka and Abano Glaciers is well defined with the approximate areas affected by these phenomena being marked. It is especially dramatic event of Kolka (2002) where its length extends more than 30 km. High hazard of these areas is visible from **Fig. 8**, when the source area is often very far from the locations that are catastrophically affected by these events. Unfortunately, these hazards are often not fully understood by the public.

On the basis of archival data of the debris flows / mud flows around the Devdoraki, Kolka and Abano Glaciers mentioned above (especially Zaporozhchenko and Chernomorets, 2004; Chernomorets, 2007), and in addition using geological analogies, the possible runouts of debris flows / mud flows that can be expected in the Kazbegi area in the future were marked in the **Fig. 8**. This marking is only schematic with a "100 m wide buffer zone". The outline of the exact extent of the potential hazard areas based only on archival materials (Chernomorets, 2007; Kotlyakov et al., 2008) cannot be determined reliably without field verifications.

Nevertheless, it is clear that the Kazbegi massif and its neighbourhood are very dangerous in terms of the potential occurrence of these devastating mass-movement events. This is evidenced by the documented locations of the damage caused, which are also shown in **Fig. 8** (red spots), and are generally concentrated at the foot of the massif in places where the mountain valleys open up, in connection with the urbanization of the area.

Integral parts of the conceptual engineering geological model are **Tables 1, 2** and **3**, which complement **Fig. 8**. These tables present a brief overview of historically recorded devastating geodynamic hazards in the area with an emphasis on debris flow / mud flows related to glacier activity.

Table 1. Documented events in the Devdoraki-Amali River Valley connect to Devdoraki Glacier. (RF - rock fall, IRF - ice- rock fall, IDF/GO - Ice-debris flow/Glacier outburst, CDF - Climatic induced debris flow, GS - Glacier surge, GLOF - Glacial lake outburst flood, A - snow avalanche, events marked in red are presented in the **Fig. 8**).

N.	year / period	affected area (km^2)	lengths (km)	type	damage	source
1	19th Jun 1776	up to 5		GO/IDF	3 days blocked river, flooded several villages (including village Gveleti), Many victims.	(J. Reineggs) Markov 1913 in Zaporozhchenko and Chernomorets 2004
2	1778	up to 4		GO/IDF		Zaporozhchenko and Chernomorets 2004
3	1785	up to 4		GO/IDF		Zaporozhchenko and Chernomorets 2004
4	1808	up to 4		GO/IDF		Zaporozhchenko and Chernomorets 2004
5	Oct 1817	up to 4		GO/IDF	1 day blocked river (1 year preventing transport) accumulation 3 km long/ 80–100 m high	Markov, 1913 in Zaporozhchenko and Chernomorets 2004
6	13th Aug 1832	up to 5	8–11	GO/IDF	8 hours blocked river (2,166 m/100m) vol. 2,2 mil m^3, Many victims.	Zaporozhchenko and Chernomorets 2004
7	1842			GO/IDF	not come to gorge	Zaporozhchenko and Chernomorets 2004
8	1843			GO/IDF	not come to gorge	Zaporozhchenko and Chernomorets 2004
9	1855			GO/IDF	not come to gorge	Zaporozhchenko and Chernomorets 2004
10	1866–1875		0.241	GS	maximal movement (150m) in year 1866, other big movement was in 1875	Panov 1993 in Zaporozhchenko and Chernomorets 2004
11	1886–1887		0.044	GS		Panov 1993 s. 217 in Zaporozhchenko and Chernomorets 2004
12	1891			GO/IDF	not come to gorge	Dubyansky 1902 in Zaporozhchenko and Chernomorets 2004
13	1893–1904		0.055	GS		Panov 1993 in Zaporozhchenko and Chernomorets 2004
14	17th Aug 1953			CDF	extreme precipitation (127 mm) The Tergi River discharge reached 450 m^3/s (multiple exceeding the average flow).	Yermakov and Ioganson 1957 in Cheronomorets, 2007
15	5-6th Aug 1967			CDF	destroyed pipeline, debris flow in tributaries Tergi River. had volumes up to 120,000 m^3, river flow was 500 m^3/s	Agibalova 1983; Grigolia and Tsomaia, 2000 in Chernomorets, 2007
16	21-22th Jun 2002			CDF	flash flood and several days of closed border crossings	Chernomorets, 2007
17	Aug 2007			CDF	destruction of 400 m military road, 1 victim	
18	2010	0.73	2.625	IRF	elevation 1,460 m, average slope 29.1 °	Dokukin, 2015
19	17th may 2014	3.7	10.9	IRF/IDF	8 victims (4 truck drivers, 4 workers), military road, 2 gas pipelines, HPP Larsi destroyed (the road closed for one month)	Gapringashvili, 2015
20	20th Aug 2014		6	CDF	2 victims (workers) HPP Larsi and customs terminal destroyed, 150 people evacuated, the road closed for 10 days	Gaprindashvili, 2015
21	23rd Jun 2016			CDF	1 km military road (closed the road 14 days)	
22	2014–2019	0.2	1.1	IRF	head scarp area at 4,090–3,860 m a.s.l. with slope 55°, average slope 47 °	

On the basis of a comprehensive evaluation of archival Internet data, documented or anticipated occurrences of debris flows / mud flows origins and runouts have been marked on **Fig. 8**. Based on these data, a conceptual engineering geological model has been generated in the form of a preliminary simple hazard map usable for first discussions of geological questions in urban planning in order to avoid urbanization in vulnerable areas. Measures other than eliminating urbanization at vulnerable areas are usually ineffective in preventing damage or financially out of the reality. However, if there are cases when construction cannot be avoided, the use of this conceptual model may warn the public of the need of increased costs to protect projects against these devastating phenomena.

However, it should be taken into account that this conceptual model is very wide with a very high level of uncertainty. High uncertainty is strongly connected with time prediction of disastrous phenomena, less with prediction of origin of debris flows / mud flows and affected (vulnerable) areas.

Table 2. Documented events in the Genaldon River Valley connect to Kolka and Maili Glacier.

N.	year / period	affected area (km^2)	Lengths\ (km)	type	damage	source
23	1752	cca 12	19	GO/IDF	7 settlements destroyed (all inhabitants died) 1 settlement displaced	Berger 2007b in Leonov, Zaalishvili (Eds.) 2014
24	Aug 1834–Mar 1835		1.6	GS	destroyed thermal spa building	Pastukhov, 1889 in Kotlyakov, 2014
25	1863–1883			GS	>4 destroyed thermal spa building due to glacier surge	Dinnik, 1893 in Kotlyakov, 2014;
26	1877			CDF		Vaskov et al., 2004 in Leonov, Zaalishvili (Eds.) 2014,
27	May 1885			CDF	the entire Kugum area was destroyed by extreme collisions and all mills were destroyed. (Wooden pieces ended in Gizel).	Vaskov et al., 2004 in Leonov, Zaalishvili (Eds.) 2014,
28	1889			CDF	all bridges and roads were destroyed, and field crops were damaged.	Yermakov and Ioganson 1957 in Chernomorets, 2007
29	June 1902	up to 1		IRF	falls 4 from 7 glaciers	Poggenpol, 1905 in Kotlyakov, 2014
30	3rd a 6th Jul 1902	up to 9	10–12	GO/IDF	the first was glacier surge, 36 victims, destroyed 28 mills, 58 horses died, destroyed thermal resort, 1,730 p. of cattle	Rototaev, 1983
31	1907			CDF		Vaskov et al., 2004 in Leonov, Zaalishvili (Eds.) 2014
32	1914			CDF		Vaskov et al., 2004 in Leonov, Zaalishvili (Eds.) 2014
33	1937			CDF		Vaskov et al., 2004 in Leonov, Zaalishvili (Eds.) 2014
34	17th Aug 1953			CDF		Yermakov and Ioganson 1957 in Chernomorets, 2007
35	5-6th Aug 1967			CDF	transported 1.9 million m^3 of solid material. Buildings, bridges, and roads were destroyed. The river flow in Karmadon Village was 100 m^3/s	Rototaev et al., 1983 in Chernomorets, 2007
36	Jun 1969–Jan 1970		4.8	GS/GO	upper thermal spa was destroyed	Panov, 1971a, b in Leonov, Zaalishvili 2014
37	21-22nd Jun 2002			CDF	damage in the Gornaya Saniba Village	Chernomorets, 2007
38	2002		3.2	IRF		Huggel et al., 2005
39	20th Sep 2002	12.3	19+17	GO/IDF	125–200 victims, 140 mil. m^3 (accumulation 110 mil. m^3), velocity up to 250 km/h	Haeberli et al., 2004; Huggel et al., 2005; Evans et al., 2009; Kotlyakov et al., 2014
40	17-19th Oct 2002	0.75	3.46	IRF	biggest post-catastrophic rock/ice falls. elevation 1,370 m	Dokukin, 2015

Table 3. Documented events in the Chkheri River and Tergi River Valley connect to Abano Glacier, and other recorded events in other valleys.

N.	year / period	affected area (km^2)	lengths (km)	type	damage	source
Abano Glacier, Chkheri River						
41	6th Jul 1909	up to 3	cca 8	GO/IDF	Destroyed bridges in Chkheri, 2 hours temporary lake on Tergi, lost crops and cattle	Dukhovskoy, 1917 in Zaporozhchenko and Chernomorets, 2004
42	14th, 27th, 29th Jun 3rd Jul 1910	up to 3	cca 8	GO/IDF	repeated movement of the glacier terminus, Gradual release of the fragment caused 4 x debris flow (largest damage Jun 27 and 29)	Dukhovskoy, 1917 in Zaporozhchenko and Chernomorets, 2004
43	1910–1913			GO/IDF	large emission of mud flow	Dukhovskoy, 1917 in Kotlyakov, 2014
44	8th, 22nd Aug 1937			CDF	Rain-induced debris flows on Chkheri River	Yermakov and Ioganson, 1957 in Chernomorets, 2007
45	17th Aug 1953			CDF	material from Chkheri R. make 5 mil m^3 temporary dam on Tergi R. (river flow 450 m^3/s)	Yermakov and Ioganson, 1957 in Chernomorets, 2007
46	1963–1972		0.051	GS		Zaporozhchenko and Chernomorets, 2004
Glaciers: Mna, Suatisi, Gergeti, Chachi and Zeigalan, Khdistskali River						
47	1827 - Mna or Denkara G., Mnaisidon R.			A	Pushkins poem “Kolaps” (probably avalanche) 2 hours temporary lake	Pushkin, 1829 in Zaporozhchenko and Chernomorets, 2004
48	1913 +- /Gergeti G., Chkheri R.			GS		Dukhovskoy, 1917 in Zaporozhchenko and Chernomorets, 2004
49	1909–1910 - Chach G., Chkheri R.			GS	periodic glacier surge tens to hundreds meters	Dukhovskoy, 1917 in Kotlyakov, 2014
50	17th Aug 1953 - Khdistskali, Tergi R.; Dariali G.			CDF		Yermakov and Ioganson, 1957 in Chernomorets, 2007
51	18th Aug 1953 - Mna G., Mnaisidon r.			GLOF	Mna Glacier lake outburst, flow wave 4–5 m high and 80–100 m wide	Grigolia and Tsomaia, 2000 in Chernomorets, 2007
52	1959 - Zeigalan Glacier, Midagrabidon River			GS	Glacier surge and terminus falls to the valley	Kovalev, 1961 in Kotlyakov, 2014
53	1966–1968 - Mna Glacier., Mnaisidon River			GS		Dukhovskoy, 1917 in Kotlyakov, 2014
54	1989–1998 - Suatisi	2.557	3.17	RF		Dokukin, 2015

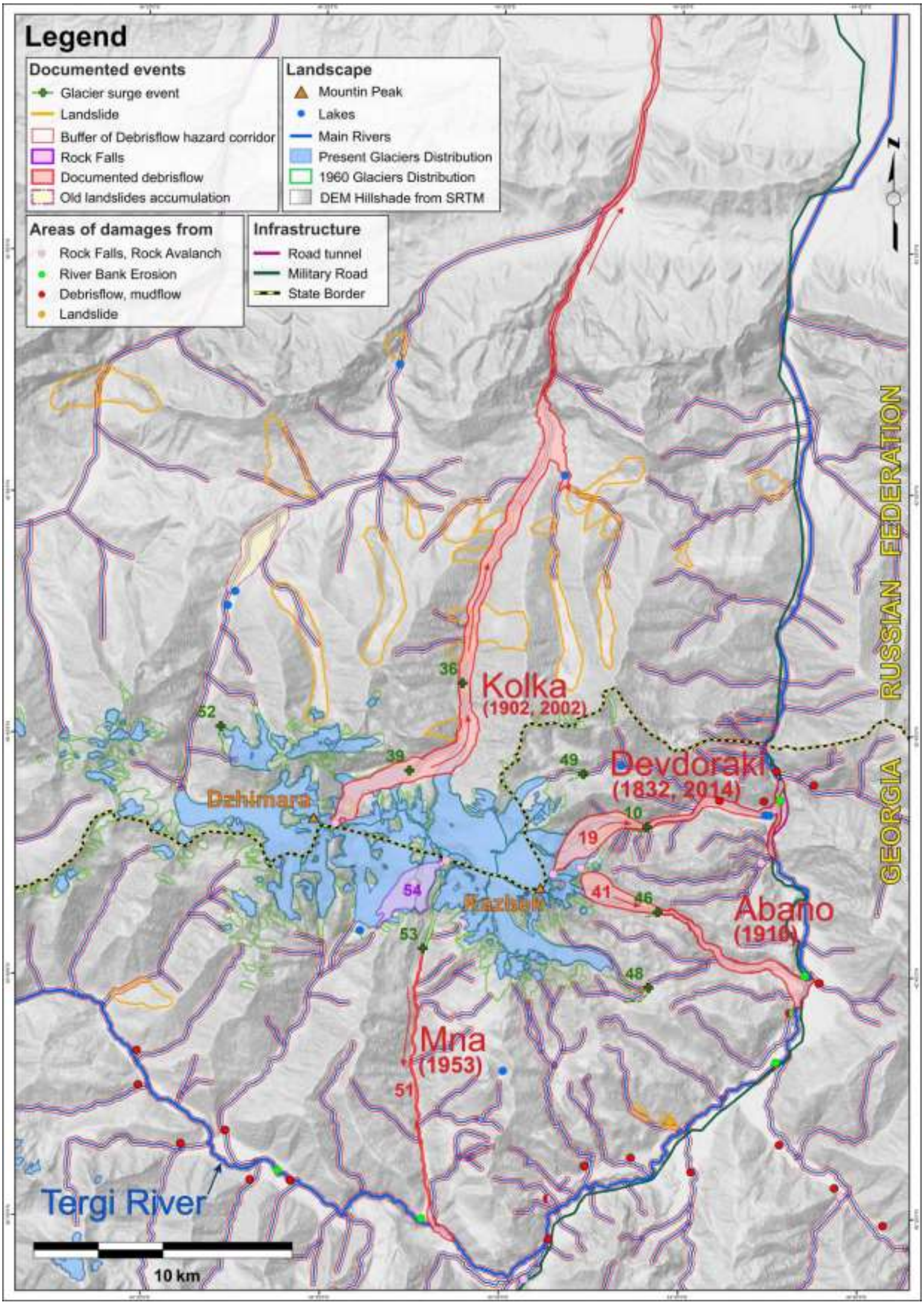

Fig. 8. Simple engineering geological hazard map. The main valleys with debris flow hazard were highlighted with a red buffer. The numbers on map is connected to the spreadsheets where are information about the events. The model can be more refined according to the type of slope movement or according to the type of initiating factor etc. Sources: DEM - USGS 2019, Present glacier – GLIMS 2019 and 1960 glaciers distribution – military topographic map 1:50 000 (ID: k_38_42_v)

For time prediction, historical records can be used to derive periodicity of events in specific locations. The problem with this approach, however, is that the available data provide only a snap-shot of the geological record of mass-movements. The events may have occurred more frequently, and were not recorded when they resulted in a lack of serious damage. Monitoring of susceptible areas is necessary to improve the time forecast. As recorded historical data indicate, a certain periodicity can be partially used for the time prediction of events and their correlation with triggers (abnormal rainfalls periods, earthquakes, temperature peaks etc.). However, caution is necessary when working with these data and determining the periodicity of events. For example, the year 1810 appears in some recent papers, although there is no record of it in historical publications, as Zaporozhchenko and Chernomorets (2004) point out.

Historically documented events can be effectively used to predict the area of damage. There have been many events in the valley of the Devdoraki-Amali and Genaldon Rivers in the past. Using this information it can be predicted what geodynamic process may occur, and roughly what the maximum runout of the sediments is. For debris flow / mud flow type slope movements, the future maximum runout can be estimated based on historical cases, based on the specific valley morphology and the amount of the material transported. And it is also possible to estimate the maximum accumulation height and the maximum width of the affected area (as far as the flow can rise when transported), which will vary according to the valley morphology. Debris flow / mud flow tends to meander in the valley floor. The curvature of the valley and the direction of the flow changes due to centrifugal forces imparted to the flow resulting in the ejection of rock blocks laterally away from the flow axis.

Poggenpol (1905) in Zaporozhchenko and Chernomorets (2004), for example, documented in the Karmadon collapse of 1902 the ejection of glacial blocks up to 20 m. At the Karmadon collapse of 2002, the highest “super elevation” (at the end of the Maili Glacier) was up to 600 m above the valley floor, the other super elevations were 200–350 m. The range of secondary phenomena can be also estimated, for example the extent of the flooded area because of landslide lake dams origination (flooding of Gveleti Village in 1776 and 1832), e.g. (**Fig. 2**) after damming the Tergi River in Dariali Gorge (Zaporozhchenko and Chernomorets, 2004).

Using the Internet visualization map tools, (e.g. Google Maps) it could be possible to allocate cone landforms. Uncertainty of the model occurs due to the fact that alluvial fans and debris flow accumulation products look as similar cone landforms on maps. Therefore, field study is needed to verify knowledge obtained from the conceptual view. The uncertainty is also due to the fact that not all cone landforms and even not all parts in one cone will be equally active in the future.

Low uncertainty is connected with the mechanism of slope movement, as the hazard map on **Fig. 8** was prepared for debris flow / mud flow phenomena. Higher uncertainty can be expected in terms of causes (triggers). One possible scenario of triggering mechanism as a part of conceptual model is presented in **Fig. 9**.

Another frequent phenomenon with a high uncertainty within the model forecast is extent of floods in the case of collapse of a dam formed on the valley floor by debris flow / mud flow sediment accumulation. The range and dynamics of this hazard is dependent on the size of the lake, some historical records are also useful (e.g. "Yermolov's Stone" settled in Verchny Lars and other documented damages in 1776 and 1817).

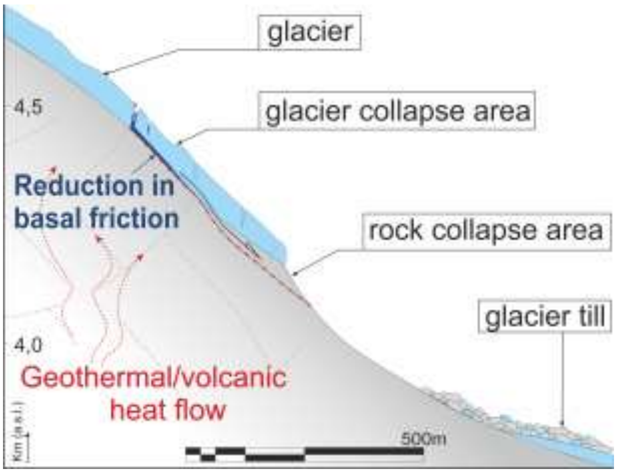

Fig. 9. One of possible scenarios of triggering mechanism for debris flow events in the area - fall of the glacier due to reduction in basal friction induced by geothermal volcanic heat flow.

Despite all the above-mentioned uncertainties of the current very broad but effectively acquired conceptual engineering geological model of the Kazbegi massif and its surroundings, known historical occurrence of debris flows / mud flows can be used for generic hazard zoning and warning with respect to human activities within the area.

5. Conclusions

The internet provides considerable geologically related information for some areas that can be used to generate conceptual engineering geological models. Many internet mapping tools can be used to visualize SRTM terrain relief with satellite images to acquire robust terrain morphology. For example, Google Earth is an exceptional tool to display not only current but also older satellite images on a digital relief model (SRTM DEM), which adds a time dimension to the analyses.

By using Internet resources and tools, valuable information about geological hazard in given areas can be obtained very quickly and efficiently in the form of a conceptual model, as demonstrated by the Kazbegi example. Endangered areas unsuitable for urbanization, where large damages or even fatal destructions and losses of lives are expected in the future, can be identified in very effective way. For example, it is obvious from the model (**Fig. 2**, **Fig. 8**) that the Hydroelectric Power Plant Larsi in the Kazbegi area was improperly situated and consequently damaged.

The model can be further refined. The above information presented in this paper is only a selection of a large amount of information, which can often be very detailed and accurate. For the Kazbegi area, it would be possible, for example, to differentiate the predicted catastrophic phenomena into events that are directly related to glaciers and to others less dependent or independent on glaciers. Valuable information can be obtained this way to be used as an input for effective design, implementation and evaluation of technical works of ground investigation, on the basis of which the quality of engineering geological model is further improved. Presented wide conceptual model can be refined in stages as well as by direct works on the place in terms of observational engineering model generation.

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