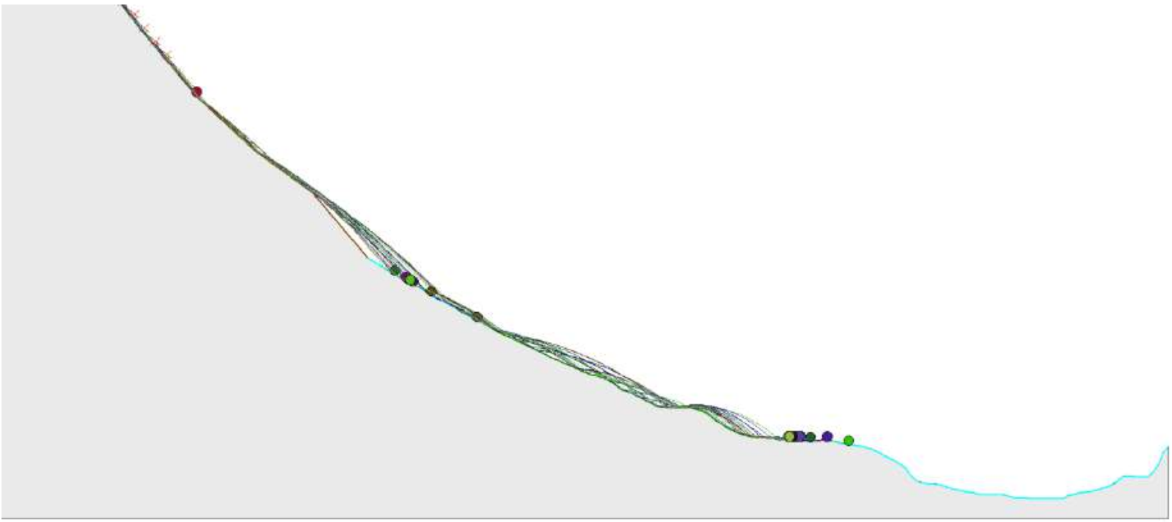

Fig. 8-4: Visualisation of the simulation result of M-D4 t_1 without placing a rockfall barrier.

B: Simulation with placing a rockfall barrier at x = 194 m

The determination of the ideal location of a protection structure is crucial and depends on multiple factors such as the jump height of the (design) boulder and its remaining energy at the envisaged position. As such, we strongly recommend placing a protection measure on the closest edge of the upper road section (x = 194 m). The simulation has shown that all design boulders can be stopped by a rockfall barrier of at least 2,000 kJ at x = 194 m (see Fig. 8-5). In Tab. 8-3 the characteristic values of the design boulder ((HpMax) Maximum height, (V_{max}) Maximum velocity, (E_{max}) Maximum energy) at the time of impact at the barrier are shown.

Tab. 8-3: Simulation result with a rockfall barrier at the position of the road (x = 194 m).

X_b [m]	Y_b [m]	HpMax [m]	V_{max}[m/s]	E_{max} [KJ]
194,318	28.988	1.404	12.153	1,629.819

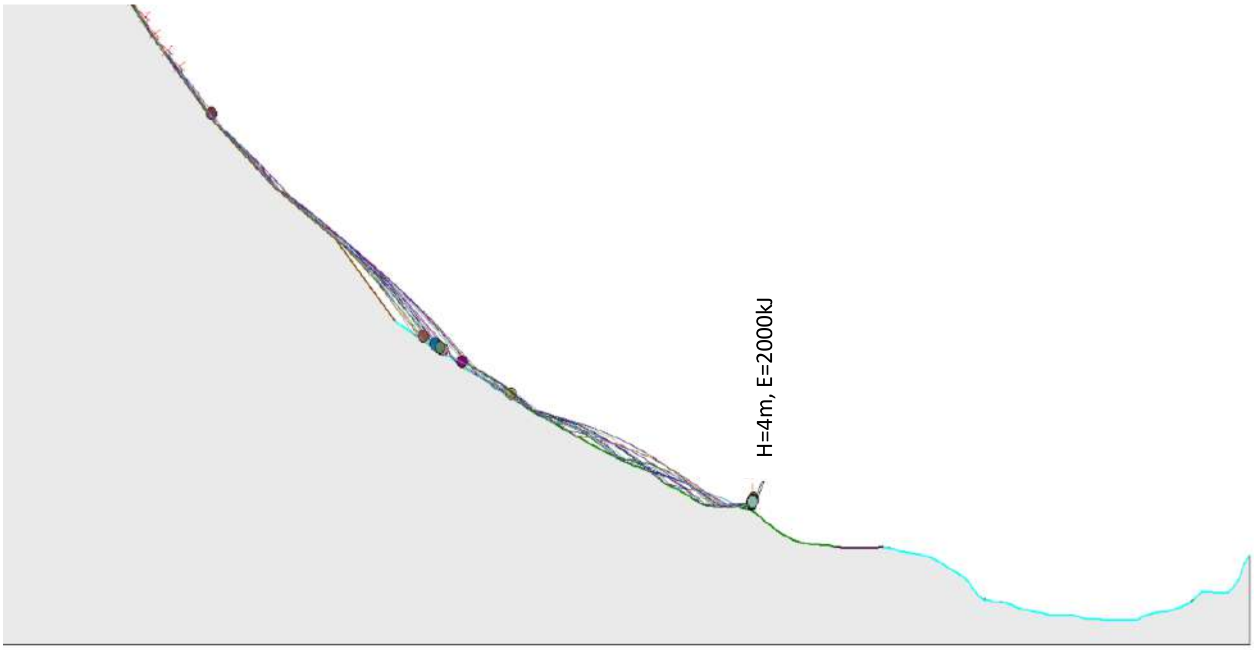

Fig. 8-5: Visualisation of the simulation result of M-D4 t_1 with placing a rockfall barrier in front of the road.

8.1.3.2 Rockfall hazard trajectory M-D4 t_2

A: Simulation <u>without</u> placing a rockfall barrier

The second rockfall event at M-D4 (M-D4 t_2) was calculated with the boulder characteristics summarized in Tab. 8-4, and the results are visualised in Fig. 8-6. While some design boulders did not reach the investigated road section, others did reach the road and pose therefore a hazard to infrastructure, penstock and the operating staff. In Tab. 8-4 the characteristic values ((HpMax) Maximum height, (V_{max}) Maximum velocity, (E_{max}) Maximum energy) of the design boulder impacting the road at position x = 287 m are presented.

Tab. 8-4: Simulation result without placing a rockfall barrier at the position of the road (x = 287m).

X_b [m]	Y_b [m]	HpMax [m]	V_{max} [m/s]	E_{max} [KJ]
287	20	3.8	17	2,664

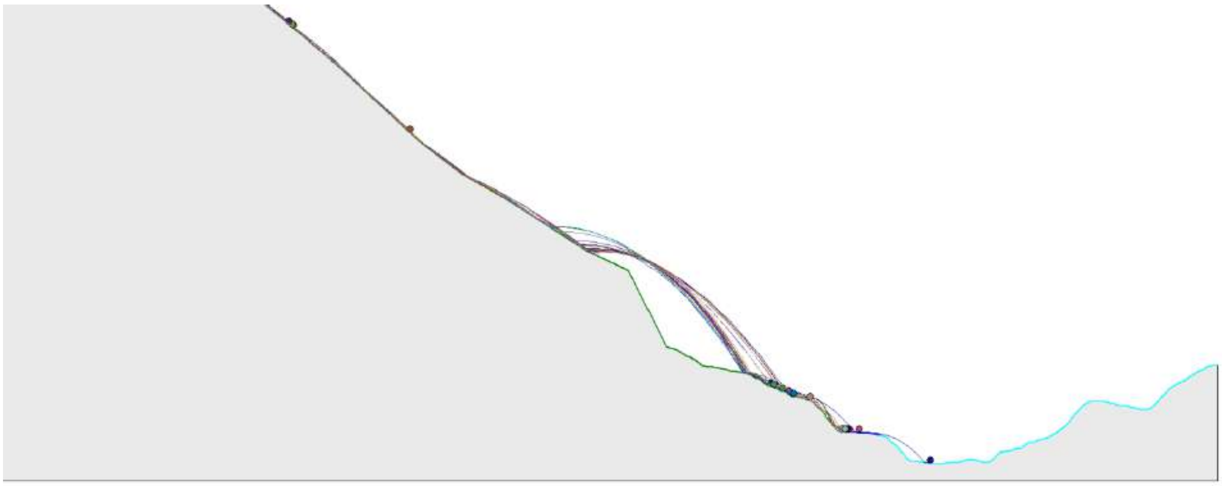

Fig. 8-6: Visualisation of the simulation result of M-D4 t_2 without placing a rockfall barrier.

B: Simulation with placing a rockfall barrier at x= 278m

The simulation has shown that all design boulders can be stopped by a rockfall barrier of at least 2,000 kJ at x = 278 m. The results are visualised in Fig. 8-7, and in Tab. 8-5, the characteristic values of the design boulder ((HpMax) Maximum height, (V_{max}) Maximum velocity, (E_{max}) Maximum energy) at the time of impact at the barrier are shown.

Tab. 8-5: Simulation result with a rockfall barrier at the position of the road (x = 278 m).

X_b [m]	Y_b [m]	HpMax [m]	V_{max} [m/s]	E_{max} [KJ]
277.688	29.462	0.958	12.777	1,724.671

Fig. 8-7: Visualisation of the simulation result of M-D4 t_2 with placing a rockfall barrier in front of the road.

8.1.4 Rockfall hazard zones M-D6

North of the deposition of the 2019 event considerable rockfall activity occurs, posing a hazard to the position of the planned new intake 1. According to our findings from field investigations, the following two cross sections (M-D6 t_1 and M-D6 t_2, see Fig. 8-8 and Fig. 8-9) were distinguished as potential rockfall trajectories and corresponding rockfall simulations were performed. Trajectory 1 follows the incision were also the M-df5 flow is located. The second trajectory (M-D6 t_2) is assumed to detach from the steep rock face to the right of M-D6 t_1 crossing trajectory 1 with a run-out at the lower plateau close to the planned new intake 1. The computer simulation was performed only for M-D6 t_2 since this is closer by the planned new intake 1. The boulder characteristics for the simulation are summarized in Tab. 8-1.

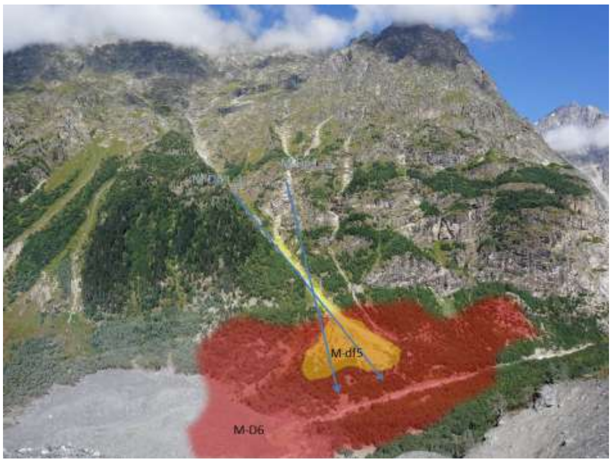

Fig. 8-8: M-D6 trajectories 1 and 2; view to NW.

Fig. 8-9: Satellite image of M-D6 trajectories 1 and 2.

A: Simulation <u>without</u> placing a rockfall barrier

As so far the exact location of the new intake 1 structure was not defined, the position x = 870 m was chosen for demonstrative purpose. Close to this position the simulation results indicated that several boulders hit the ground and bounce back. Hence, the energy level in front of this point is very high with several 1,000 kJ. Afterwards a large portion of the energy is dissipated and the remaining energy histogram is visualised at x = 870 m in Fig. 8-10. The rockfall simulation for M-D6 t_2 (Fig. 8-11) provided evidence for rocks impacting at x = 870 m with energy levels up to 2,450 kJ. This hazard should be taken into account when choosing an appropriate position for the new intake 1 structure.

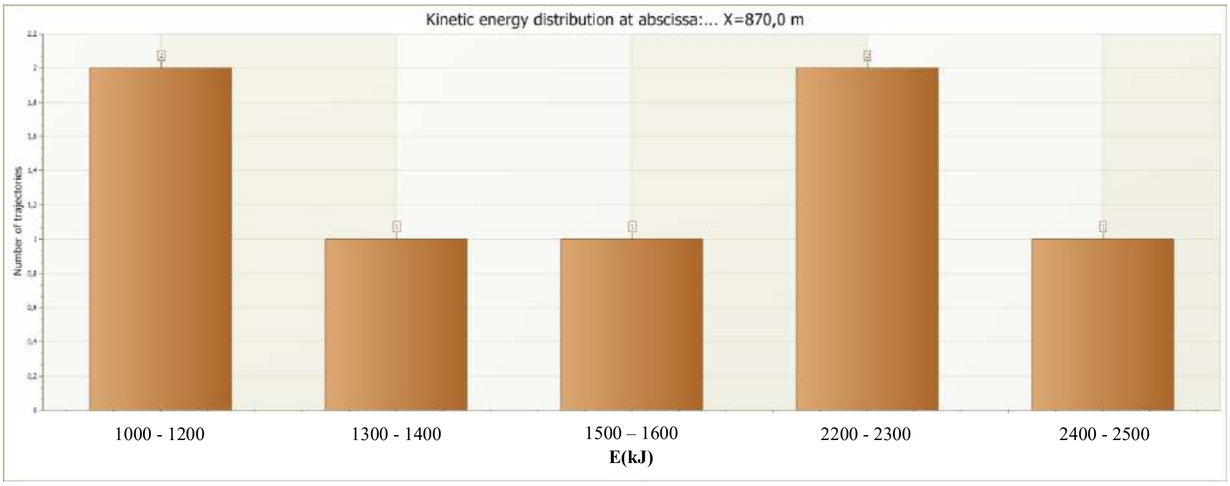

Fig. 8-10: Kinetic energy distribution at (x = 870 m)

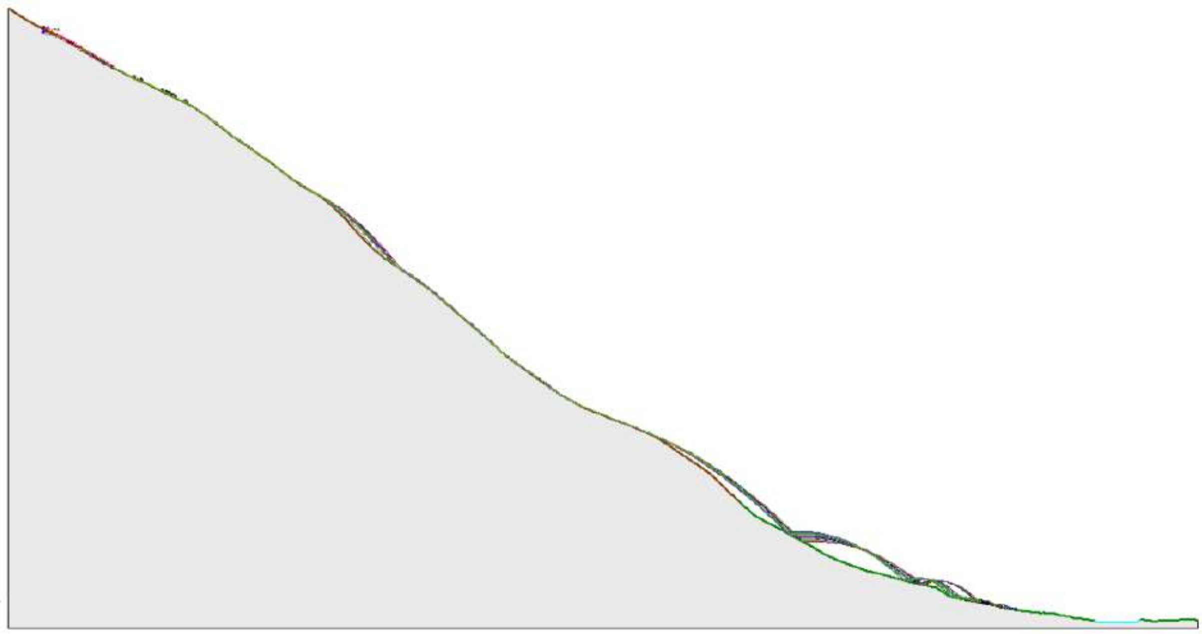

Fig. 8-11: Simulation result of M-D6 t_2 without placing a rockfall barrier.

B: Simulation <u>with</u> placing a rockfall barrier at M-D6 t_2 (x = 881 m)

The simulation provided evidence (Fig. 8-12) that all design boulders can be stopped by a rockfall barrier of at least 2,000 kJ at x = 881 m. In the following table (Tab. 8-6) the characteristic values of the design boulder ((HpMax) Maximum height, (V_{max}) Maximum velocity, (E_{max}) Maximum energy) at the time of impact at the barrier are introduced.

Tab. 8-6: Simulation result with a rockfall barrier at the position of the road (x = 881 m).

X_b [m]	Y_b [m]	HpMax [m]	V_{max} [m/s]	E_{max} [KJ]
881.509	23.298	2.844	8.406	1,047.536

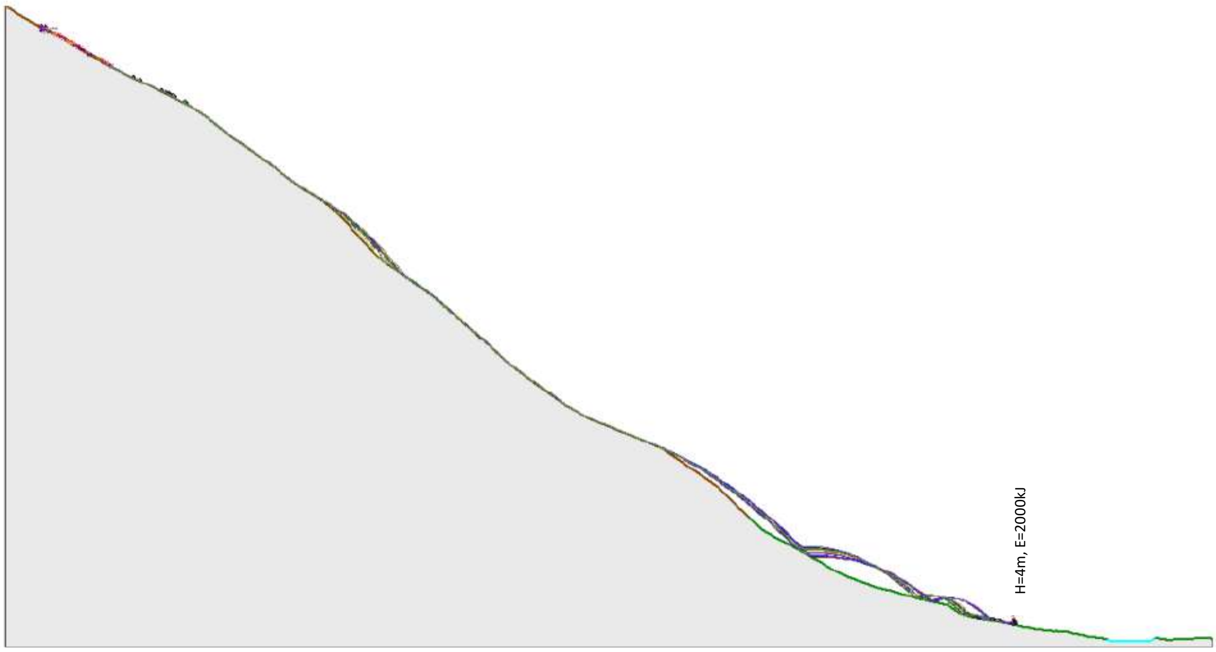

Fig. 8-12: Visualisation of the simulation result of M-D6 t_2 with placing a rockfall barrier.

8.1.5 Conclusions on the rockfall simulations

In Tab. 8-7 the simulated impact values at the two locations are summarised. For a possible location of the new intake 1, only a roughly-estimated range is provided. Please note that the impact energy level is highly dependent on the location of impact and hence, choosing an appropriate location for a barrier is crucial.

Tab. 8-7: Simulated rockfall impact energies.

	Impact energy without placing a barrier.	**Impact energy at favored location of barrier**
Exposed penstock	1,050 - 2,664 kJ	1,630 - 1,725 kJ
Planned new Intake1	2,450 kJ up to several 1,000 kJ	1,048 kJ

8.2 Rock slope stabilities

Attachment 2 shows an overall stability classification of the rock slopes in the HPP 1 catchment in a scale of 1 : 25,000 based on satellite and drone imagery as well as field surveys. Instable rock slopes are a common feature in any mountain environment which will most probably increase due to climate change effects.

Remark: It is impossible to detect all potential future rock slope failures in such a large catchment or to do detailed full-area geotechnical assessment. Such software-supported modelling requires additional input (e.g. terrain model etc.) and exceeds the contract and targets of this study. An impact analysis, however, can be attempted based on experience (empirical values) and an analysis of previous events.

In principle, in all rock slopes minor and medium rock mass wasting is present (few to 100s of m^3). However, two areas can be identified which have a significantly higher volume at risk and/or immediate impact on the HPP1 facilities:

Release areas: T-R1 – T-R6 (Detachment zone of the 2019 event s.l.)

Release areas: M-R3b and M-R5b (instable rock towers and slope, Mestiachala west flank)

Possible further larger instabilities cannot be excluded absolutely, which must be considered in and future scoping of the area.

8.2.1 Detachment zone 2019 (T-R1 to T-R6)

8.2.1.1 Engineering geology

The detachment zone of the 2019 event s.l. is composed of several areas prone to release (T-R1 to T-R6), which can be seen in detail in the images below (e.g. Fig. 8-15, see also Chapter 3.2). The geology is highly unfavorable. The whole sequence of Lower Jurassic rocks of the Mestia-Tianeti Zone, which comprises different slate members, dips to the Northeast and is cutoff obliquely by the steep MCT thrust zone. The critical rock faces (esp. T-R3 and T-R1) are located in a few 100 m thick member of comparably weak dark slates, characterized by fine bedding and intense cleavage. The majority of material of the 2019 event is derived from this dark slate member. In addition, the cleavage is very pronounced and serves as main detachment (s1).

The hanging Murkvami glacier tongue covers the shear zone of the MCT. The Jurassic slates and sheared crystalline rocks (mainly gneisses) form a melange of friable rock masses with reduced strength. Here, detachments T-R5 and T-R6 are located.

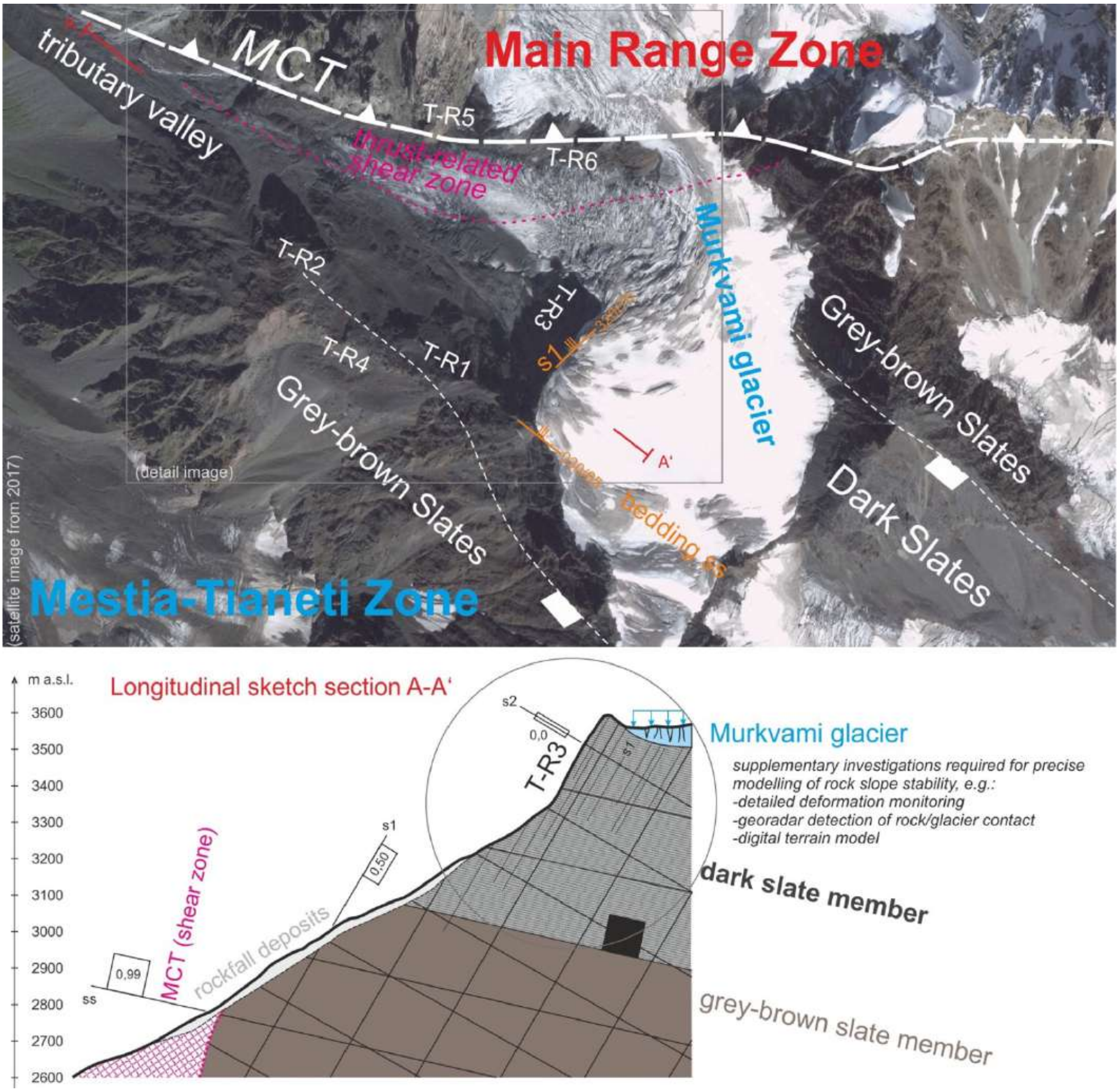

Fig. 8-13: Overview of the geology in the Murkvami area (satellite image from 2017 obtained from https://pereval.online/object/2812#image-12). Longitudinal section along rockfall travel path.

8.2.1.2 Activity of the detachment zone

The entire release area shows high activity (minor to large rockfalls and active joints; see debris plumes on snow fields in Fig. 8-14) as can be inferred from our previous investigations (see report_02). This means that the detachment zone has obviously not come to a semi-stable condition after July 2019, but future events must be expected. Monitoring is strongly recommended (see Chapter 11).

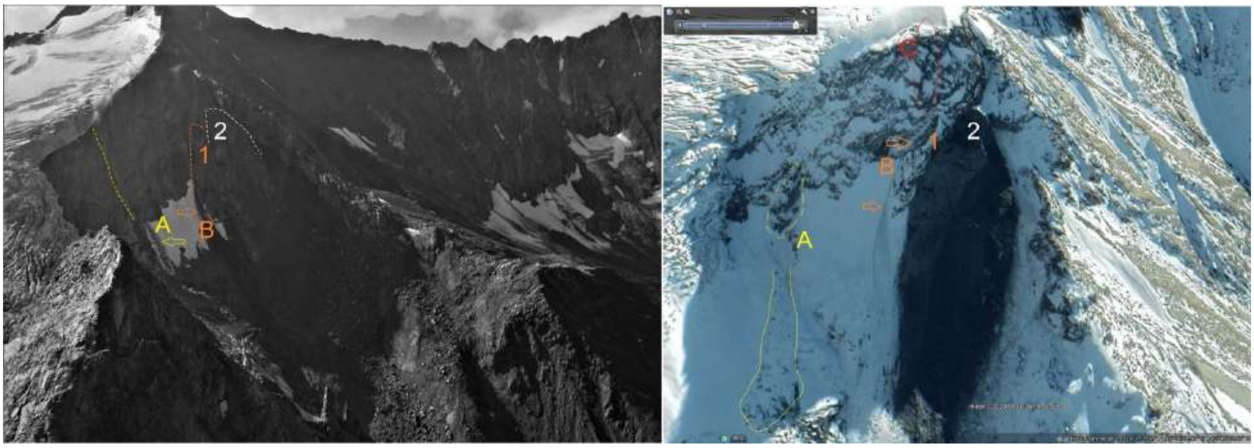

Fig. 8-14: Activity indicators. Left: Overview of the detachment area from helicopter in August 2019. Right: Google earth image of October 2019. ***2****: Rock tower collapse in 10/2019;* ***1****: near-future event;* ***A*** *and* ***B****: joints with active debris release,* ***C****: new joint developing (for further explanation see also our Report 02).*

8.2.1.3 Event analysis and hazard situation

Post-event satellite images (October 2019) as well as drone imaging of August 2020 show the release zones of rock masses and glacier ice of July 2019 in detail. The major detachments were identified in T-R1 and in a second wave in T-R2 with roughly calculated volumes of 1,300,000 m^3 and nearly 300,000 m^3 respectively (see Chapter 7). The red fields show potential future release areas, here we identified T-R3 and T-R6 as probably the most hazardous ones.

The potential detachment zone T-R3/T-R1 comprises the steep and smooth rock face below the glacier edge, which resembles one of the prominent regional cleavages in the Lower Jurassic slate formation. This discontinuity is a plane of weakness (shear plane) with reduced shear strength. According to the intersection with other discontinuity sets (esp. original sedimentary bedding, ss), sliding wedges of different dimensions are likely to develop.

In addition, the southern part of the wall has been steepened by removal of rock mass due to detachment in T-R1. The entire “rock abutment” at the southwestern foot is drifting apart and eroding (see processes in T-R1- and 2 and T-R4). Drone imaging clearly indicated the development of large vertical cracks as well as probable initial shear fractures at the foot of the wall. These cracks seem comparably fresh and it has to be assumed that they are active. The rock mass is thus prone to intensified weathering impact (freeze-thaw cycles, precipitation and melt water influx from Murkvami glacier) and accompanying reduction of shear strength along discontinuities.

The potential detachment zone T-R6 is situated in the ultimate shear zone of the MCT which must be seen as a mechanically weak melange of friable rock masses.

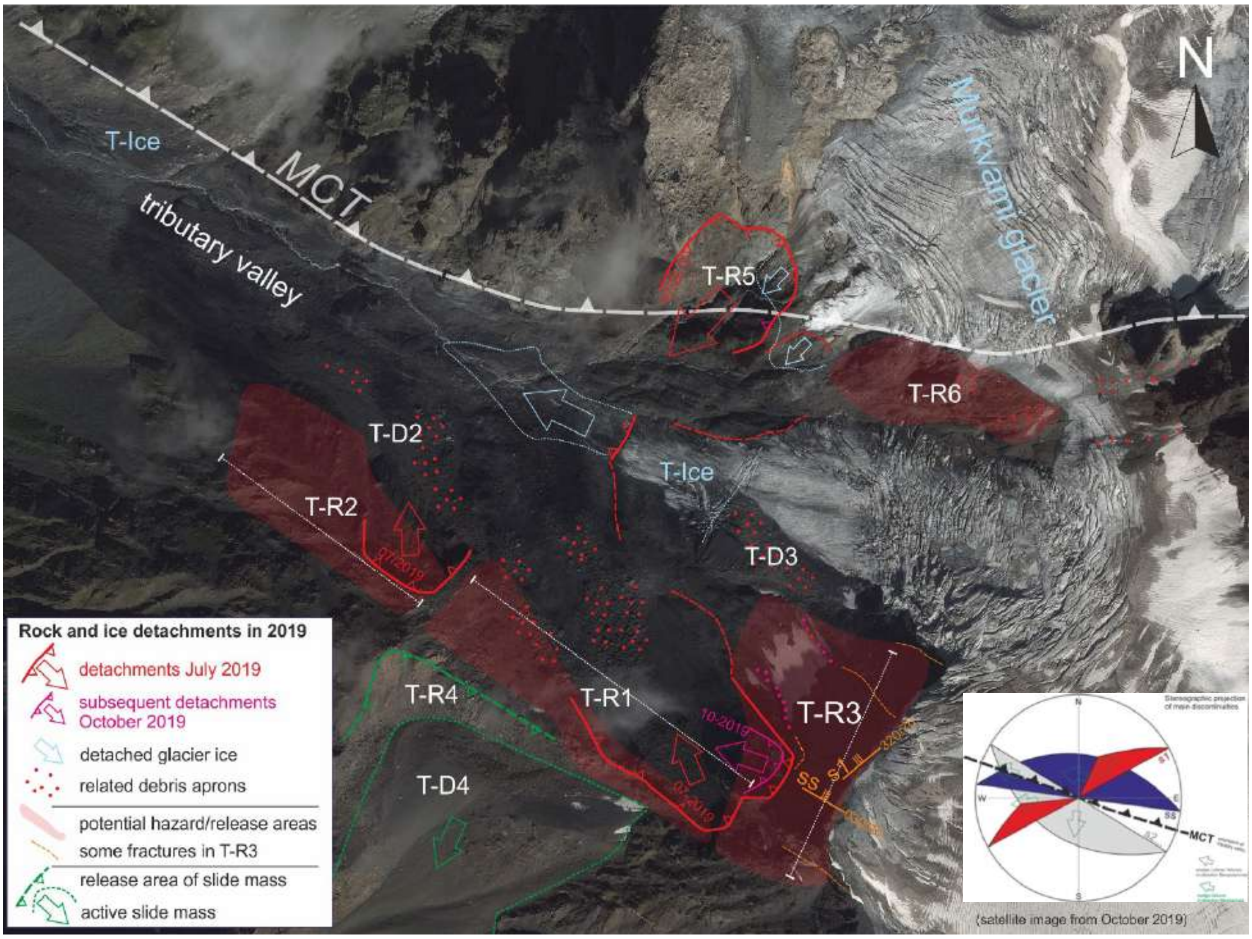

Fig. 8-15: Overview of the entire detachment area of the 2019 event (based on Report_02).

The probability of re-occurring rock slides in T-R1 to T-R6 is thus comparably high. Regarding the following factors, we have to assume **future rock slope failures within the next 30 years (EF 2: 1-30 years):**

- Location on a fault and thrust zone in unfavourable geology (weak dark slate member)
- Oversteepend wall with dense cleavage and loaded by plateau glacier
- Absolute height in permafrost retreat range (see Chapter 9.4)
- High level of rockfall activity and active debris release from joints
- Loss of rock abutment at the foot by mountain splitting of rock mass below T-R1
- Expectable ice detachments of hanging ice and debris

The maximum volumes (magnitude) can be estimated as roughly up to 500,000 m^3 from the area of T-R3 / T-R1 and 300,000 m^3 from T-R6. This is a rough number since detail data (e.g. DTM) is missing. Minor rock slides in the scale of several 100s to 10,000s m^3 might occur anytime, as could be seen in October 2019. A near-future event expected in the next years is indicated in Fig. 8-16 with an approximate volume of around 50,000 m^3 (very large rockfall).

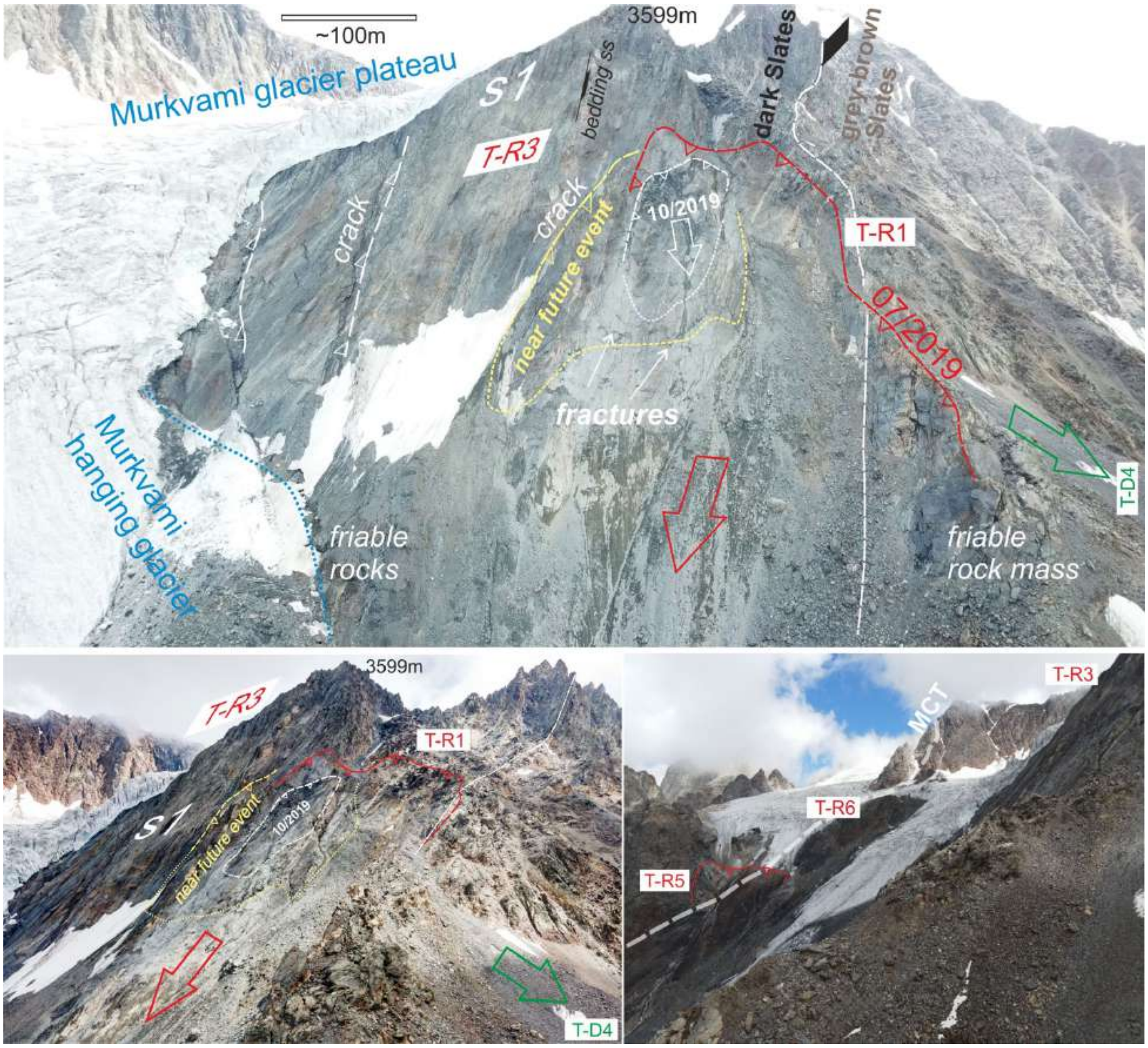

Fig. 8-16: Top and bottom left: Overview of release areas T-R3 and T-R1 with geomechanical condition and geometry of recent detachments. Bottom right: View to the North on MCT shear zone with T-R5 and T-R6. Note the steepness of T-R3.

8.2.1.4 Outlook on impact analysis

The impact of a very large or high-magnitude rock slide has to be considered in the context of the so-called high-magnitude compound events (see Chapter 7). The rock slide s.s. will impact in the Tributary/Murkvami valley and not directly affect the HPP1 structures. However, the rock slide event can be one of the triggers of a cascade of mass movements as in July 2019.

The stability of the rock wall can, in principle, be investigated in more detail by rock mechanical software modelling, which should be supported by monitoring data and high-resolution terrain model. These data, however, are not available so far. In this context, we also want to emphasize the impact of Murkvami glacier, its load and its subsurface rock conditions on the overall stability of the steep rock face T-R3, which could be investigated by georadar.

8.2.2 Rock towers on Mestiachala west slope (M-R3b and M-R5b)

8.2.2.1 Engineering geology and hazard situation

Along the western Mestiachala valley friable and loose rock towers can be observed, which can be source of large or even very large rockfalls reaching the valley bottom and the HPP structures (gallery, penstock).

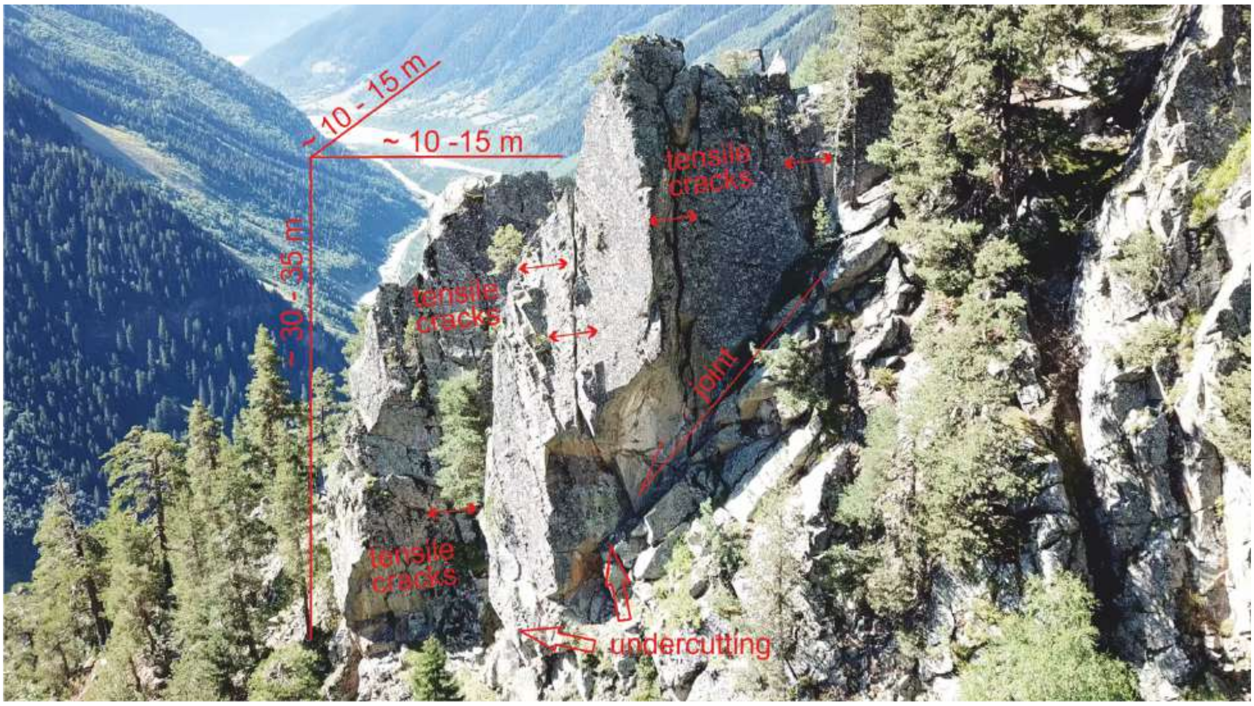

Fig. 8-17: Instable rock towers in the west slope above gallery (M-R3b). Measured rock volumes range between 2,500m³ and 10,500 m³ (mainly class: large rockfall).

The **rock towers at M-R3b** are located above the gallery and show clear indications of mountain splitting. Drone imaging resulted in detailed insight into the structural situation (Fig. 8-17). More or less vertical or steeply inclined cleavages (most likely s1 and s2) serve as detachments along which the ridge is splitting apart. The fracturing appears rather fresh in parts and hints at active deformation. Also undercutting can be observed in the images.

It has to be assumed that wedge-shaped parts of these towers or the entire towers can detach and fail, leading to rockfalls of large volumes up to some 1,000s of m^3. We roughly assume a frequency class of 1-30 years (EF 2). More precise assumptions are only possible incorporating monitoring data and detailed DTM.

The rock masses of M-R3b will most likely transit the gully leading to depositional area M-D3 at the gallery. Details can be seen on the images in Fig. 4-2 to Fig. 4-5.

A **friable rock slope is located in M-R5b** as shown in the following image (Fig. 8-18). Further details can be seen in Fig. 4-8 and Fig. 4-9. The geomechanical situation is characterized by strongly fractured rocks with an apparent cleavage/joint set dipping eastward, parallel to the Mestiachala valley flank. This is a typical fault orientation in this region.

It has to be assumed that this area is an active release area with annual minor events, but also a probable large or even very large rockfall event in a range of 1-30 years (EF 2). More precise assumptions are only possible incorporating monitoring data and detailed DTM.

Fig. 8-18: Instable rock towers in the west slope (M-R5b). Measured rock volumes range between 5,000m³ and 12,000 m³ (mainly class: large rockfall). Note the steep joint parallel to the slope.

8.2.2.2 Outlook on impact analysis

Potential events in the scale of large or very large rockfalls will definitely affect the Mestiachala valley bottom and the HPP1 structures as far as can be assumed from topography and experience. (The stability of the rock masses can be investigated in more detail by software modelling based on a high-resolution terrain model. This is detailed study and not part of this contract, but an issue for designing countermeasures).

Rockfall from M-R3b will most likely impact on top of the gallery. The rock mass of Jurassic slates will disintegrate into a blocky mass, which will override the gallery. A volume of up to 10,000 m^3 at maximum has to be assumed. Supporting measures are recommended for the gallery (see Chapter 11).

Minor rockfall from M-R5b will not reach the road due to a comparably wide forested depositional area (M-D5). However, large or even very large volumes (up to 12,000 m^3) composed of slates and crystalline lithologies will disintegrate and result in a flow of boulders with single larger blocks of 10 m^3 or more. A part of the moving rock mass will reach the road, infrastructure and Mestiachala river and not be trapped in M-D5.

9 Glacier study

The following glacier study is based on data collected during a field survey in August 2020 as well as on a literature review of the glaciers in the Greater Caucasus, especially the glaciers in the catchment of the Mestiachala river.

A detailed survey was conducted in the Chalaati valley. The other glaciers were assessed remotely because of the considerable spatial extent and the impassable terrain. Wherever possible, drone flights were carried out. Furthermore, satellite images were used for evaluation (Pleiades satellite imagery of 06 September 2014 and 31 August 2019, SPOT6 scene of 01 August 2017), as well as GIS software.

9.1 Background

Glaciers shape the landscape and are an important freshwater resource, as well as a water supplier for mountain rivers. Besides, glaciers can also be a potential source for natural hazards. As a consequence of glacier retreat, material is successively released which is then available as bed load for channel processes (e.g. debris flows). Glacier retreat will change the conditions on the earth's surface and leads to a shift of the cryosphere and their hazard zones (ZEMP and HAEBERLI 2007: 116). The maximum extent of the glaciers in the greater Caucasus occurred during the Little Ice Age around the year 1810. The Little Ice Age lasted from about 1650 to 1850 in the Caucasus region (TIELIDZE et al. 2015b: 75).

9.2 Mestiachala glaciers

This glacier study describes the retreat of the glaciers and the resulting consequences for the HPP1 in the catchment area of the Mestiachala river.

Three large glaciers dominate the Mestiachala basin (TIELIDZE et al. 2015: 74 f.) and constitute 86.56% of the total glaciated area in the catchment area (TIELIDZE 2017: 39):

- Lekhziri glacier: Lekhziri glacier is a compound valley glacier with two main flows joining at E318,000, N4,782,00. They are fed by the slopes of the surrounding mountain ridges. The highest elevations are Mt. Bashiltau (4248 m asl), Mt. Mestiatau (4036 m asl), Ulukara (4,302 m asl). Lekhziri glacier is the largest of its kind in Georgia, the current surface extent is about 23.3 km².
- Northern Lekhziri glacier: Northern Lekhziri glacier is a cirque glacier. This glacier is fed by the slopes of Mt. Dzhantughan (4,012 m asl), Mt. Gumachi (3,823 m asl), Mt.

Chienghietau-Chana (4,019 m asl) and Mt. Latsgha (3,946 m asl). The current surface extent of Northern Lekhziri glacier is about 6.3 km.

- Chalaati glacier: Chalaati glacier is a compound valley glacier. There are two main flows joining at E313,600, N4,777,700. They are both fed by the slopes of Mt. Ushba (4,700 m asl), Mt. Chatini (4,412 m asl) and Mt. Bzhedukhi (4,270 m asl). The current surface extent of the glacier is about 8.6 km².

In addition to these three large glaciers, two glaciers on the orographic left side of the Mestiachala valley have to be considered as they are situated in the Tributary:

- Murkvami glacier, with a current surface extent of around 1.5 km²
- Banguriani glacier, with a current surface extent of about 0.3 km²

9.2.1 Chalaati glacier

Chalaati glacier is one of the most famous glaciers in Georgia and an important tourist attraction in the Mestia region. The glacier tongue is easily accessible because the terminus is situated in a relatively low altitude.

Fig. 9-1 illustrates the glacier retreat from 1887 to 2011. It is evident that the glacier filled the entire valley and reached up to the height of the lateral moraines (named “1850” moraines in the preliminary report, visible on the right image). The loose material uncovered by the retreat of the glacier is clearly visible in the right image. The ongoing glacier retreat gradually uncovers more loose material of different grain sizes, which can be mobilized by subsequent erosion and remobilization processes and might pose a threat to the structures of HPP1 (see Chapter 5 for more details).

The two peaks on the left are Ushba South (4,700 m asl) and Ushba North (4,698 m asl).

Fig. 9-1: Left: Chalaati glacier 1887 (Dechy 1905: 313), Right: Chalaati glacier 2011 (Tielidze 2019: 73)

The maximum extent of the glacier tongue was recorded around 1810 at an elevation of 1,620 m asl (Tielidze et al. 2015: 76). In 1887 the glacier reached an altitude of 1,628 m asl (Dechy 1905: 314). As the altitude of HPP1 is about 1,645 m asl, it becomes evident that the extension of Chalaati glacier was below the current location of HPP1. In 1911 the glacier tongue reached an altitude of 1,650 m asl, just slightly above the location of HPP1, and the surface extent of the glacier was measured with 12.2 km² (Podozerskiy 1911). The moraine material consisted of gneiss granites, syenites with fine grain (feldspar and amphibolite) and pegmatides with quarz inclusions of different grain sizes (Dechy 2005).

The lateral moraines on the left and on the right margin of the valley give a visual impression of the thickness of the glacier in 1810. These moraines provide loose material which is successively transported downhill towards the channel bed by erosion processes, and may be further mobilized during periods of high discharge in terms of fluvial sediment transport or debris flows. Fig. 9-2 was taken by a drone and shows the glacier mouth, the debris-covered glacier tongue and the loose material available on both slopes (north and south).

Fig. 9-2: Chalaati glacier terminus (© Sebastian Resinger)

During the field survey on 14 August 2020, historic glacier levels and terminus marks were recorded using a GPS device. The marks were set by the Institute of Geography, Tbilisi State University and are located along the hiking trail between HPP1 and the glacier mouth. The recorded points were transferred into a GIS program to analyse the spatio-temporal glacier retreat rates. Besides, terminal and lateral moraines were mapped. Lateral moraines provide information on the former thickness of the glacier in the valley, and terminal moraine positions provide information on periods where neither retreat nor advance were dominant and therefore, the glacier tongue was in a stable position. The data is visualised in Fig. 9-3.

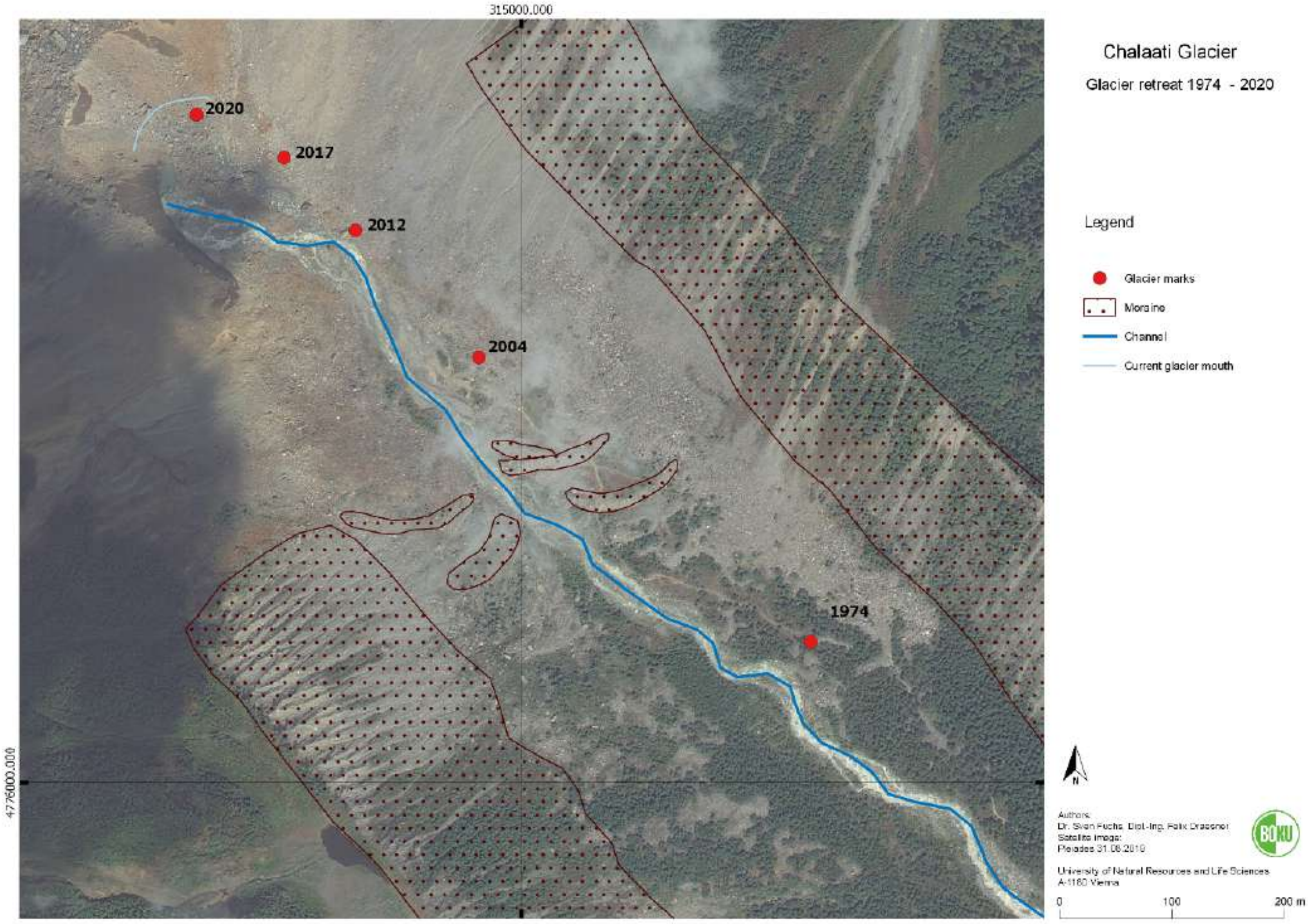

Fig. 9-3: Map of Chalaati glacier retreat 1974-2020

On the basis of the recorded glacier levels the retreat and decline can be measured. It has to be considered that the recorded waypoints only roughly correspond to the exact glacier levels of the corresponding year. For each year only one mark was found in the field, thus, the location of the lowest point of the glacier cannot be proven with absolute accuracy. Besides, no reference is made to the exact date of recording, and therefore a deviation of ± 20 m has to be assumed. As such, a rough estimation of the glacier retreat can be made.

Comparing information from the literature review with in-situ field observations, two different points in altitude for the current geographical position of the glacier terminus and mouth revealed. This may have occurred due to different interpretation of the ice body shown in Fig. 9-2. While in TIELIDZE 2020 the ice body is seen as dead ice, during the field survey it was interpreted as active glacier tongue. For an assessment of potential hazards originating at this location the question of whether the glacier mouth and the surrounding ice is dead ice or still an active part of the glacier can be neglected. Because the ice body is considerably debris covered, this distinction would need an in-depth analysis which was not possible giving the temporal constraints during the August 2020 field visit.

According to the collected data, the glacier has retreated over the last 46 years (1974-2020) with an average of 15.9 meters in length per year. The total change in elevation between 1974 (1,824 m asl) and 2020 (1,880 m asl) is 56 meters. Between 1974 and 2004 the retreat was 13 meters in length per year. Between 2004 and 2012 the retreat was measured with 20 meters in length per year. Between 2012 and 2017 the retreat was about 18 meters in length per year and in the last three years the retreat of the glacier was 30 meters in length per year. These data prove that glacier retreat in the Chalaati valley has increased significantly in the last two decades. This trend is supported by the analyses of TIELIDZE et al. (2020).

If this trend continues, a glacier retreat of at least 500 meters in the next 30 years is expected. As a result, some 100,000 m³ of material will become available as potential bed load for erosion and remobilisation in the channel. This material will become available particularly during periods of heavy rainfall as well as if subglacial water pockets will spontaneously release, however, evidence for the latter processes were not found during the assessment.

9.2.2 Lekhziri glacier (Northern Lekhziri glacier and Lekhziri glacier)

The Lekhziri glacier is the largest glacier in Georgia (TIELIDZE 2015b: 74). The glacier had a cross-shape footprint until it split up in 2012, with two main flows from east and west (the actual Lekhziri glacier, which is a compound valley glacier) and a central, northern flow (the Northern Lekhziri glacier, which is a typical circle glacier). According to Dechy (1905: 315), in the year 1887 the glacier tongue terminated at 1,734 m asl. In 1890, the glacier surface area was 38.49 km² (TIELIDZE 2017: 100). Other historical data, however, state that the glacier mouth had an elevation of 1,730 m asl in the year 1911 and that the glacier covered an area of about 40.8 km² (PODOZERSKIY 1911). Consequently, the maximum extension at the turn of the twentieth century was about 40 km² and the glacier tongue reached a height of about 1,730 m asl. In 1960, the surface area of the glacier was 35.96 km² and the glacier mouth ended at an elevation of 1,970 m asl (TIELIDZE 2017: 41).

Between the years 1960 and 1985, the retreat rate of the glacier tongue was around 17.1 meters per year, with a total of 240 meters (TIELIDZE 2017: 104). In 2014, the surface area of Lekhziri glacier was measured with 23.26 km² and the surface area of Northern Lekhziri glacier was 6.27 km². The glacier mouth of Lekhziri glacier was located at an elevation of 2,320 m asl (TIELIDZE 2015: 41). In 2020, the remaining area of the Lekhziri glaciers is less than 30 km² together.

Accordingly, the glaciated area decreased by 25 percent in the last century. The glacier mouth has shifted upwards by almost 600 meters in altitude. This trend will continue in the coming decades, most probably with accelerating speed of deglaciation. This retreat will successively release loose material which will become available for typical high-mountain mass wasting (such as e.g. debris flows) and further destabilize the lateral valley flanks. A glacier retreat of at least 500 meters in the next 30 years is expected (such as discussed with respect to the Chalaati glacier). As a result, some 100,000 m^3 of material will become available for erosion and remobilization and, as such, contribute to an increase of potential bed load in the channel. This increase in hazard potential can particularly be attributed to external triggering factors, such as periods of heavy rainfall. Moreover, the spontaneous release of subglacial water pockets may also contribute to an increased discharge and, consequently, increased sediment transport rates. While in-situ evidence for the latter was not found during the field survey (an ascent to the glacier was not possible), the interpretation of satellite imagery provided some evidence in particular from the eastern Lekhziri valley glacier (superficial circular cones on the ice body).

Fig. 9-4: Lekhziri glacier, with the glacier mouth from the compound valley-type glacier originating from the two main eastern and western flows. Northern Lekhziri glacier can be seen in the background, and in the foreground the bedrock constriction is located (© Sebastian Resinger)

In 2018, a large amount of dead ice has broken into the channel about 400 meters below the glacier mouth of Lekhziri glacier, leading to excessive discharge. The main reason was due to meteorological triggering leading to intense melting of the dead ice body during the summer months, as reported by the National Environmental Agency of Georgia (Agenda 2018). Such episodes are typical during periods with above-average temperatures and occur specifically during the summer months. These high-discharge events, eventually associated with a blockage of the channel by ice masses, may lead to further mobilisation of bed load and may pose a threat to the HPP infrastructure.

At E318,248, N4,779,038, right below the glacier mouth, a narrow passage composed from bedrock is located in the course of the channel. This constriction acts as a bottleneck by retaining bedload during average discharge conditions, however, it is not sufficiently large in case of high-discharge event. This was confirmed during the field visit as well as by means of analyzing high-resolution satellite imagery (see also Fig. 9-4, foreground).

9.2.3 Murkvami glacier

Only few data is available on the Murkvami glacier (Fig. 9-5). A GIS analysis showed that the current surface extent is around 1.5 km². Between the years 1960 and 1985, the retreat rate was around 21.4 meters per year, which totals 300 meters in 25 years (TIELIDZE 2017: 104). It has to be assumed that the glacier retreat is comparable to the neighboring glaciers Chalaati and Lekhziri. There is evidence that the stabilizing factor of the glacier will decrease and, as a consequence, an increasing amount of loose material becomes available for erosion and remobilization which poses a threat for the HPP constructions in particular if compound events occur. For details about such events please refer to Chapters 3 and 7.

Fig. 9-5: Murkvami glacier (© Sebastian Resinger)

9.2.4 Banguriani glacier

The debris-covered Banguriani glacier is located south of Murkvami glacier in the southern tributary valley of the Murkvami valley and has a current surface extent of about 0.3 km² (Fig. 9-6). Compared to the other glaciers in the Mestiachala valley, the catchment is rather small. It has to be assumed that a further retreat of this glacier will continue and increasing amounts of loose material will become available both, from the debris cover of the ice body as well as from the ground and side moraines. Because the inclination of the tributary valley is rather small, the Banguriani glacier was rated as being not very relevant as a source for future hazard events that may endanger HPP facilities.

Fig. 9-6: Debris-covered Banguriani glacier (© Sebastian Resinger)

9.3 Climate change in the Upper Svaneti region

At Mestia meteorological station (1,440 m asl), the mean annual air temperature was reported with 6 °C between 1961 and 2013 (Tielidze 2015a: 398). As shown in Fig. 9-7 by the red dotted line, there is an upward trend towards warmer annual air temperatures detectable.

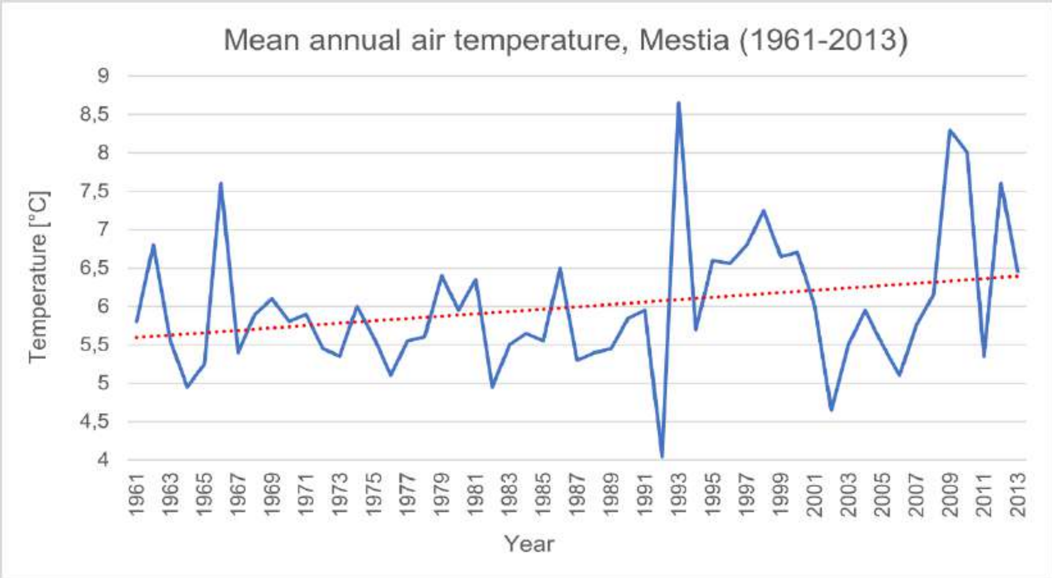

Fig. 9-7: The mean annual air temperature recorded at the Mestia weather station for the period between 1961 and 2013, the red dotted line shows the linear trend (adapted from: TIELIDZE 2015c)

In Fig. 9-8, the mean monthly air temperatures are shown for different periods recorded at the Mestia meteorological station (1,440 m asl). The solid black line depicts the mean monthly air temperature for the period 1961-2013, the red solid line for the period 1961-1986, and the blue solid line for the period 1987-2013. While these lines follow generally a similar pattern it becomes obvious that in August and October values are slightly increasing over time, leading to increased glacier melt (TIELIDZE et al. 2015: 319).

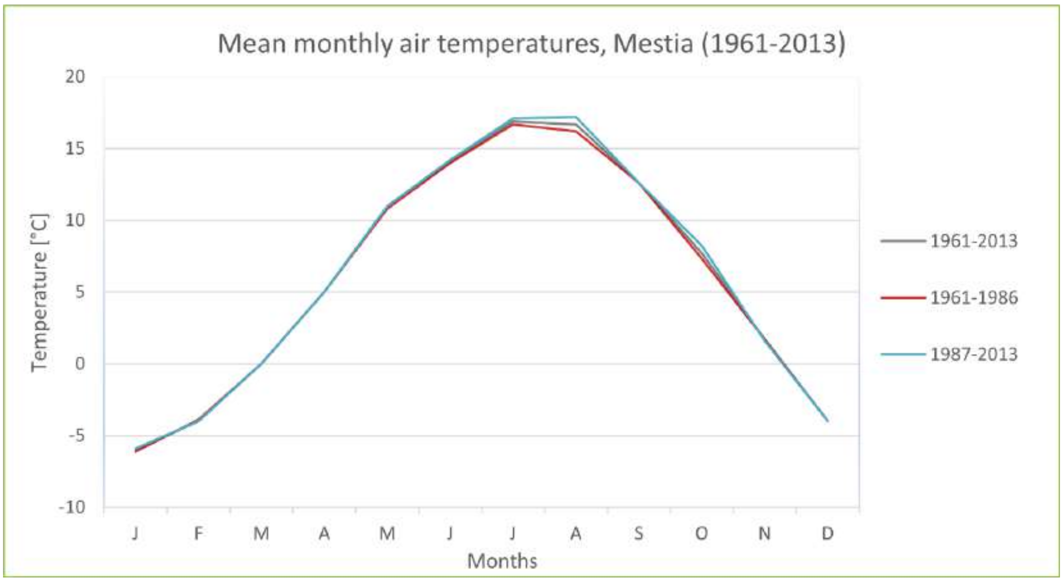

Fig. 9-8: Mean monthly air temperatures in Mestia for the periods 1961-2013, 1961-1986, and 1987-2013. (adapted from: TIELIDZE et al. 2015: 319)

There are only few studies focusing on the effects of climate change in the Svaneti region and in particular on the development of the glaciers in the upcoming decades. It is evident, however, that high-mountain regions will be increasingly affected by global warming (WYMANN VON DACH et al. 2017: 10).

According to UNDP GEORGIA (2015), it is assumed that the annual average temperature in this region will increase by around 4 °C until 2100. This increase is assumed to be 1.2 °C by 2050, and a further 2.8 °C in the years 2050 to 2100. According to climate projections, the increase in average annual temperature will thus be much faster in the second half of the 21st century. The recorded average annual air temperature increased over the last century by about 0.6 °C.

Between 1890 and 1965, the glaciated surface area in the Enguri river basin decreased by 13 % (332 km² to 288 km²). Within this time, the average annual temperature increased by 0.3 °C. A similar relative reduction (288 km² to 251 km²) is reported between 1961 and 2010, with a similar temperature increase. Compared to the data of Lekhziri glacier, which had an area of approximately 40 km² in 1911 and an area of slightly below 30 km² in 2020 (decrease of about 25 %), and to the data of Chalaati Glacier, with an area of 12.2 km² in 1911 and an area of 8.6 km² in 2014 (decrease of about 30 %), the values for the whole Enguri River Basin are quite well represented.

Due to the ongoing global warming, and a delayed reaction of the glaciers to the warming of the last century, the glaciated area is expected to decrease by 57 % by 2100 (from 251 km² to 108 km², UNDP GEORGIA 2015: 37).

9.4 Consequences of deglaciation on slope stability

Due to the constant advance and retreat of the glaciers over the past millennia, the valleys of the Higher Caucasus were steepened and the slopes undercut. Steep high-mountain rock walls such as the 2019 detachment zone in Murkvami valley were formed, which are often characterised by hanging glaciers and firn fields as well as permafrost occurrence (GORBUNOV 1978; LURIE et al. 2019). Due to general warming since the Little Ice Age in the 19th century, the slope stability of such flanks is influenced significantly by a number of processes resulting in increased rockfall activity, which we currently observe (see Chapter 2.1).

1. Unloading of the rock walls: A semi-stable state of the slopes is maintained as long as the glaciers still cover the rock slopes and form a natural abutment. In the 1960s the valley from the middle moraine to the rock wall was still plugged by Murkvami glacier ice. As soon as the glacier retreats the mechanical balance changes and owing to relaxation, a redistribution of strain and stress within the rock starts. New cracks generate and older cracks expand (ERISMANN & ABELE 2001: 125f). This has definitely happened in the Murkvami detachment zone and still continues since only a geologically small time span has passed.

2. Mechanical and thermal erosion: The formerly ice-covered rock is unprotected from mechanical and thermal erosion. The penetration of the freezing front into previously thawed or unfrozen material has the potential to intensify rock destruction through ice formation in cracks and fissures. Additionally, thermal stress (heating/cooling cycles) as well as freeze/thaw cycles increase the local stress concentrations. These permanent fatigue cycles decrease the amount of intact rock bridges, rockfall frequency increases and total rock slope stability decreases. These processes can be observed either close to the Chalaati glacier mouth where large areas are prone to rock and boulder falls (Chapter 5.2.1) or in the Murkvami valley and presumably is one reason for the destabilisation of the rock face that collapsed in July 2019.
3. Another phenomenon linked to glacier retreat and climate change is the retreat of permafrost: Since the Little Ice Age maximum, the lower permafrost limit is estimated to have risen vertically by about 1m/year according to different literature sources for European Alpine regions. Many detachment zones are located at the altitude of the lower boundary of the estimated permafrost distribution, where presumably warm and degrading permafrost exists. In the Greater Caucasus permafrost soils in the form of significant thicknesses (up to 1.5–2.5 m) are observed at altitudes of more than 3,000-3,200 m asl, mainly confined to slopes of northern exposure (LURIE et al. 2019). The 2019 detachment ranges between 3,200 m and 3,500 m and is most likely affected by this process. After KRAUTBLATTER et al. (2012) rock-mechanical properties in degrading permafrost may control early stages of destabilization and become more important for higher normal stress, i.e. higher magnitudes of rock-slope failure.

All these active processes will continue to deteriorate the large-scale rock stability in the detachment zone and in the entire catchment reducing resisting forces in the rock masses and thus leading to real-time failures on different scales.

9.5 Outlook

The glaciers in the catchment of the Mestiachala valley are clearly affected by global warming. In the upcoming decades, the glaciers will continue to retreat, thus releasing more potential bedload for mountain hazard processes, such as debris flows or rock-ice avalanches. The glacier melt is particularly severe in the summer months. The rising average temperatures during this period therefore lead to an increasing glacier retreat in the coming decades. Especially heavy rainfall events as well as spontaneous outbreaks of potential subglacial water pockets might mobilize the loose material and can pose a considerable threat for the HPP infrastructures.

10 Conclusions on the geohazard situation

In the following, the observations described in previous chapters (event analysis) as well as the results of modelling/simulations (impact analysis) are translated into geohazard scenarios for the HPP priorities and civil works. General geohazards for the municipality will also be considered. These results are prerequisites for an exposure and vulnerability analysis of the people, objects and properties at risk, which has to be performed in subsequent steps of risk assessment.

The following map (Fig. 10-1) indicates the rough position of the structural elements at risk.

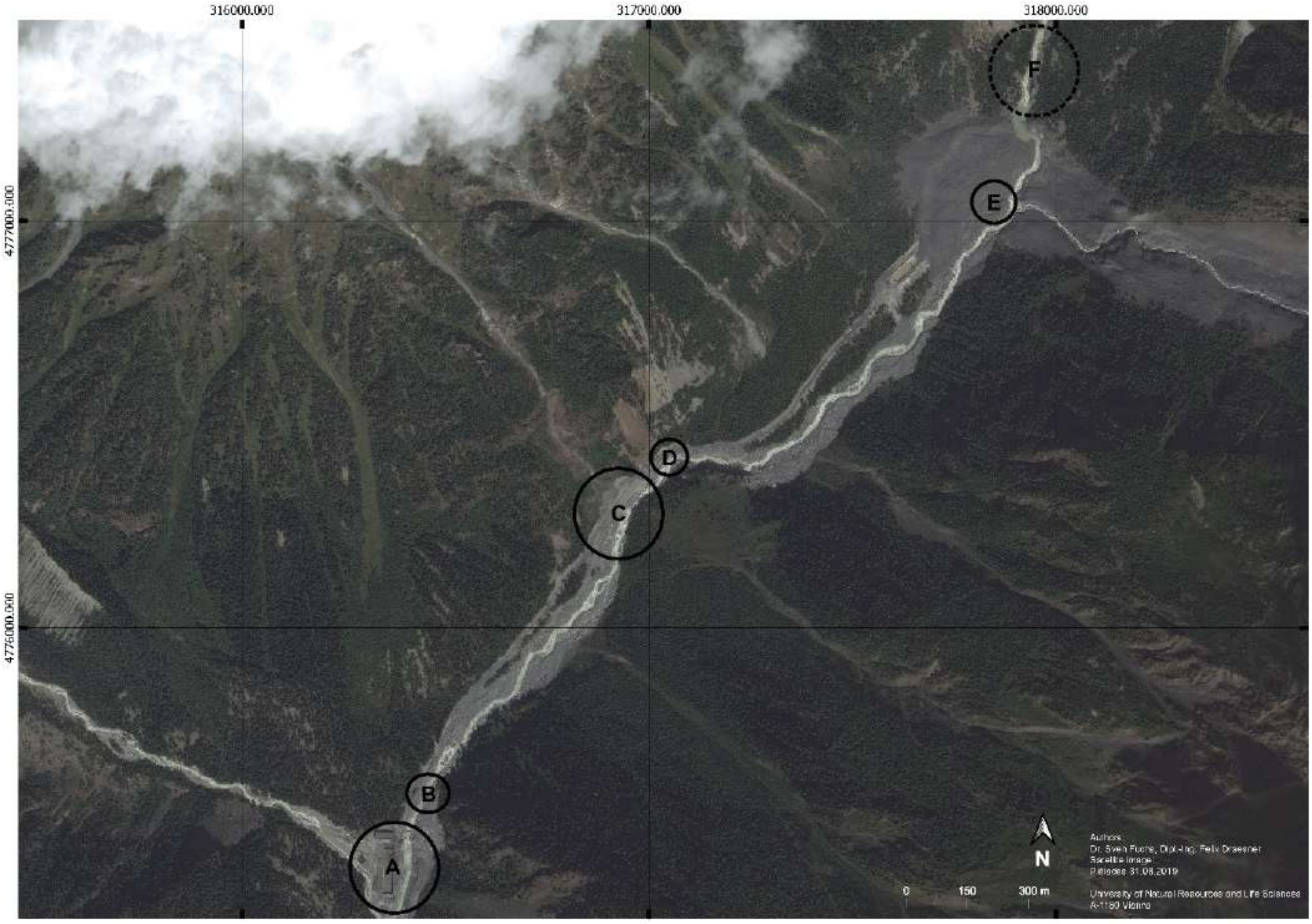

Fig. 10-1: Map of the locations of HPP 1 constructions: A = HPP, B = suspension bridge, C = gallery, D = exposed penstock, E = former intake1, F = estimated position of alternative intake 1.

10.1 Discussion of geohazards for HPP 1 civil works

10.1.1 Intake 1 in original position

Although the 2019 event appears to be extraordinary in magnitude and onset, our investigations clearly have proven that the entire process area is still highly active, and, as such, similar mega-events or cascading events in the tributary may occur in the future (see e.g. the descriptions in Chapters 3, 7 and others). In addition, the remaining deposits of the July 2019 event in the tributary have a considerable potential for remobilization during periods of high discharge and thus, they are expected to impact the original location of Intake 1. The hazard from the tributary remains high and debris flow modelling has revealed flow heights, flow velocities as well as travel times and volumes in ranges that may impact HPP structures.

Furthermore, a certain debris flow activity has to be expected from the Lekhziri catchment (as the August 2018 event). Moreover, episodes of high discharge with sediment transport – eventually with considerable amounts of ice – will lead to higher erosion rates in the 2019 deposits. Results of modelling have proved evidence for a hazard to HPP structures.

Tab 10.1 summarizes the detected geohazards affecting the original position of Intake 1.

Tab. 10-1: Major geohazards affecting the location of Intake 1 (original position).

Hazard type	Event analysis			Impact analysis
	Location / Coverage	**Possible magnitudes /** and/or design event	**Probabilities / Frequencies**	**Specific results/values of the event simulation**
High-magnitude compound event from Tributary Remobilisation of deposited material / cascading process / possibly including rock failure below Murkvami glacier	Tributary along the valley bottom. Mestiachala valley.	Up to several 100,000 m^3; (Magnitude of 2019 event is possible)	EF2: 1 event within 1 - 30 years)	**Simulation performed** (see Chapter 7.3) **Flow velocity** > 13 m/s **Deposition height** ≤ 18 m – 20 m **Flow pressure** > 700 kN/m^2 **Intake 1 fully affected**
"Flash flood" from Lekhziri valley High discharge depending on the overall discharge volume and the amount of floating ice	Lekhziri valley section, potential to mobilize the 2019 deposits at the Tributary mouth.	Up to several 100,000 m^3	EF2: 1 event within 1 - 30 years)	**Simulation performed** (see Chapter 7.4) **Flow velocity** = 12 m/s – 15 m/s **Flow height** = around 1 m **Flow pressure** up to 120 kN/m^2 - 140 kN/m^2 **Intake 1 fully affected**

10.1.2 Alternative Intake 1 in new position

The new position of Intake 1 is envisaged further north of the old location to avoid exposure to geohazards originating in the Tributary / Murkvami valley. While a relocation of Intake 1 increases the safety level for such possible events, other aspects have to be considered:

Debris flow activity is highly critical. As discussed in Chapter 10.1.1 high discharge with sediment transport – eventually with considerable amounts of ice – has to be expected from the Lekhziri catchment (as the August 2018 event), leading as a result also to higher rates of erosion of the 2019 depositions. Our modelling has shown that the new position of intake 1 may be considerably affected, however, technical mitigation seams feasible (see Chapter 12).

In addition, attention has to be given to the debris flow channel depositing material behind the 1850 lateral moraine (also see Chapter 4.2, M-df6). In case of future events overtopping the moraine crest, considerable incision will result and several 1,000 m³ of unconsolidated material is expected to be deposited also in the area foreseen for building the new intake 1. Though currently the moraine crest is still intact and not incised, such a hazard scenario cannot be excluded in the future and must be considered in risk assessment and monitoring, especially since activity data in the release area are missing.

Furthermore, the location will be affected by rockfall, mainly depositing in M-D6 and possibly also in M-D8 which is currently rated as minor hazard (see also Chapter 4.2). Rockfall simulation of M-D6 gives further insight into travel paths (trajectories) and energies (see Chapter 8.1). Mitigation by rockfall fences is feasible.

Moreover, debris flows and snow avalanches with a moderate occurrence probability and a medium magnitude are expected coming from the west side of the valley (M-df5).

Tab 10.2 summarizes the detected geohazards affecting the new planned position of Intake 1.

Tab. 10-2: Geohazards affecting the location of Intake 1 (new position).

Hazard type	Event analysis			Impact analysis
	Location / Coverage	**Possible magnitudes /** and/or design event	**Probabilities / Frequencies**	**Specific results/values of the event simulation**
High-magnitude compound event from Tributary Remobilisation of deposited material / cascading process / possibly including rock failure below Murkvami glacier	Tributary along the valley bottom. Mestiachala valley.	Up to several 100,000 m³; (Magnitude of 2019 event is possible)	EF2: 1 event within 1 - 30 years)	**Simulation performed** (see Chapter 7.3) **Flow velocity** ≤ 6 m/s **Deposition height** ≤ 4 m **Flow pressure** ≤ 60 kN/m² **Impact depending on exact positioning.**
"Flash flood" from Lekhziri valley High discharge depending on the overall discharge volume and the amount of floating ice	Lekhziri valley section, potential to mobilize the 2019 deposits at the Tributary mouth.	Up to several 100,000 m³	EF2: 1 event within 1 - 30 years)	**Simulation performed** (see Chapter 7.4) **Flow velocity** = 8 - 10 m/s **Flow height** = 3.0 – 3.5 m **Flow pressure** = 60 - 70 kN/m² **New Intake 1 fully affected.**
Debris flow	Orographic left 1850 lateral moraine (M-df6)	Several 1,000 m³	Frequencies of 1 - 30 years (EF 2)	(no simulation)
Debris flow	Orographic right (M-df5)	Medium debris flow with several 100 m³	Frequencies of 1 - 10 up to 30 years (EF 2.1, EF 2.2)	**New Intake most likely not affected.**
Snow avalanches	Orographic right (M-df5)	---	annually	(no simulation)
Minor to medium rockfalls	Main hazard from western flank: Deposition area M-D6 (M-D8 at east side regarded as minor hazard)	Up to 10 m³	Several times per year (EF 3)	**simulation performed at M-D6** (design block = 8.5 m³, see Chapter 4.3 and 8.1) **Travel paths can reach new Intake** **Impact energy** = 2,450 kJ up to several 1,000 kJ
		Medium rockfalls with a magnitude of more than 100 m³ possible	Frequencies of 11 - 30 years (EF 2.1)	

10.1.3 Transit area (penstock, gallery)

As seen in the 2019 event, the whole Mestiachala valley between HPP1 and Intake 1 was affected by a high discharge volume of sediment and water. A future event of such type and volume may occur again at any time, with an origin either in the Lekhziri valley (debris flows, flash floods) or in the Tributary/Murkvami valley (landslides, cascading events).

Additionally, the deposits of the 2019 event in the Murkvami valley and the deposits at the Tributary mouth are prone to remobilization in case of high discharge. As a result, lateral erosion is expected to endanger especially the penstock.

The results of our impact analysis (debris flow modelling) indicated a moderate hazard to the penstock and the gallery, which may be mitigated by suitable permanent measures (see Chapter 12).

Considerable rockfall hazard areas are located along the western slopes between the HPP1 and Intake 1, with special focus on M-D3 - M-D5 around the gallery and further north. In M-D4 numerous fresh boulders with a volume around 5 m³ were located right next to the construction road. Other deposition areas are currently less active, such as M-D1. The rockfall volumes differ significantly (see Chapter 4 and 8.1).

Furthermore, instable rock towers of volumes between 2,500 m³ and 12,000 m³ (potential large to very large rockfalls) were explored about 450 m above the gallery (M-R3b and M-R5b), which need to be considered in risk assessment, planning and monitoring.

Debris flow activity originating from gullies next to the penstock are only of minor importance for delivering considerable amounts of material to the valley bottom and consequently to the Mestiachala river. Hence, even if activity is rated as high, effects are negligible.

Tab. 10.3 summarizes the detected geohazards affecting the penstock and the gallery.

Tab. 10-3: Geohazards affecting the penstock and the gallery.

Hazard type	Event analysis			Impact analysis
	Location / Coverage	**Possible magnitudes /** and/or design event	**Probabilities / Frequencies**	**Specific results/values of the event simulation**
High-magnitude compound event from Tributary (in combination with high discharge from Lekhziri valley) Remobilisation of deposited material / cascading process / possibly including rock failure below Murkvami glacier	Tributary along the valley bottom. Mestiachala valley.	Up to several 100,000 m³ (Magnitude of 2019 event is possible)	EF2: 1 event within 1 - 30 years)	**Simulation performed** (see Chapter 7) **Flow velocity** = 11 - 13 m/s **Flow height** = 2.0 - 3.5 m **Flow pressure** = 110 - 135 kN/m²
"Flash flood" from Lekhziri valley High discharge depending on the overall discharge volume and the amount of floating ice	Lekhziri valley section, potential to mobilize the 2019 deposits at the Tributary mouth.	Up to several 100,000 m³	EF2: 1 event within 1 - 30 years)	**Simulation performed** (see Chapter 7.4) **Flow velocity** = 11 - 13 m/s **Flow height** = 2.0 - 3.5 m **Flow pressure** = 110 - 135 kN/m²
Debris flow	In association with avalanche trenches (M-df1 and M-df7-9)	Several 100 m³	Frequencies of 1 - 30 years (EF 2)	(no simulation)
Snow avalanches	Gallery (M-D3 / M-D5a)	---	annually	(no simulation)
Minor to medium rockfalls	Section between gallery and Intake 1 (M-D3 to M-D5a)	Smaller boulders up to 2,5 m³	At least 10 events per year (EF 4)	**simulation performed at M-D4** (design block = 5.4 m³, see Chapter 4.3 and 8.1) **Travel paths can reach gallery and penstock.** **Impact energy** = 1,050 - 2,664 kJ
		Up to 10 m³ (see design block, Chapter 4.3)	Several times per year (EF 3)	
		Medium rockfalls with a magnitude of up to 100 m³ possible	Once in 1 - 30 years (EF2)	
Medium to large rockfalls	Section between gallery and Intake 1 (M-D3 and M-D5b) Travel path can reach gallery and penstock.	Instable rock towers of volumes between 2,500 m³ and 12,000 m³	Frequencies of 11 - 30 years (EF 2.1) are expected	**Impact on top of the gallery (M-D2-M-D3) / Impact of single rock blocks on construction road in M-D5** (assumption based on event analysis, no simulation)

10.1.4 Powerhouse HPP1

The powerhouse and related structures can be affected by high-magnitude debris flow and flash flood-like events originating in Mestiachala, Lekhziri and Murkvami valleys. An event similar to the 2019 event may even be expected during periods of high discharge.

Our impact analysis (modelling) provided evidence for considerable impacts on the structures adjacent the channel bank and on the weir, both in dependence of the flow behavior and the lateral accumulation in the area used as a parking lot (orographic left side). An overtopping with direct impact on the power house has been rated as possible but not highly-probable, depending on the performance of existing block walls along the right channel bank, for details see Chapter 7.

In addition, geohazards from Chalaati valley have to be considered. Two major processes directly or indirectly endangering the area of the powerhouse include firstly rockfall from the valley margins, producing considerable amounts of loose debris, and secondly, remobilisation of already deposited debris flow material and/or new debris flows from the channel on the left valley margin. Due to the expectable retreat of the glacier tongue additional material currently blocked by the ice masses will become available for mobilisation. Such processes can develop into high-magnitude events and directly affect the HPP. These scenarios, either originating from the right or left valley flank, or a combination from both, have so far not been evaluated using a process model since data on the hydrologic situation in the valley are required. If such events are of smaller magnitude, material may be re-deposited along the relatively flat valley bottom (low inclination), however, in-depth studies are essential if more quantitative predictions are required.

Tab. 10.4 summarizes the detected geohazards affecting the powerhouse and related structures.

Tab. 10-4: Geohazards originating affecting the location of the Powerhouse and related structures.

Hazard type	Event analysis			Impact analysis
	Location / Coverage	**Possible magnitudes /** and/or design event	**Probabilities / Frequencies**	**Specific results/values of the event simulation**
High-magnitude compound event from Tributary (in combination with high discharge from Lekhziri valley) Remobilisation of deposited material / cascading process / possibly including rock failure below Murkvami glacier	Tributary. Mestiachala valley. Powerhouse possibly in the reach	Up to several 100,000 m³ (Magnitude of 2019 event is possible)	EF2: 1 event within 1 - 30 years)	**Simulation performed** (see Chapter 7) **Flow velocity** = 8 - 11 m/s **Flow height** = 4.0 – 7.0 m **Flow pressure** = 100 - 250 kN/m²
"Flash flood" from Lekhziri valley High discharge depending on the overall discharge volume and the amount of floating ice	Lekhziri valley section, potential to mobilize the 2019 deposits at the Tributary mouth. Powerhouse possibly in the reach	Up to several 100,000 m³	EF2: 1 event within 1 - 30 years)	**Simulation performed** (see Chapter 7.4) **Flow velocity** = 8 - 11 m/s **Flow height** = 4.0 – 7.0 m **Flow pressure** = 100 - 250 kN/m²
Debris flow	Chalaati valley, around the present glacier terminus (north of glacier mouth)	Volumes of several 100,000 m³ if deposited volumes become mobilized due to the glacier retreat and subglacial water break out	Expected frequencies within 11 - 30 years (EF 2.1)	**Powerhouse most likely affected / in the reach** (no simulation)
Rockfall of different magnitude	Chalaati valley flanks, around the present position of the glacier terminus and others.	Supplementary material involved in debris flow processes	Activity within a range of 1 - 10 years (EF 2.2), locally higher (EF 3)	**Powerhouse most likely not affected / out of reach**

10.2 Significance of geohazards for Mestia municipality

The investigated catchment of the Mestiachala valley is a highly attractive and frequently visited recreational area. The geohazard situation is thus also relevant for regional authorities (Mestia municipality) and the tourism branch and requires consideration in the context of municipal risk assessment. In summary, we differentiate the following scenarios and consequences:

Geohazards from "Group 1 events": These geohazards comprise rockfalls, local rock and snow avalanches or debris flows from lateral gullies which may affect hiking paths. We want to focus on the following locations.

- Hiking path along HPP construction road in Mestiachala valley west flank. These are passing rockfall-prone runout zones (M-D3, M-D4, M-D5 and M-D6),
- Hiking paths in Mestiachala valley east flank. Here, rockfall and other mass movements may occur. Rockfall activity is lower than at the western rim, e.g. in M-D9 around the car park and the adjoining hiking path. Additionally, the lateral gullies show snow avalanche activity.
- Hiking paths in Chalaati valley north flank are repeatedly affected by falling rock and boulders of considerable block size; several fresh blocks were detected. The hazard arising from falling blocks originates in the steep and exposed 1850 moraine and is regarded as high.

Geohazards from "Group 2 events": Events of the high-magnitude mass wasting category can be initiated spontaneously without prior notice. Such intense events can lead to serious destruction of infrastructure such as the suspension bridge or subjacent fresh water pipe. Such damage is likely to occur, due to the spontaneous onset of such processes also a concept for warning or evacuation of the valley should be envisaged.

11 Monitoring

This report clearly has shown that the Mestiachala catchment is an area where many different geological, morphological and glaciological processes combined with meteorological events can create a wide variation of natural hazards with different magnitudes and occurrence intervals.

We suggest further instrumental monitoring of these processes for following reasons:

- To verify and validate the findings of our short field trip and the remote sensing
- To learn about quality and quantity of active regions and active processes
- Instrumentation for Monitoring can be the nucleus for a future warning system
- Can help determining thresholds for a future warning system

These facts and reasons make it challenging to give a simple one-stop-shop solution for monitoring and/or early warning applications. The crucial questions, which need to be defined in a first step, include:

What is the function or purpose of the system?	→	E.g., data collection or detection of an event
Which parameters and values should be determined?	→	E.g., movements or gauge level
Where should the system be placed?	→	E.g., detachment or transit zone
What actions are intended?	→	E.g., warning , alarm or restricted access
Who will operate and maintain the system?	→	E.g., locally or remote controlled

In order to provide answers to these important questions and to evaluate possibilities it is required to discuss with all relevant stakeholders. Therefore, the question cannot be fully answered by our team and, thus, this chapter focuses on general concepts and ideas, which could be a potential solution for long-term monitoring of the entire catchment.

11.1 Technical installations - State of the art: InSAR

The tributary valley is a highly active landslide zone which has to be acknowledged also during reconstruction works, probable future scientific campaigns and beyond. In order to deal with the "Group 2 events", which cannot be prevented by technical (passive) protection structures, a monitoring system is recommended.

Options of warning systems in the Tributary valley below Murkvami glacier

In a conference on 26 March 2020, the current high-risk situation in the detachment area of 2019 as well as technical warning measures were evaluated and discussed with support of

Hydrodiagnostics. Combined with our expert knowledge from BOKU, TRUMER and BBB, we have to distinguish different approaches, regarding safety during construction works and safety of daily operational business in the context of risk acceptance.

The following technical measures are available, however, they are comparably cost-extensive and design and on-site installation are challenging. In discussion are:

- Ground-based InSAR Survey (radar survey)
- Satellite-based InSAR survey (radar survey)
- Lidar survey (ground-based or drone-based laser scanning survey of detachment areas)

These systems have different accuracies and applicability as well as varying pros and cons, which have been summarized by Hydrodiagnostics separately.

Proposed system:

Ground-based InSAR. (= recommendation of our group, other systems are also possible as discussed in earlier meetings).

Proposed locations and expedition

In Attachment 10 we propose two different positions for ground-based InSAR. For both, we regard helicopter support as essential. The northern spot is very questionable due to exposure and difficult access, landing a helicopter might be challenging. The southern spot appears more suitable. Experienced mountaineers will be able to cross Banguriani glacier and access the spot by foot, but from our experience on site we strongly recommend helicopter flight since it saves time and allows transport of equipment.

Keep in mind that also other areas are susceptible to geohazards and general awareness has to be kept up.

11.2 Sentry monitoring and alarm system

The most reliable and hence favourable state-of-the-art automatic warning system may be unfeasible due to costs and timing. Therefore, a suitable alternative may be a survey powered by a “simple” sentry system. This system can be implemented quick and easy and can safeguard construction works, employees working in hazard zones, and daily operational business.

11.2.1 Concept

The aim of the proposed sentry monitoring and alarm system is to permanently observe the defined hazard zone shown in Fig. 11-1 and Fig. 11-2 in the tributary valley by a security guard. The total detachments of July 2019 and subsequently are shown in Attachment 10 according to our most recent evaluation. In case of an observed large-scale event the security guard will be responsible to transmit a warning to the chief security officer of the construction site with a portable radio device. The chief security officer will be responsible to activate the warning and evacuation protocol. In order to ensure an effective warning of all construction workers, internal and external staff that is on site will require a safety briefing. We recommend installing an acoustic warning system such as a siren at each construction site (powerhouse and intake) which can be activated and controlled by the chief security officer. In addition, an evacuation route to a higher-elevated place needs to be defined and communicated during the safety briefing. Furthermore, the chief security officer should inform the local authority of Mestia about the observed event immediately.

The hazardous areas which need to be monitored are shown in Fig. 11-2. The three main release areas (T-R1-3) include those detachment areas, where future events have to be expected to be released from the rock cliff. The red arrows are marking the transit zone where most likely individual rockfall events will be visible and can be noticed before an event of larger magnitude will occur. Therefore, the hazard areas 1-3 have to be observed with a telescope or binoculars from the sentry point during the course of the day. In addition, smaller events such as individual rocks being released or dust clouds, which appear in the hazard zone or in other sections of the tributary valley, need to be documented in the event documentation sheet proposed in the Attachment 10.

Fig. 11-1: Image showing an overview of the overall hazard zone for observation. See also Fig. 8-15 for entire release zone overview.

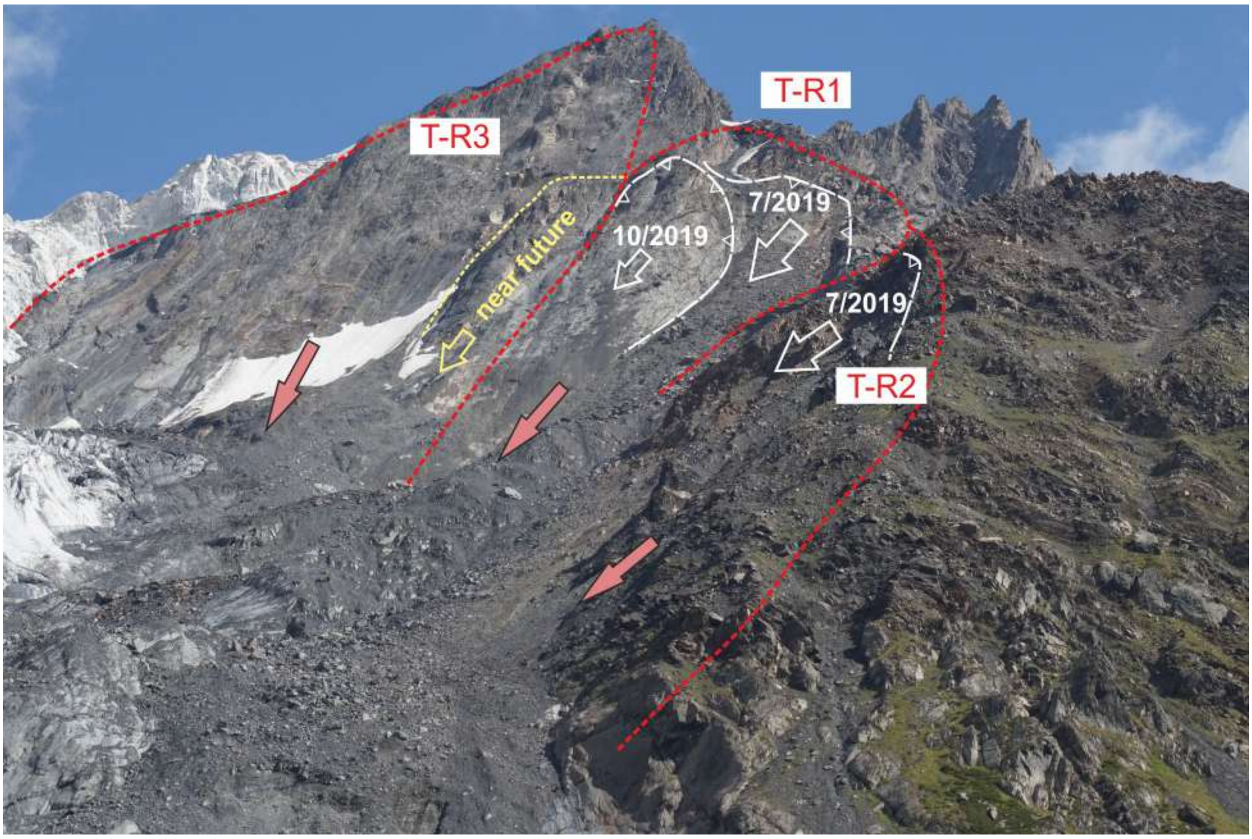

Fig. 11-2: Image showing three main release (detachment) areas (T-R1, T-R2, T-R3) where future events are to be expected. The photo was taken in August 2019. We have indicated the releases of July 2019. The younger detachment of October 2019 is also shown as well as the potential next medium-large event (up to 10.000s m^3).

11.2.2 Sentry position and operation

The basic idea of the concept is to install a permanent sentry in the lower section of the tributary valley at the location shown in Fig. 11-3. From this position the hazard zone is visible and in case of an event the sentry point location can be considered as a safe place based on the visible evidences from the 2019 event. A trained and instructed person should be selected to serve the sentry spot during the daily operation time of the construction site in the Mestiachala valley or as long as local or international staff is operating somewhere in between the powerhouse 1 and the hazard zone.

Fig. 11-3: Image showing proposed location of sentry spot (yellow triangle).

11.2.3 Lead time

As a part of our contract for “Field research, hazard analysis and mitigation concept for HPP Mestiachala” the BOKU University in Vienna has conducted a computer simulation of the 2019 event (see Chapter 7). We consider this event as our design event for the monitoring and warning system which leads us to the following results which are back-calculated form the 2019 event.

- The flow velocity reaching values exceeding v = 27 m/s, the average velocity is approx. 60 km/h
- The volume of the rock mass was about 1,600,000 m^3
- The transit time from detachment down to the proposed sentry point was t = 200 s
- The transit time from detachment to the intake was t = 240 s

The simulation was performed based on a 12.5 m digital terrain model.

Based on the results of the simulation it becomes obvious that the lead time is very short. If we estimate that the security guard will notice the event within the first 30 seconds from detachment and places the warning to the chief security officer, an effective warning and evacuation time of 2 - 3 minutes for the intake 1 location/power house will remain.

In Attachment 10 we have proposed a sheet for documentation of events by the sentry guard.

Additionally, also other observations should be recorded, if possible, e.g. rockfall from neighbouring cliffs along the Tributary valley or the opposite side from Mestiachala valley.

An alarm system like the one proposed here is highly recommended to enhance safety for reconstruction!

11.3 Annual inspections inspired by the ONR 24810 guideline

The field surveys performed in 2019 and 2020 clearly unveiled the actual situation in the catchment. However, it can only represent a snapshot of the current hazards. Obviously, the entire catchment is subjected to high-dynamic changes which can only be detected by continuous monitoring. Therefore, we propose in addition to a sentry alarm system an annual monitoring procedure of the catchment, which is also foreseen in the Austrian Standard ONR 24810. The results obtained during such annual observation can be compared to a very good baseline from the 2019 and 2020 field campaigns.

11.3.1 Some examples for remotely sensed change detection

Satellite remote sensing techniques: On satellite images acquired prior the 2019 event, several small events have been detected by our experts. These events may have been recognized as signs for the occurrence of a larger event because it has often been observed that increasing activity of minor events can indicate the advance of a larger mass wasting processes in hazard-prone detachment or release areas.

In the same way, new detachment zones or small to medium rockfalls and debris flows detected during the annual inspection will provide evidence for a larger event developing. These changes in the catchment could be monitored by a annually-performed remote study of satellite imagery.

In a report in 2020, Hydrodiagnostics has presented similar technical solutions such as satellite based InSAR (radar) analysis (see also Chapter 11.1). Other satellite remote sensing techniques are also possible.

Specific areas requiring high-resolution change detection by updated satellite imagery include:

- Detachment zone below Murkvami glacier (T-R1 – T-R6)
- Lekhziri glacier front
- Sediment-filled valley in the catchment of M-df6 (hazard of larger debris flows)
- Chalaati valley and glacier front
- Mestiachala valley west flank (Dalrakora massif) including M-R3b, M-R5b, M-R5a and M-R6.

UAS photogrammetry: Change detection of specific hazard areas should be recorded applying UAS photogrammetry. Apart from simple individual inspection, the drone footage (4k video) can be transformed into a 3D photogrammetric model of the rock detachments. It should be linked to geodetic survey data, increasing precision. This model supports analysis of geological features like joint sets, dips, and others and thus the determination of block sizes. By employing periodical drone survey (e.g. annual), activity of the detachments can be figured out and zones with high deformation can be detected and thus hazard estimation can be updated and warnings can be given.

Target areas for such UAS survey are e.g. the release zones in T-R3b and T-Ra and 5b. The survey can be carried out in the course of yearly in-situ field inspections (see 11.3.2).

11.3.2 Annual in-situ field observation

In addition to the annually-performed study based on remote sensing we propose an annual field observation by a group of experts. This group should comprise qualified experts who have local knowledge and insights in the event history of the entire catchment (at least a geologist and a geomorphologist).

12 Discussion of feasibility and efficiency of mitigation measures

In this chapter, we provide principle ideas for risk reduction considering the new results of this study. Basically, the hazard potential and thus risks for HPP structures are to be considered as high and events of different magnitude are expected to occur during the coming years and decades. Our modelling and simulation results highlight possible impacts of different event types, which facilitates risk assessment, decision-taking and feasibility studies of technical mitigation concepts in the course of risk management.

Remark: Risk reduction planning, and in particular the implementation of different technical protection strategies, however, will require further in-depth studies on hazard magnitudes and intensities different HPP facilities (such as intake 1 (new position), avalanche gallery, HPP1 power plant) are exposed to under multiple hazard scenarios. Given the data available as well as restrictions on results discussed in the previous chapters, uncertainties on the effects of different hazard scenarios remain. Therefore, our recommendations cannot be seen as precise instructions of how to protect individual elements at risk nor can they provide the fundamentals of construction design for individual protective structures. In contrast, results support decision-making on possibilities (and necessities) of different mitigation concepts, and are therefore a starting point for in-depth studies on mitigation design.

12.1 Technical mitigation measures and concepts

Comprehensive mitigation planning starts with the choice of optimum locations, i.e. building out of reach of geohazards as far as possible (choice of new intake position), and a continuous "monitoring" for updating geohazard knowledge and for warning of future events (see Chapter 11). Structural measures finally, serve for prevention of mass movements and / or the reduction of impact. The following measures should be taken into account for the HPP1 structures.

12.1.1 Rockfall protection

As described in Chapter 8 several areas prone to rockfall depositions are a permanent hazard to the power plant infrastructure and the operating staff. In particular, these areas include M-D3, M-D4 as well as M-D6. From field investigations and data collection it has to be concluded that rockfall occurs frequently in these areas (EF3, according to ONR 24810). With these data acquired during field investigations rockfall simulations were performed which underline the need for action. Furthermore, rockfall simulation visualises the effectiveness of a rockfall barrier. Nevertheless, any simulation can only represent a simplified model of the reality and inaccuracies occur to a lesser or greater extent. As discussed earlier in this report, the underlying coarse digital elevation model lead to some uncertainties and hence results have to be interpreted with caution.

During the construction phase of the new intake 1 structure employees are endangered by rockfall from M-D6. Therefore, it is not only essential to protect the intake structure itself but also to protect employees working in exposed areas. Implementing a rockfall barrier at M-D6 has to be completed before constructing the new intake 1 structure. Examples for technical rockfall protection fences are shown in Fig. 12-1 and Fig. 12-2. In case of a rockfall event hitting either the new intake 1 structure or the penstock the operation of the power plant is no longer ensured. Hence, a failure of the protection structure is associated with considerable economic loss. According to the ONR 24810 these "high economic consequences" require the classification as consequence class 3 (severe, CC3). For the proof of concept with CC3, a safety factor of 1.15 for both load and resistance has to be applied. Following this concept we propose a technical rockfall protection fence with at least 2,000 kJ resistance for both hazard areas (for example "TSV-2000 ZD H4", see Fig. 12-3 and Fig. 12-4). The system should use steel components and steel wire ropes made from high-quality materials, following a stringent quality assurance program. The structure needs to be tested and certified as per ETAG 27 according to the European Technical Assessment ETA-14/0357. Some characteristic values of an appropriate system are summarized in Tab. 12-1. The exact location, the operating height as well as anchoring has to be determined in a further step. At location M-D6 an additional load from avalanche snow has to be considered. During winter the barrier will be backfilled with snow which exerts pressure to the posts, causes an activation of the break elements, and pre-elongates the deformable net, if not correctly dimensioned. Hence, it is crucial for durability reasons to take this load into account. Some characteristic values of an appropriate system regarding snow load are summarized in Tab. 12-2.

Fig. 12-1: Technical rockfall protection fence (2,000 kJ) on a dam embankment

Fig. 12-2: Technical rockfall protection fence (2,000 kJ) on a natural slope

Tab. 12-1: Characteristic values of TSV-2000 ZD H4.

Model	TSV-2000-ZD h4
Style	Hinged System
Energy class	5
Maximum Energy Level (Certified)	2,000 kJ
Approved Heights	4.0 - 5.0 m
Post spacing	max. 10 m
Certification	ETAG 27 Certified
Maximal Elongation	5.83 m
Residual Height Class	A (> 50 %)

Tab. 12-2: Characteristic values of TSV-2000 ZD H4 plus additional snow load dimensioning.

Model	TSV-2000-ZD h4+S
Style	Hinged System
Energy class	5
Maximum Energy Level (Certified)	2,000 kJ
Approved Heights	4.0 - 5.0 m
Post spacing	max. 8 m
Certification	ETAG 27 Certified
Maximal Elongation	5.83 m
Residual Height Class	A (> 50 %)

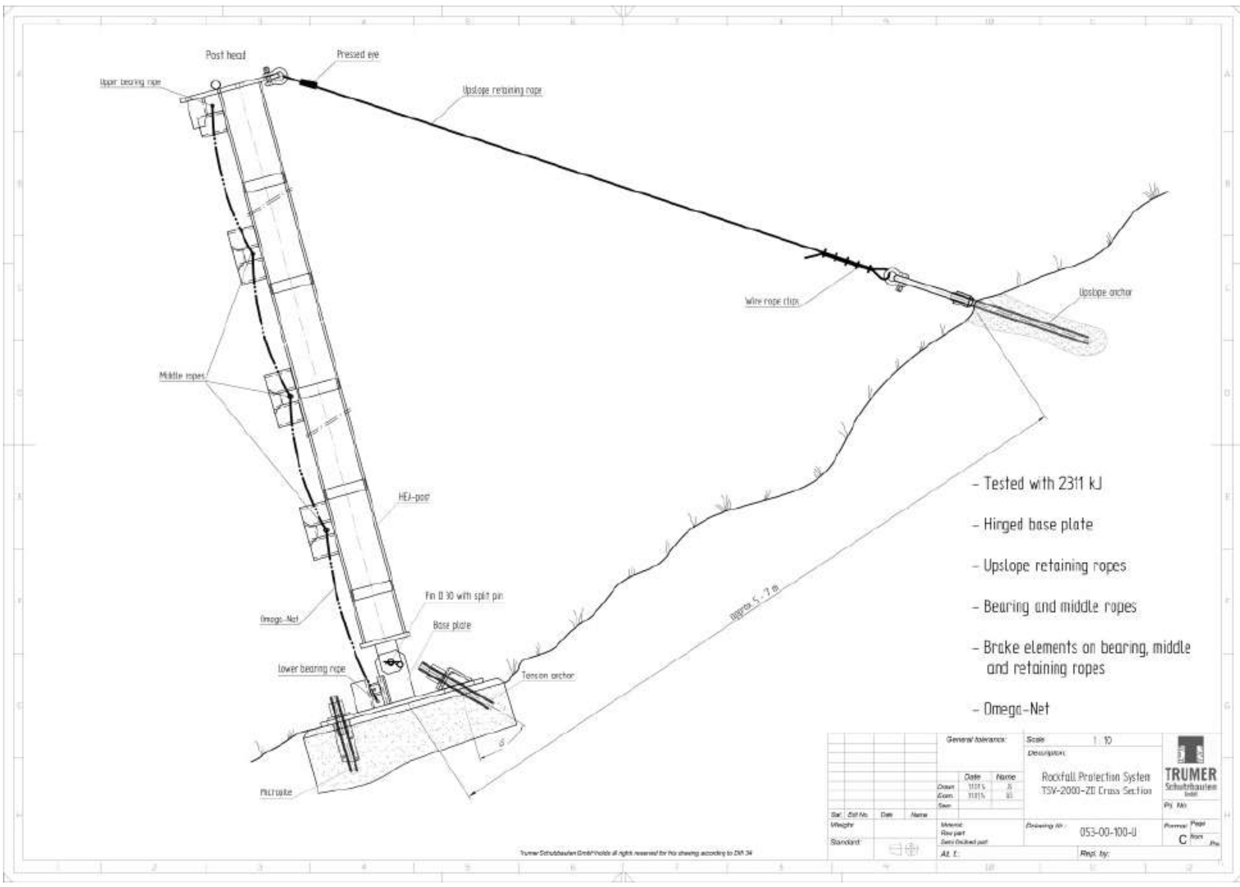

Fig. 12-3: Cross section of TSV-2000 ZD H4

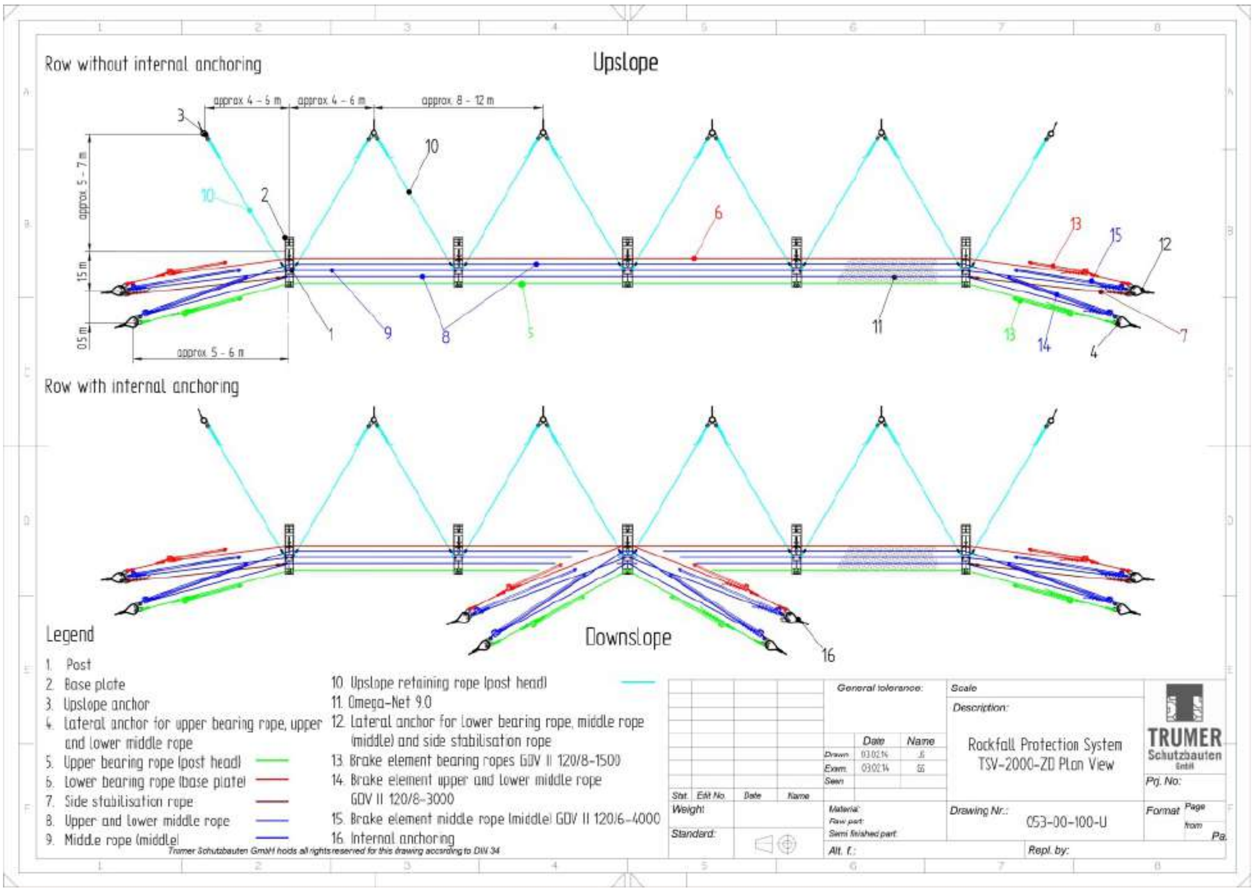

Fig. 12-4: Plan view of TSV-2000 ZD H4

12.1.2 Protection against large or very large rockfalls

Rockfall prone areas that directly affect HPP 1 are located at the western rim of Mestiachala valley (e.g. M-R3b, M-R5a and 5b, M-R6). The release of minor or medium events and its possible countermeasures were discussed in the previous chapters. However, also larger failures (large to very large rockfalls or rock slides) have to be considered according to our hazard assessment results. These were attributed with an 1-in-30-year likelihood. The impact is described in Chapter 8.2.2.2.

The release areas in M-R3b and M-R5b are quite large and located high above the valley ground. Technical support measures are highly difficult in execution, however, the hazard needs to be addressed. As minimum requirement, the following combination of measures should be taken into consideration:

Monitoring / survey of all critical detachments (see Chapter 11.3):

- Continuous satellite remote sensing for change detection of activity and new instabilities.
- UAS photogrammetry of detachments and, if possible, installation of automatic crackmeters.

Possible structural protection measures:

- Impact of large rockfall in M-D3 above gallery (release from M-R3b): Protection of gallery by **protective earth cover**, which reduces impact energy of falling rock masses (damping). The potential damage on the gallery can be reduced.
- Impact of large rockfall in M-D5 (release from M-R5a and 5b): The runout zone is a forested debris cone, which will trap a portion of the disintegrating falling and sliding rock masses. Safety can be increased by **fence installations** similar to M-D4, which requires modelling of the rock mass behaviour.

12.1.3 Debris flow and flash flood protection

As shown in Chapter 7 of this report, effects of debris flows and related processes for the infrastructure of HPP1 are rated as considerable. In the following, the focus is on the facilities located along the Mestiachala valley.

The new intake 1 requires not only a well-chosen position regarding run-out zones of rockfalls or debris flows, but also a sustainable design concept. Systems like a **Tyrolean weir**-type intake should be taken into consideration. In addition, **bed load safety nets** can increase safety of the intake. Possible locations, however, are rare with the exception of the narrow Lekhziri valley section to the north.

The penstock is highly-exposed to lateral bank erosion north of the avalanche gallery, and should be protected by either a **longitudinal block wall** (comparable to the one already constructed along the gallery) or even a **reinforced concrete wall** which is additionally armed in areas of potential high impact forces, both adjusted to the impact forces and flow heights that may occur. In any case, further incision of the channel has to be prevented as this destabilizes the lateral bank, which will lead to a further erosion of the penstock.

Similarly, the flow section along the gallery has to be protected so that scouring of the foundation of the gallery is prevented. During the field survey, the existing longitudinal block wall has been assessed superficially. Suggested mitigation includes has to be focused on a re-evaluation of the stability of this structure given the estimated impact (pressure, flow height and velocity) of the flow. Moreover, the channel bed should be consolidated so that further lateral incision, eventually leading to a destabilization of the lateral block wall, can be prevented. Suggested measures include a series of **groundsills** and additional channel stabilization to create fixed points in the longitudinal profile by either natural blocks of suitable size (adjusted to flow velocity and erosion potential) or even concrete.

Similarly, the lower channel sections between the suspension bridge and the weir next to HPP1 have to be evaluated with respect to possible destabilization of the longitudinal block wall, as modelling results indicated considerable flow heights, flow velocities and also pressures. Depending on incision of the channel or lateral channel lifting as a result of decreasing slope, effects may become an issue for the power house. The weir and the intake to the desander will most probably be destroyed as they cannot be protected from the impact of a major debris flow event. Sediment retention by **retention basins** or sediment dosing by **check dams** may be a possibility to reduce these impacts, and areas suitable for such constructions are located in the channel section between the old intake 1 and the suspension bridge.

From Chalaati valley possible hazards relevant for the power house and the Chalaati intake are related to low-frequency but high-magnitude debris flow events. Generally, it is recommended to **change the river course** between the Chalaati intake and the confluence with the Mestiachala river so that an obtuse angle of the main current line will be achieved and the lateral left bank (protected by a block wall) will become hydraulically more balanced.

13 Outlook

As outlined above, multiple geohazards are present in the investigated area and the risk level is considerably high. The principle feasibility of mitigation and thus a rehabilitation of the HPP depends on risk evaluation and finally on risk acceptance of GRPC, investors and authorities.

In case of a decision for rehabilitation of HPP 1, comprehensive risk assessment is indispensable to prove the investment volume for safety measures. A preliminary geoscientific database is given in this report, in which we also display possible technical mitigation measures which are expected to substantially increase the safety level of structures and operation of the HPP and personnel. These include:

- Rockfall protection against high-frequent “Group 1 events” (Chapter 12.1.1)
- Erosion protection against debris flow / flash flood “Group 2 events” (Chapter 12.1.3)
- Requirements for monitoring and regular controls as well as additional exploration (e.g. Chapter 11)
- Recommendations for safety at works during reconstruction by sentry monitoring

In order to gain more regional detailed and validated data a continuous monitoring program is essential. This will support an economical planning of protection measures, but will be essential for designing and running (early) warning systems as well.

Nevertheless, the risk level will remain high since a recurrence of mega-events such as the 2019 event is possible, for which we indicated a 30 year return period as well as possible physical impact (flow heights etc.). Also other sources of “Group 2 events” not yet detectable may occur, e.g. the development of new active debris flow channels. For this reason regular inspection and high-resolution monitoring are prerequisites for risk detection and reduction. Minor events will affect the HPP, but can be mitigated quite well (e.g. by rockfall fences). Possible damage to the HPP structures during a “Group 2 event” can be lessened with the above measures, but are not entirely avoided.

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EOTA (2008): Guideline for European technical approval of falling rock protection kits (ETAG 27), February 2008.

ONR 24810:2017-02 Technical protection against rockfall – Terms and definitions, effects of actions, design, monitoring and maintenance.- Austrian Standards Institute, Wien.

Dr. Sven Fuchs
University of Natural Resources and Life Sciences, Vienna

Markus Haidn
Trumer Schutzbauten GmbH

Christoph Wichert
Baugeologisches Büro Bauer GmbH

ppa. Dr. Peter Neumann
Baugeologisches Büro Bauer GmbH

<u>Contributors and co-authors:</u>

Felix Draesner (BOKU Vienna)

Stefan Strelow (TUM)

Alexander Sauer (TUM)

Sebastian Averdunk (TRUMER)

HPP Mestiachala Priority Projects

Final report on field research and geohazard assessment 2020

Attachments

Attachment 1	Geological base map, Scale 1 : 25,000
Attachment 2	Detachment zone base map, Scale 1 : 25,000
Attachment 3	Geomorphological map – Sheet Chalaati, Scale 1 : 12,000
Attachment 4	Geomorphological map – Sheet Mestiachala, Scale 1 :12,000
Attachment 5	Geomorphological map – Sheet Tributary, Scale 1 : 12,000
Attachment 6	Geohazard maps for Mestiachala HPP1 – rockfalls, scale 1 : 12,500
Attachment 7	Geohazard maps for Mestiachala HPP1 – flow processes, scale 1 : 12,500
Attachment 8	Debris flow modelling maps
Attachment 9	Electrical Resistivity Tomography (ERT)
Attachment 10	Monitoring of the July 2019 detachment area

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Attachment 1 Geological base map, Scale = 1 : 25,000

Geological base map, HPP Mestiachala 1 - 1:25,000

- 2019 compound event deposit
- Glacier
- Debris covered glacier

Quaternary Sediments

Quaternary
- Polygenetic valley fill
- Creeping landslide
- Slope debris
- Holocene moraine / Kame terrace

Mestia-Tianeti-Zone

Lower Jurassic
- Jurassic Quarzit
- Jurassic Shale, grey
- Jurassic Shale, red
- Jurassic Shale, dark

Main Caucasus Thrust
- Thrust-related shear zone

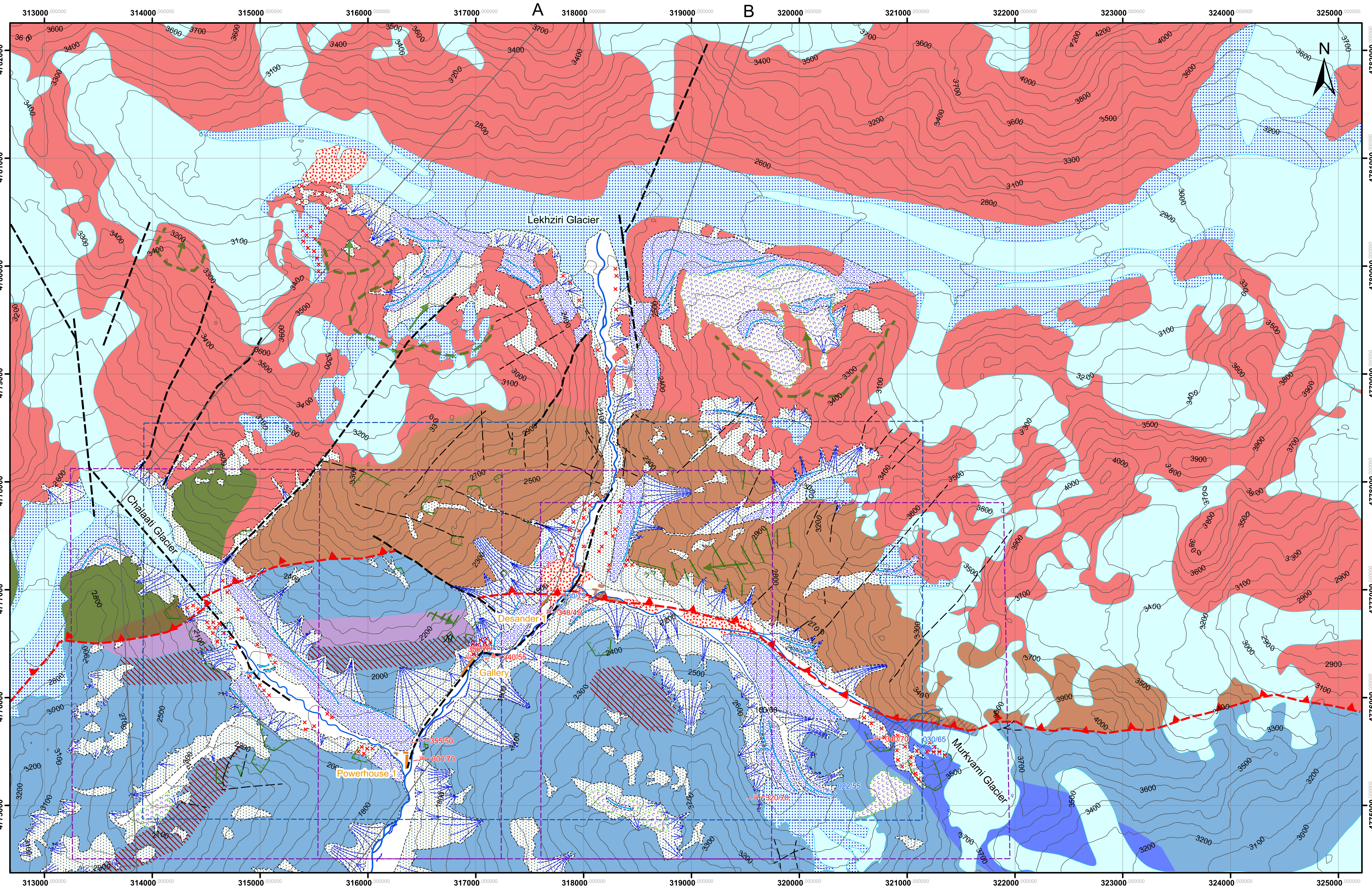
Main Range Zone

Mekara Metamorphic Complex

Silurian/Devonian
- Dark Phyllite
- Amphibolite
- Crystalline undifferentiated

Gondaray Metamorphic Complex

Ordovician
- Banded Gneiss



- Moraine Crest / Kame terrace edge
- Debris cone/fan
- Recently deposited large boulders
- River terrace edge
- Main Caucasus Thrust
- Major Faults ensured
- Major Fault assumed
- Minor Faults ensured
- Minor Fault assumed
- Mountainsplitting
- Large Landslide
- Edges
- main cleavage, > 60°
- main cleavage, 30 - 60°
- Bedding, > 60°
- Bedding, 30 - 60°
- cleavages/joints (lower order), 30 - 60°
- Detachment zone base map 1:25,000
- Geomorphological maps and geohazard maps

0 250 500 1.000 1.500 2.000 Meters

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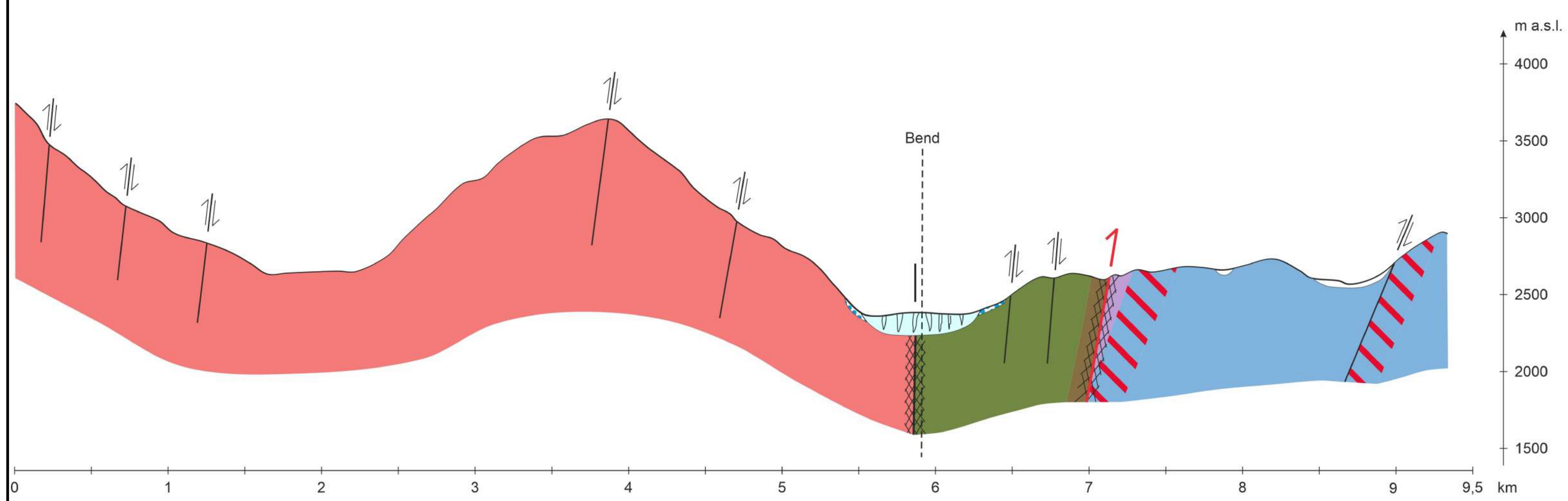
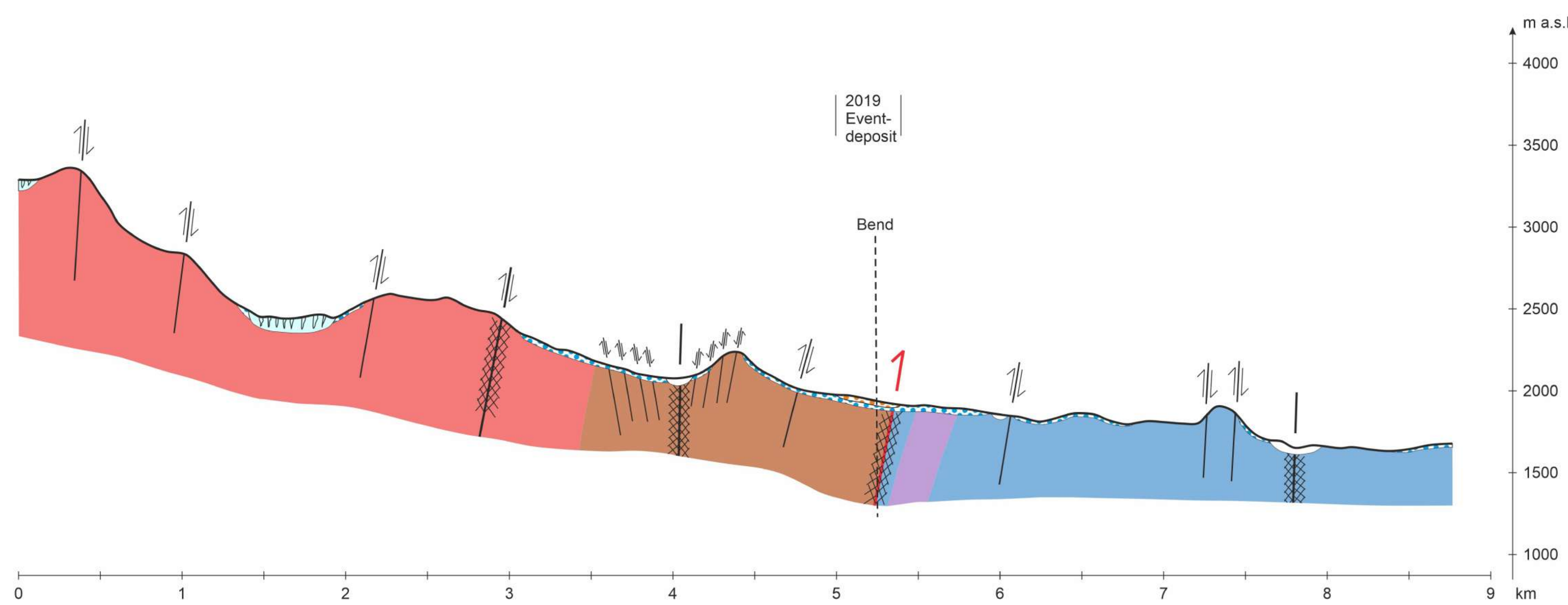
University of Natural Resources and Life Sciences, Vienna

Date: 27.11.2020	HPP Mestiachala 1
Attachment 1	Geological base map
Scale: 1:25.000	GRPC Georgian Renewable Power Company JSC
Sheet size [cm]: 891 / 594	

Profile A



Profile B



HPP Mestiachala Priority Projects

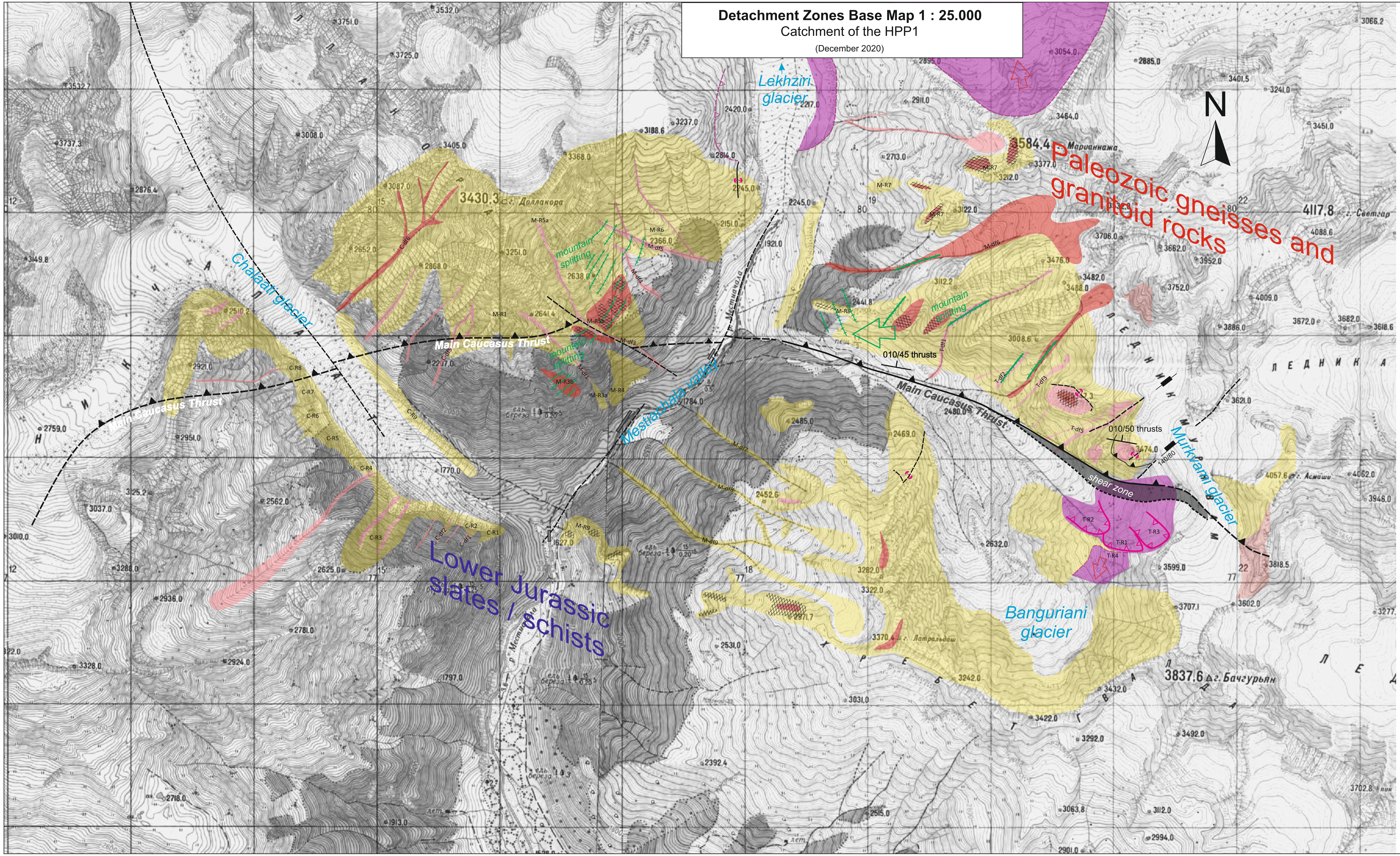
Final report on field research and geohazard assessment 2020

Attachment 2 Detachment zone base map, Scale 1 : 25,000

Detachment Zones Base Map 1 : 25.000

Catchment of the HPP1

(December 2020)



Major potential mass movement processes and Distinction of Hazard Zones (detachment areas)

Minor to medium magnitude
- Hazard area – rock falls / rock slides / debris flows / snow avalanches – up to 500 m³ (mass movements of higher magnitudes may not be excluded in these areas)

Large / very large magnitude
- Hazard area – rock falls / rock slides / debris flows – up to 5.000 m³
- Hazard area – rock falls / rock slides / shallow slides / eroded flanks – up to 100.000 m³

High magnitude compound events
- Hazard area – rock slide / landslide – up to several 100.000 m³

Residual Risk / Not included in map

Mass movement phenomena / deposits / morphological features

- Detachment zones of July 2019 event
- Detachments (general)
- Open cracks, fractures
- general transport direction of mass movement
- deep-seated mountain splitting and general direction
- thrust fault with associated shear zones
- thrust fault assumed
- minor parallel thrust faults
- fault
- rock towers

Thrusts / faults / fractures / large joints
- flat <45°
- steep >45°
- vertical

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Date: 27.11.2020	HPP Mestiachala 1
Attachment 2	Detachment Zones Base Map
Scale: ~1:25.000	GRPC Georgian Reneweable Power Company JSC
Sheet size [cm]: 594 / 297	

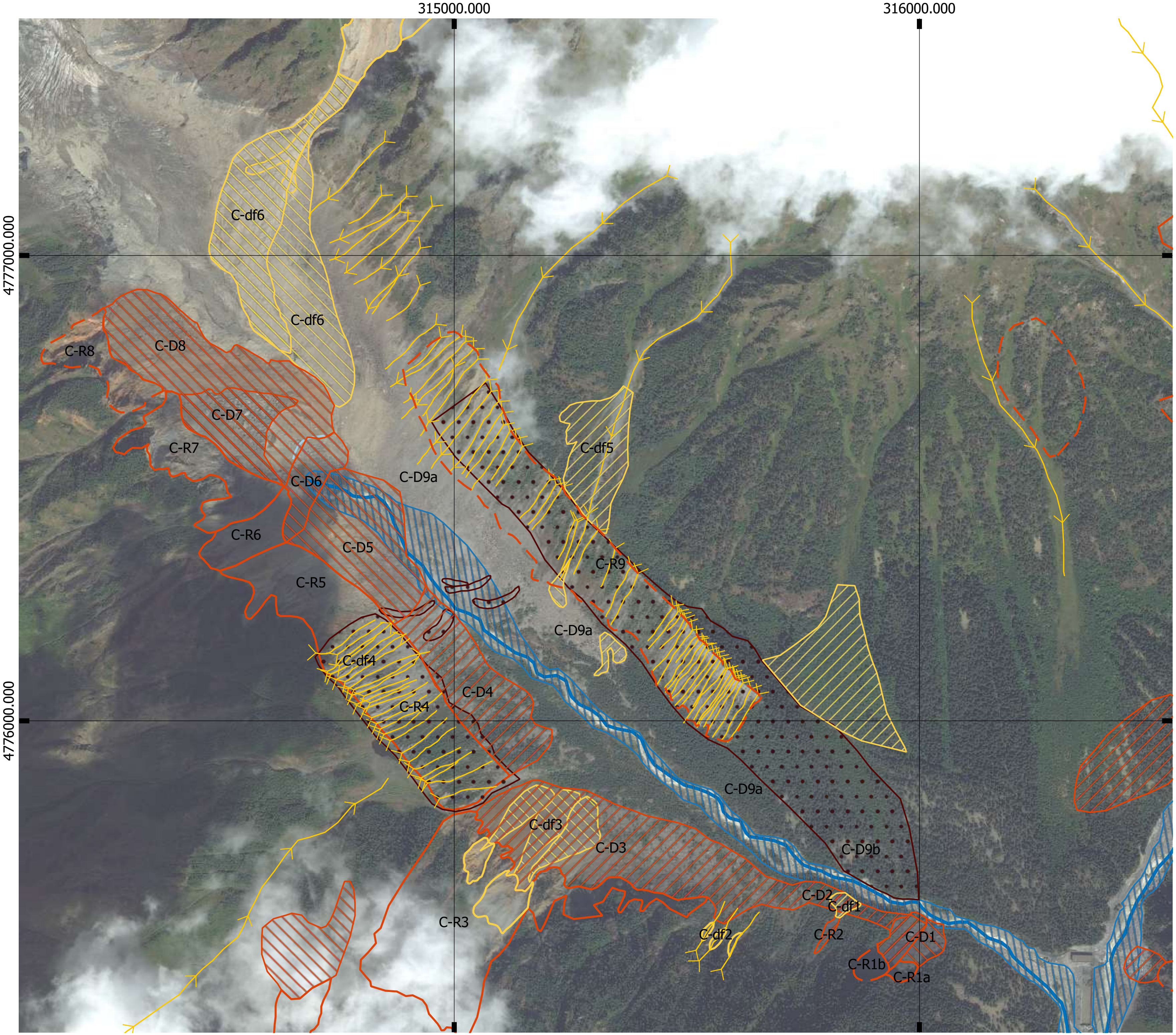
HPP Mestiachala Priority Projects

Final report on field research and geohazard assessment 2020

Attachment 3 Geomorphological map – Sheet Chalaati, Scale 1 : 12,000

Geomorphological Mapping

Chalaati Valley (August 2020)



Rockfall

- Release (Frequent)
- Deposition (Frequent)
- Release (Infrequent)
- Deposition (Infrequent)

Debris flow

- Release (Frequent)
- Deposition (Frequent)
- Release (Infrequent)
- Deposition (Infrequent)

- Moraine
- Channel bed
- Channel
- Glacier mouth
- Linear erosion

N

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BOKU University of Natural Resources and Life Sciences, Vienna

Date: 27.11.2020	**HPP Mestiachala 1**
Attachment 3	Geomorphological map – Sheet Chalaati
Scale: 1:12.000	GRPC Georgian Renewable Power Company JSC
Sheet size [cm]: 297/210	

Authors:
Dr. Sven Fuchs, Dipl.-Ing. Felix Draesner
Satellite image:
Pléiades 31.08.2019

University of Natural Resources and Life Sciences
A-1180 Vienna

0 250 500 m

HPP Mestiachala Priority Projects

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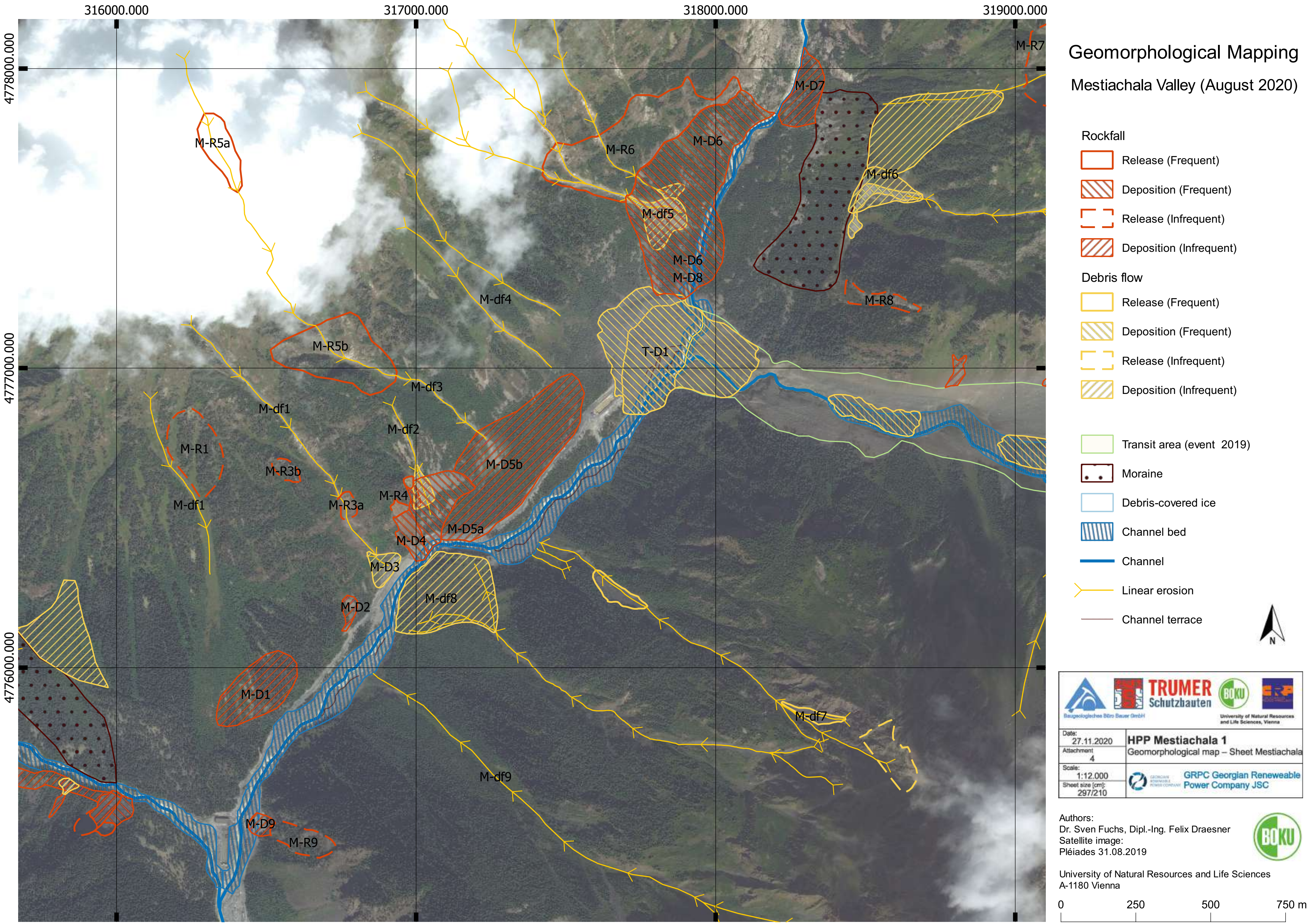
Attachment 4 Geomorphological map – Sheet Mestiachala, Scale 1 : 12,000


316000.000
317000.000
318000.000
319000.000
4778000.000
4777000.000
4776000.000
M-R5a
M-R5b
M-R6
M-R7
M-D7
M-D6
M-df5
M-df6
M-D6
M-D8
M-R8
M-df4
T-D1
M-df3
M-df1
M-df2
M-R1
M-R3b
M-R3a
M-R4
M-D5b
M-D5a
M-D4
M-df1
M-D3
M-df8
M-D2
M-D1
M-df7
M-df9
M-D9
M-R9
Geomorphological Mapping
Mestiachala Valley (August 2020)
Rockfall
Release (Frequent)
Deposition (Frequent)
Release (Infrequent)
Deposition (Infrequent)
Debris flow
Release (Frequent)
Deposition (Frequent)
Release (Infrequent)
Deposition (Infrequent)
Transit area (event 2019)
Moraine
Debris-covered ice
Channel bed
Channel
Linear erosion
Channel terrace
N
Baugeologisches Büro Bauer GmbH
TRUMER Schutzbauten
University of Natural Resources and Life Sciences, Vienna
Date: 27.11.2020
Attachment 4
HPP Mestiachala 1
Geomorphological map – Sheet Mestiachala
Scale: 1:12.000
Sheet size [cm]: 297/210
GRPC Georgian Renewable Power Company JSC
Authors:
Dr. Sven Fuchs, Dipl.-Ing. Felix Draesner
Satellite image:
Pléiades 31.08.2019
University of Natural Resources and Life Sciences
A-1180 Vienna
0
250
500
750 m

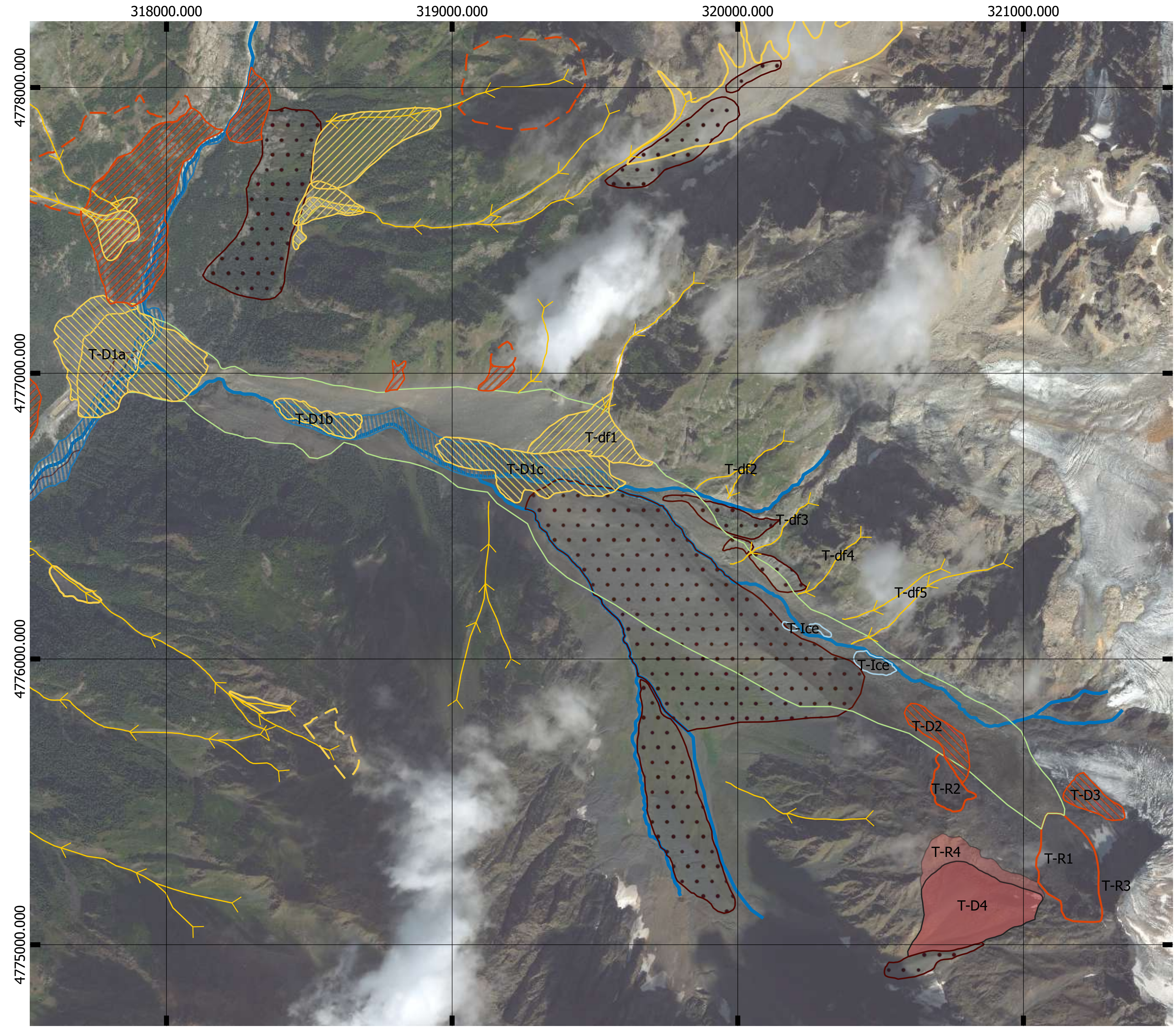
HPP Mestiachala Priority Projects

Final report on field research and geohazard assessment 2020

Attachment 5 Geomorphological map – Sheet Tributary, Scale 1 : 12,000

Geomorphological Mapping

Murkvami Tributary (August 2020)



Rockfall

- Release (Frequent)
- Deposition (Frequent)
- Release (Infrequent)
- Deposition (Infrequent)

Debris flow

- Release (Frequent)
- Deposition (Frequent)
- Release (Infrequent)
- Deposition (Infrequent)

Landslide

- Release (Active)
- Deposition (Active)

- Transit area (event 2019)
- Moraine
- Debris-covered ice
- Channel bed
- Channel
- Linear erosion
- Channel terrace

N

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Date: 27.11.2020	**HPP Mestiachala 1**
Attachment 5	Geomorphological map – Sheet Tributary
Scale: 1:12.000	GRPC Georgian Renewable Power Company JSC
Sheet size [cm]: 297/210	

Authors:
Dr. Sven Fuchs, Dipl.-Ing. Felix Draesner

Satellite image:
Pléiades 31.08.2019

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A-1180 Vienna

0 250 500 750 m

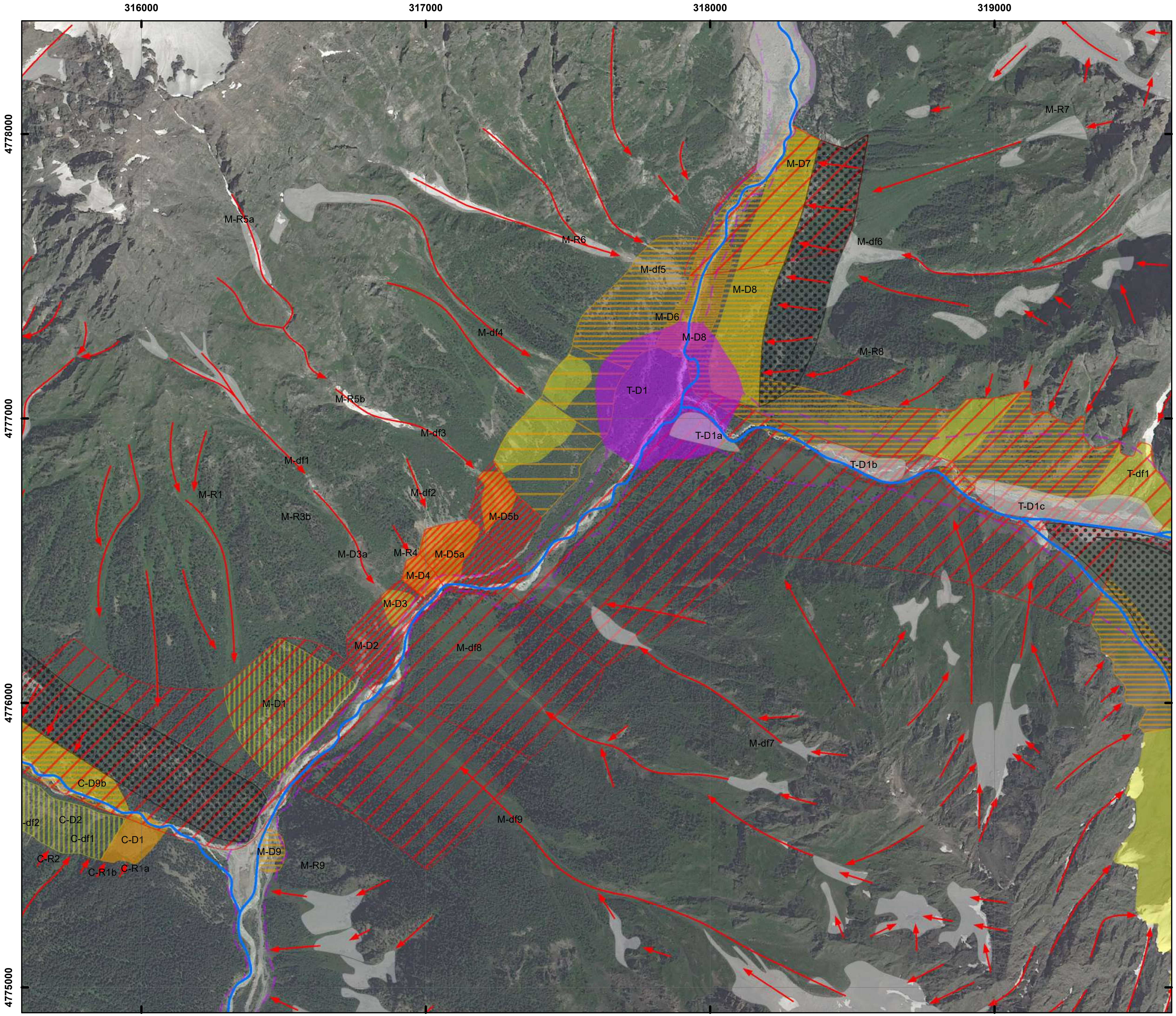
HPP Mestiachala Priority Projects

Final report on field research and geohazard assessment 2020

Attachment 6 Geohazard maps for Mestiachala HPP1 – rockfalls, scale 1 : 12,500

Mestiachala hazard map - rockfall

Scale: 1:12.500



High magnitude compound event

- Primary impact area
- Secondary impact area / transit area

Very large magnitude

- EF 2.2 / EF 3 / EF 4 (1 event in 1-10 a)
- EF 2.1 (1 event in 11-30 a)
- EF 1 (1 event in >30 a)

Large Magnitude

- EF 2.2 / EF 3 / EF 4 (1 event in 1-10 a)
- EF 2.1 (1 event in 11-30 a)
- EF 1 (1 event in >30 a)

Medium magnitude

- EF 2.2 / EF 3 / EF 4 (1 event in 1-10 a)
- EF 2.1 (1 event in 11-30 a)
- EF 1 (1 event in >30 a)

Minor magnitude

- EF 2.2 / EF 3 / EF 4 (1 event in 1-10 a)
- EF 2.1 (1 event in 11-30 a)
- EF 1 (1 event in >30 a)

- Moraine
- Sediment deposits
- Dead ice

- Transport direction
- Channel
- Moraine crest
- Glacial transport
- Creeping landslide

N

0 250 500 750 Meters

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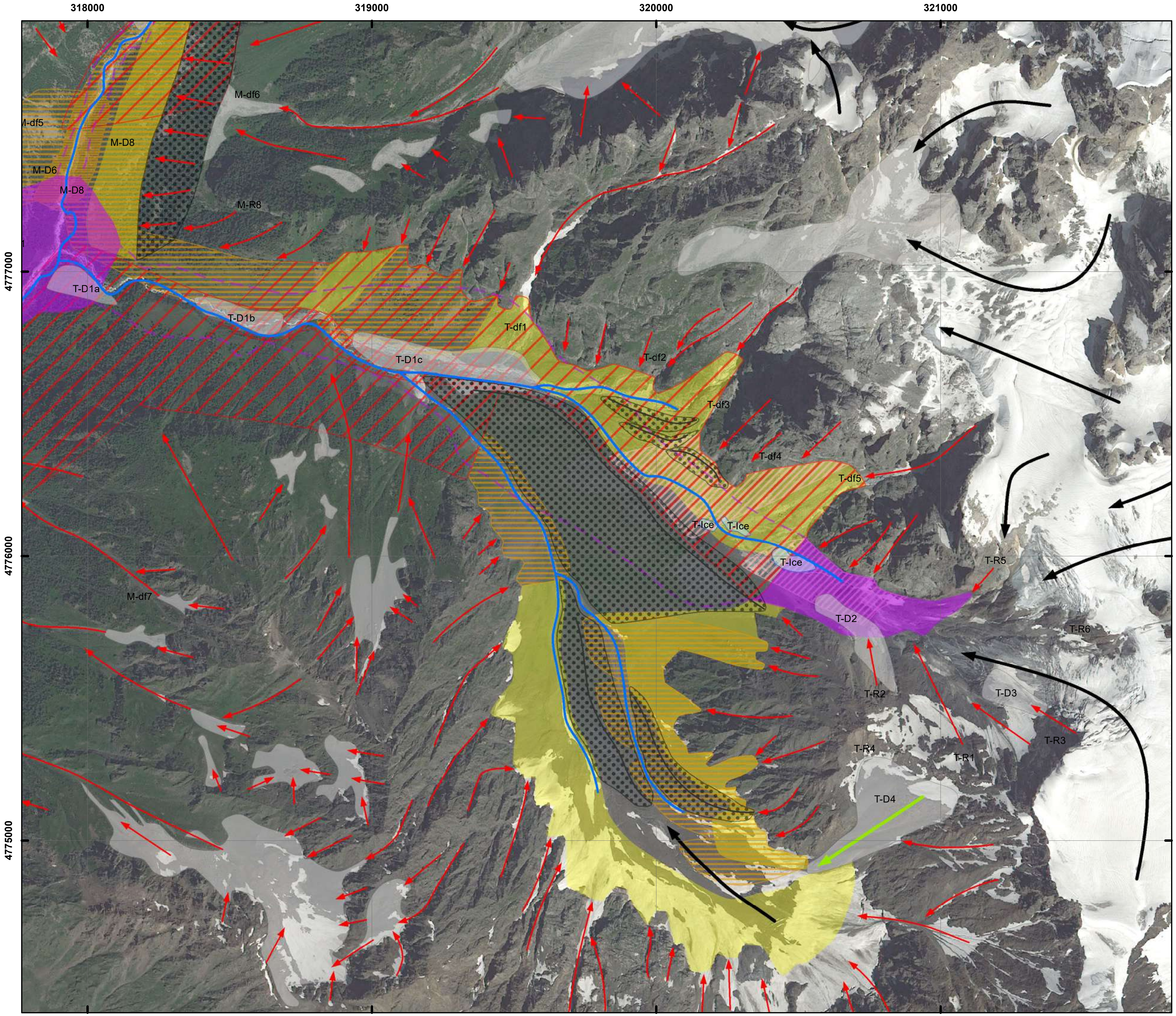
University of Natural Resources and Life Sciences, Vienna

Date: 27.11.2020	**HPP Mestiachala 1**
Attachment 6.1	Geohazard map, Mestiachala valley – rock falls
Scale: 1:12.500	GRPC Georgian Renewable Power Company JSC
Sheet size [cm]: 420/297	



Tributary hazard map - Rockfall

Scale: 1:12.500

High magnitude compound event

- Primary impact area
- Secondary impact area / transit area

Very large magnitude

- EF 2.2 / EF 3 / EF 4 (1 event in 1-10 a)
- EF 2.1 (1 event in 11-30 a)
- EF 1 (1 event in >30 a)

Large Magnitude

- EF 2.2 / EF 3 / EF 4 (1 event in 1-10 a)
- EF 2.1 (1 event in 11-30 a)
- EF 1 (1 event in >30 a)

Medium magnitude

- EF 2.2 / EF 3 / EF 4 (1 event in 1-10 a)
- EF 2.1 (1 event in 11-30 a)
- EF 1 (1 event in >30 a)

Minor magnitude

- EF 2.2 / EF 3 / EF 4 (1 event in 1-10 a)
- EF 2.1 (1 event in 11-30 a)
- EF 1 (1 event in >30 a)

- Moraine
- Sediment deposits
- Dead ice

- Transport direction
- Channel
- Moraine crest
- Glacial transport
- Creeping landslide

N

0 250 500 750 Meters

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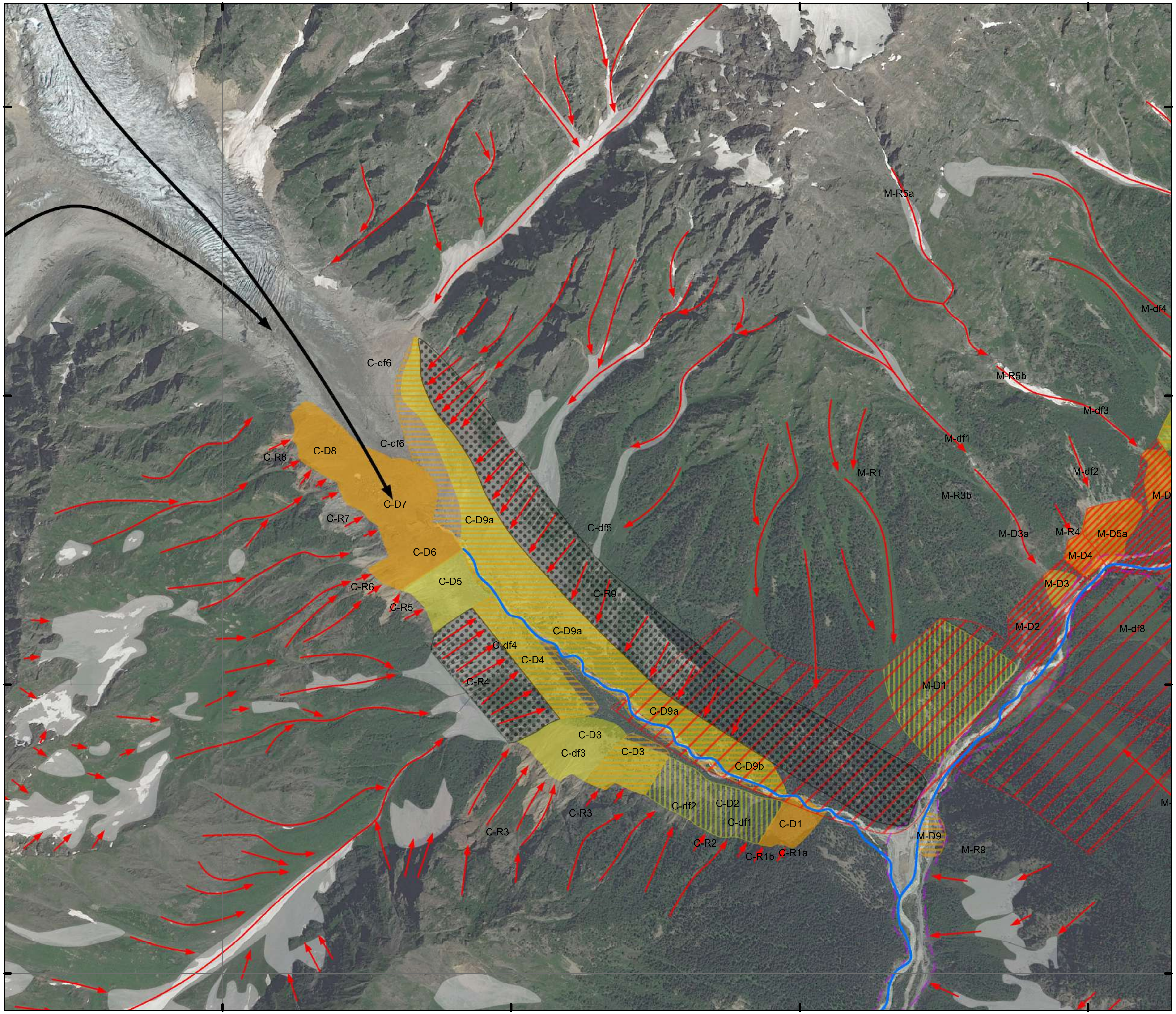
BOKU University of Natural Resources and Life Sciences, Vienna

Date: 27.11.2020	**HPP Mestiachala 1** Geohazard map, Tributary/Murkvami valley – rock falls
Attachment 6.2	
Scale: 1:12.500	GRPC Georgian Renewable Power Company JSC
Sheet size [cm]: 420/297	



Chalaati hazard map - rockfall

Scale: 1:12.500

High magnitude compound event

- Primary impact area
- Secondary impact area / transit area

Very large magnitude

- EF 2.2 / EF 3 / EF 4 (1 event in 1-10 a)
- EF 2.1 (1 event in 11-30 a)
- EF 1 (1 event in >30 a)

Large Magnitude

- EF 2.2 / EF 3 / EF 4 (1 event in 1-10 a)
- EF 2.1 (1 event in 11-30 a)
- EF 1 (1 event in >30 a)

Medium magnitude

- EF 2.2 / EF 3 / EF 4 (1 event in 1-10 a)
- EF 2.1 (1 event in 11-30 a)
- EF 1 (1 event in >30 a)

Minor magnitude

- EF 2.2 / EF 3 / EF 4 (1 event in 1-10 a)
- EF 2.1 (1 event in 11-30 a)
- EF 1 (1 event in >30 a)

- Moraine
- Sediment deposits
- Dead ice

- Transport direction
- Channel
- Moraine crest
- Glacial transport
- Creeping landslide

N

0 250 500 750 Meters

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Date: 27.11.2020	**HPP Mestiachala 1**
Attachment 6.3	Geohazard map, Chalaati valley – rock falls
Scale: 1:12.500	GRPC Georgian Renewable Power Company JSC
Sheet size [cm]: 420/297	

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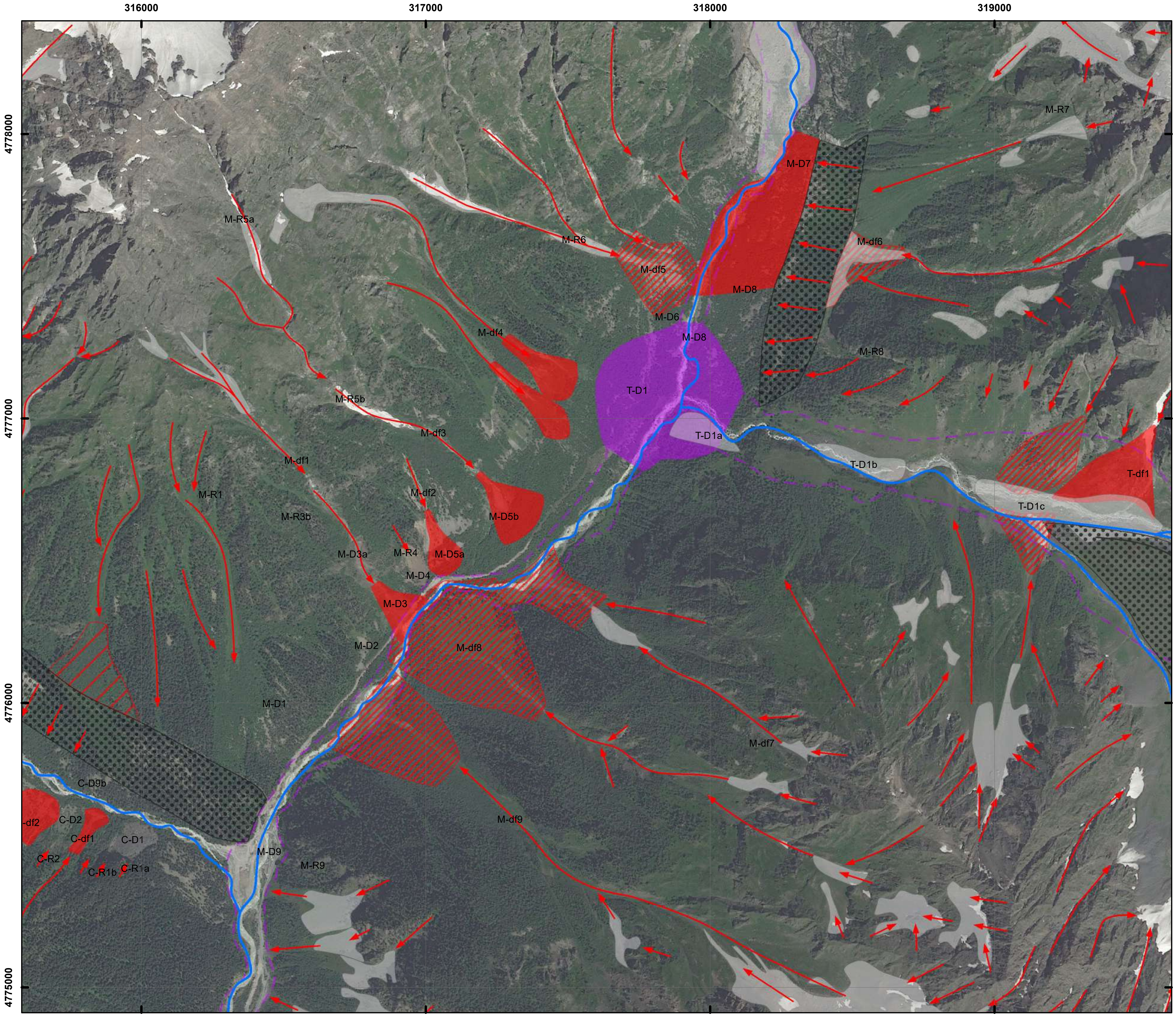
Final report on field research and geohazard assessment 2020

Attachment 7 Geohazard maps for Mestiachala HPP1 – flow processes, scale 1 : 12,500

Mestiachala hazard map - flow-like processes

Scale: 1:12.500



High magnitude compound event

- Primary impact area
- Secondary impact area / transit area

Medium to large magnitudes

- EF 2.2 / EF 3 / EF 4 (1 event in 1-10 a)
- EF 2.1 (1 event in 11-30 a)
- EF 1 (1 event in >30 a)
- Moraine
- Sediment deposits
- Dead ice
- Transport direction
- Channel
- Moraine crest
- Glacial transport
- Creeping landslide

N

0 250 500 750 Meters

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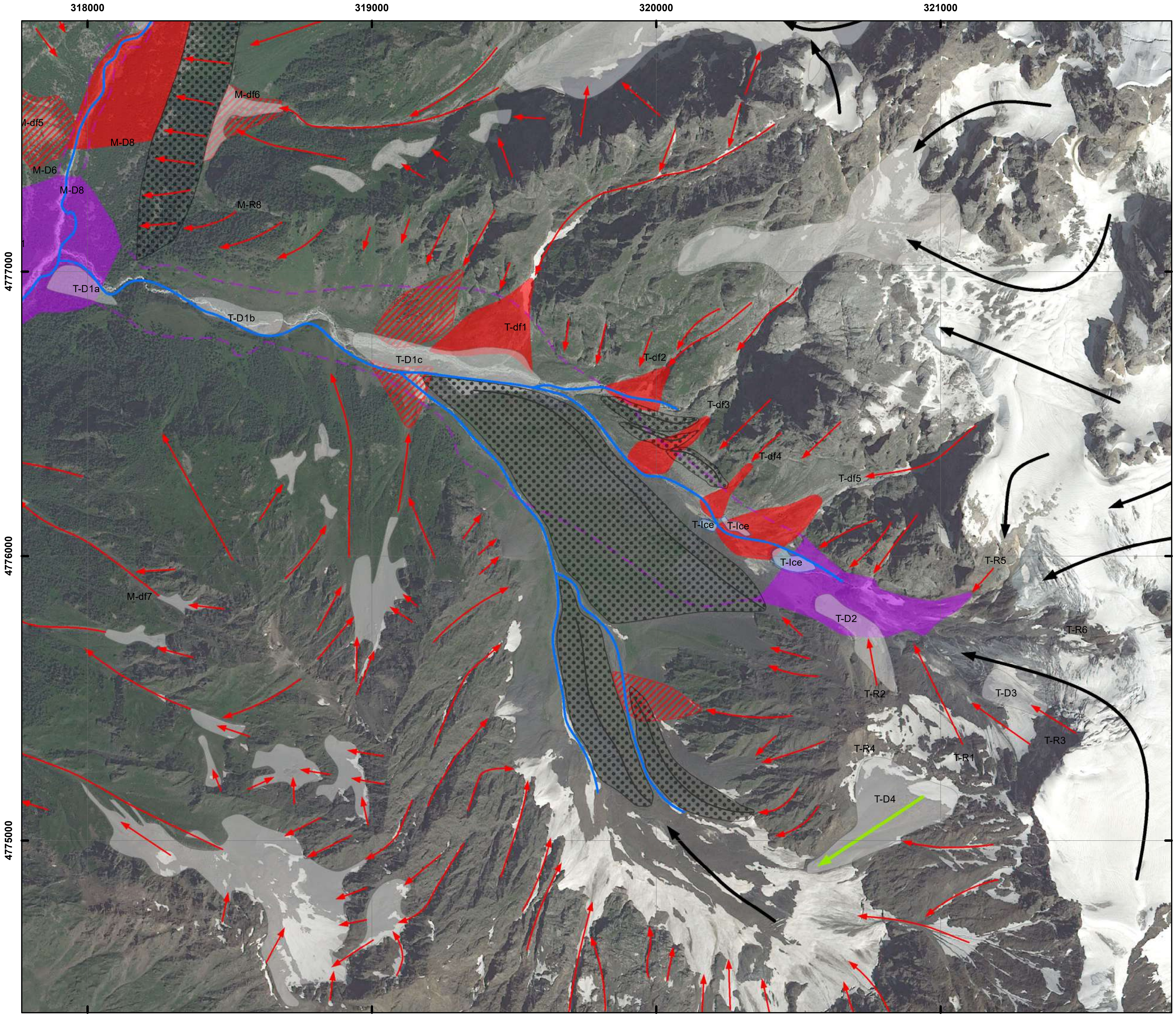
Date: 27.11.2020	**HPP Mestiachala 1**
Attachment 7.1	Geohazard map, Mestiachala valley – flow-like processes
Scale: 1:12.500	GRPC Georgian Renewable Power Company JSC
Sheet size [cm]: 420/297	



Tributary hazard map - flow-like processes

Scale: 1:12.500

High magnitude compound event

- Primary impact area
- Secondary impact area / transit area

Medium to large magnitudes

- EF 2.2 / EF 3 / EF 4 (1 event in 1-10 a)
- EF 2.1 (1 event in 11-30 a)
- EF 1 (1 event in >30 a)

- Moraine
- Sediment deposits
- Dead ice

- Transport direction
- Channel
- Moraine crest
- Glacial transport
- Creeping landslide

N

0 250 500 750 Meters

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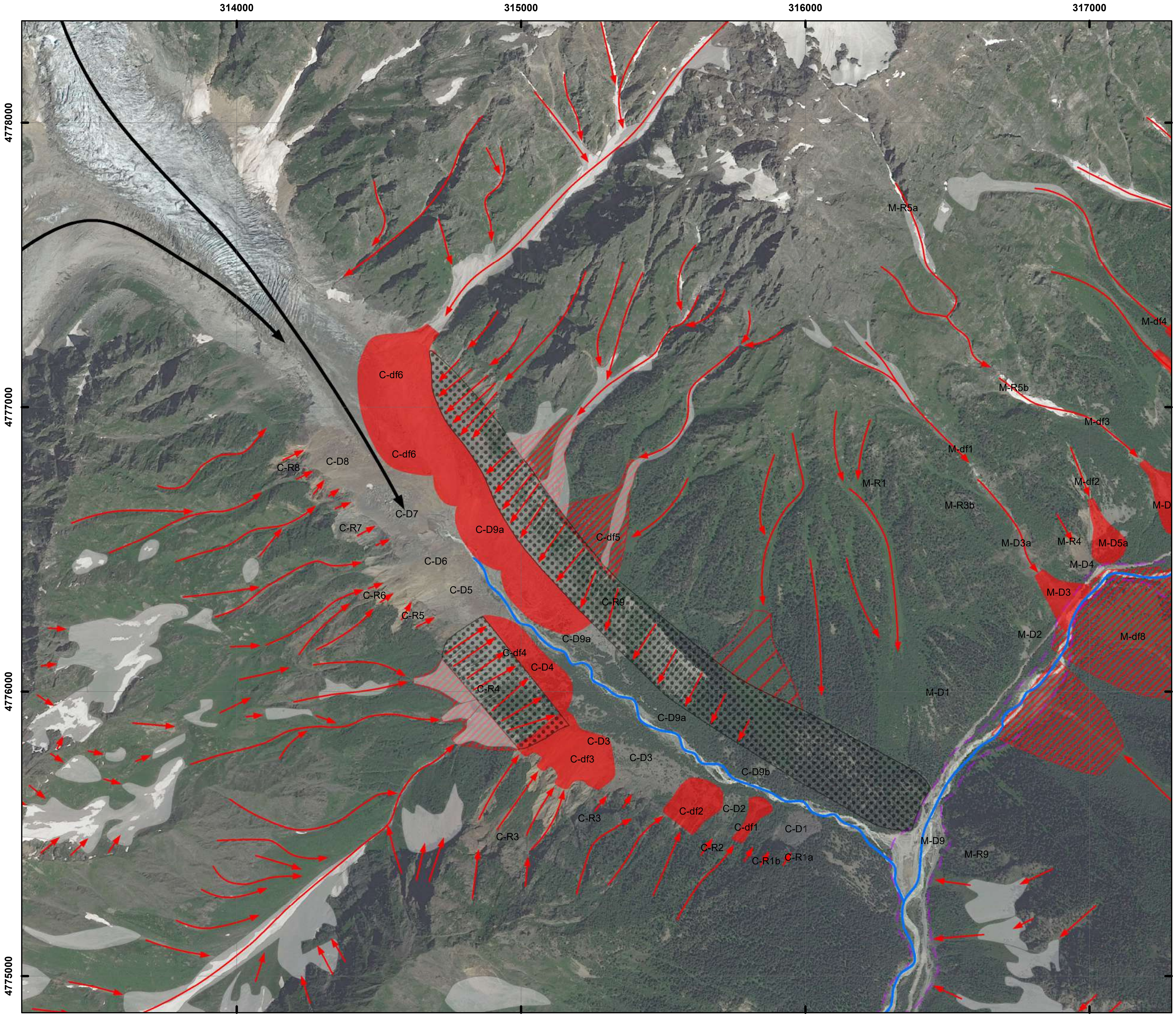
Date: 27.11.2020	**HPP Mestiachala 1**
Attachment 7.2	Geohazard map, Tributary/Murkvami valley – flow-like processes
Scale: 1:12.500	GRPC Georgian Renewable Power Company JSC
Sheet size [cm]: 420/297	

Chalaati hazard map - flow-like processes

Scale: 1:12.500



High magnitude compound event

- Primary impact area
- Secondary impact area / transit area

Medium to large magnitudes

- EF 2.2 / EF 3 / EF 4 (1 event in 1-10 a)
- EF 2.1 (1 event in 11-30 a)
- EF 1 (1 event in >30 a)

- Moraine
- Sediment deposits
- Dead ice

- Transport direction
- Channel
- Moraine crest
- Glacial transport
- Creeping landslide

N

0 250 500 750 Meters

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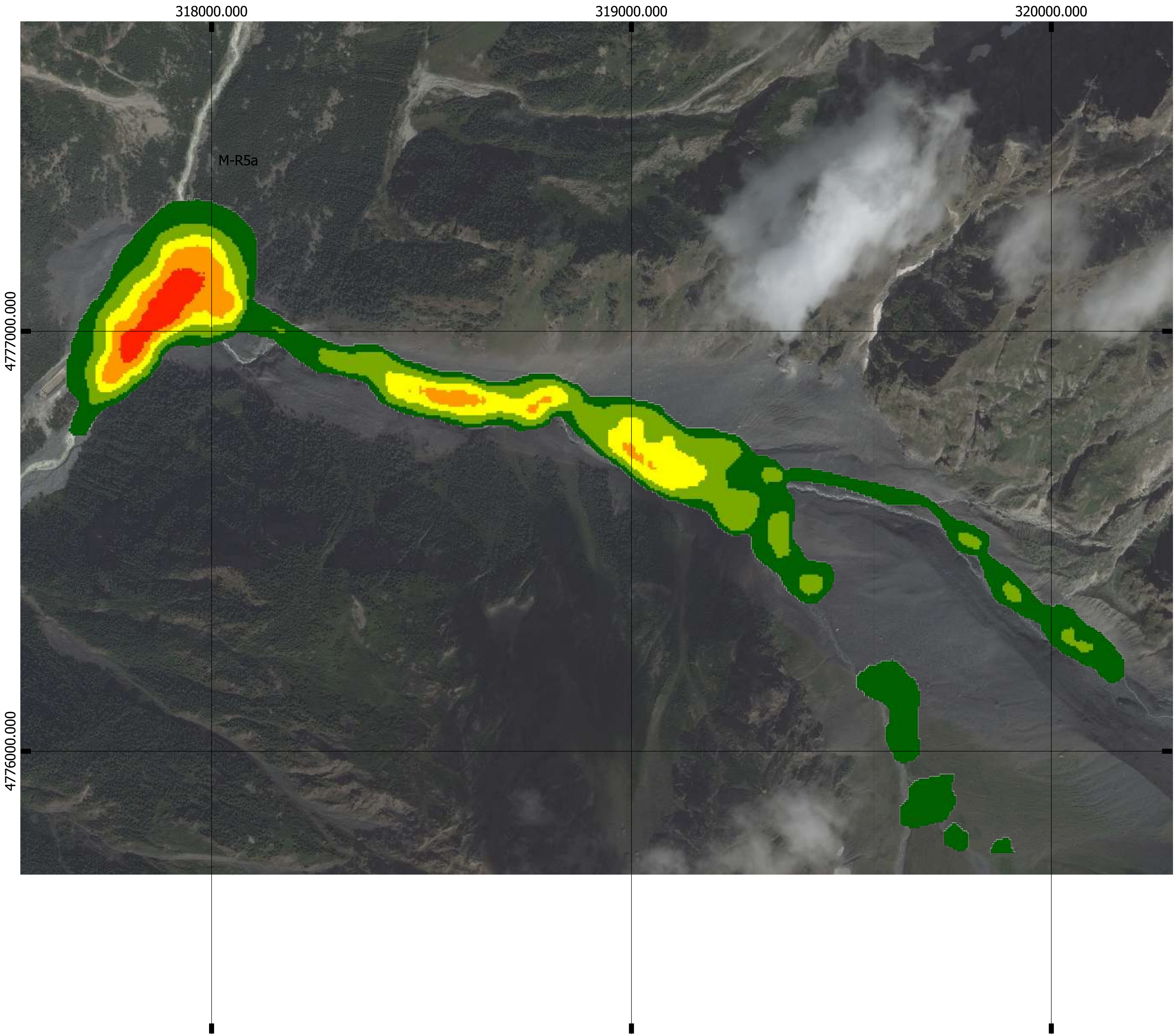
Date: 27.11.2020	**HPP Mestiachala 1**
Attachment 7.3	Geohazard map, Chalaati valley – flow-like processes
Scale: 1:12.500	GRPC Georgian Renewable Power Company JSC
Sheet size [cm]: 420/297	

HPP Mestiachala Priority Projects

Final report on field research and geohazard assessment 2020

Attachment 8 Debris flow modelling maps



Simulation Murkvami Tributary

rock-ice avalanche

Deposition height

Event 25.07.2019

Deposition height [m]

- 0.1 - 2.2
- > 2.2 - 6.2
- > 6.2 - 9.3
- > 9.3 - 12.4
- > 12.4

N

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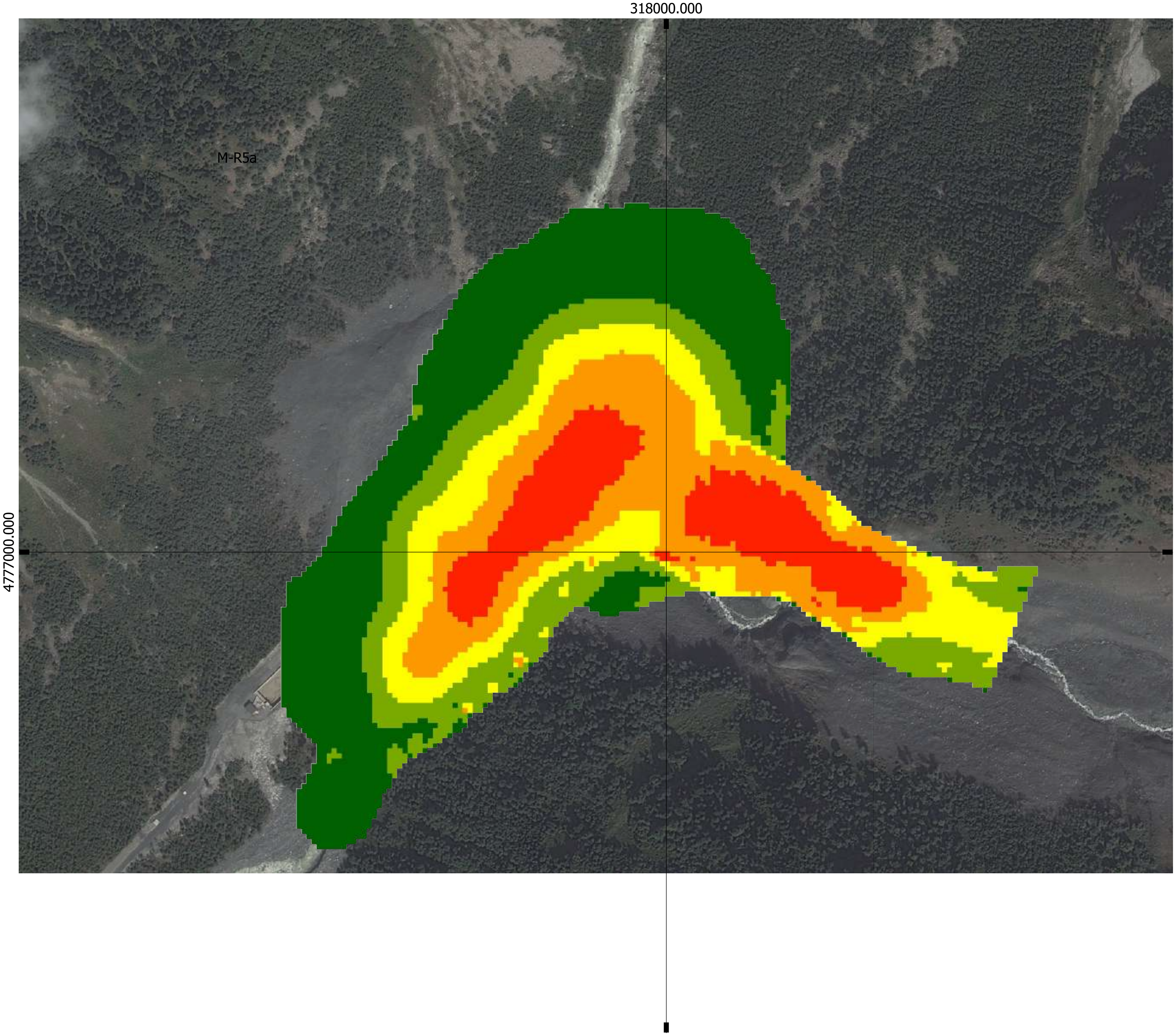
University of Natural Resources and Life Sciences, Vienna

Date: 27.11.2020	**HPP Mestiachala 1**
Attachment 8.1	Rock-ice avalanche modelling maps - Murkvami Tributary
Scale: -	GRPC Georgian Renewable Power Company JSC
Sheet size [cm]: 297/210	

Authors:
Dr. Sven Fuchs, Felix Draesner
Satellite image:
Pléiades 31.08.2019

University of Natural Resources and Life Sciences
A-1180 Vienna

0 250 500 m



Simulation Murkvami Tributary Deposition area

Rock-ice avalanche

Maximum flow pressure over the entire time intervall

Event 25.07.2019

Flow pressure [kN/m²]

- <= 61.4
- > 61.4 - 155.4
- > 155.4 - 247.5
- > 247.5 - 333.8
- > 333.8

N

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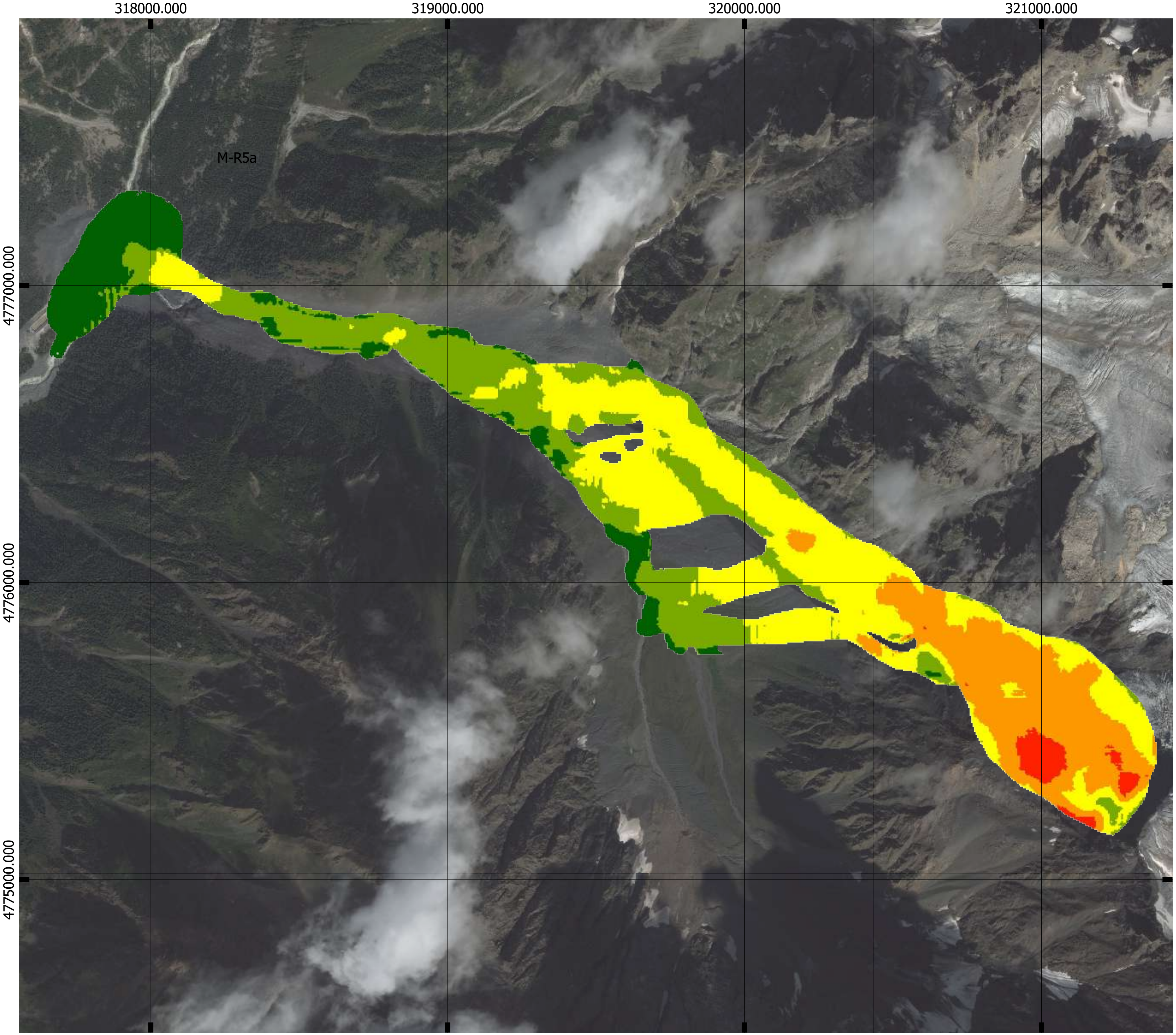
Date: 27.11.2020	HPP Mestiachala 1
Attachment 8.1	Rock-ice avalanche modelling maps - Murkvami Tributary
Scale: -	GRPC Georgian Renewable Power Company JSC
Sheet size [cm]: 297/210	

Authors:
Dr. Sven Fuchs,.Felix Draesner

Satellite image:
Pléiades 31.08.2019

University of Natural Resources and Life Sciences
A-1180 Vienna

0 125 250 m



Simulation Murkvami Tributary

rock-ice avalanche

Maximum flow velocity over the entire time intervall

Event 25.07.2019

Flow velocity [m/s]

- <= 6.9
- > 6.9 - 13.7
- > 13.7 - 20.7
- > 20.7 - 27.5
- > 27.5

N

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TRUMER Schutzbauten

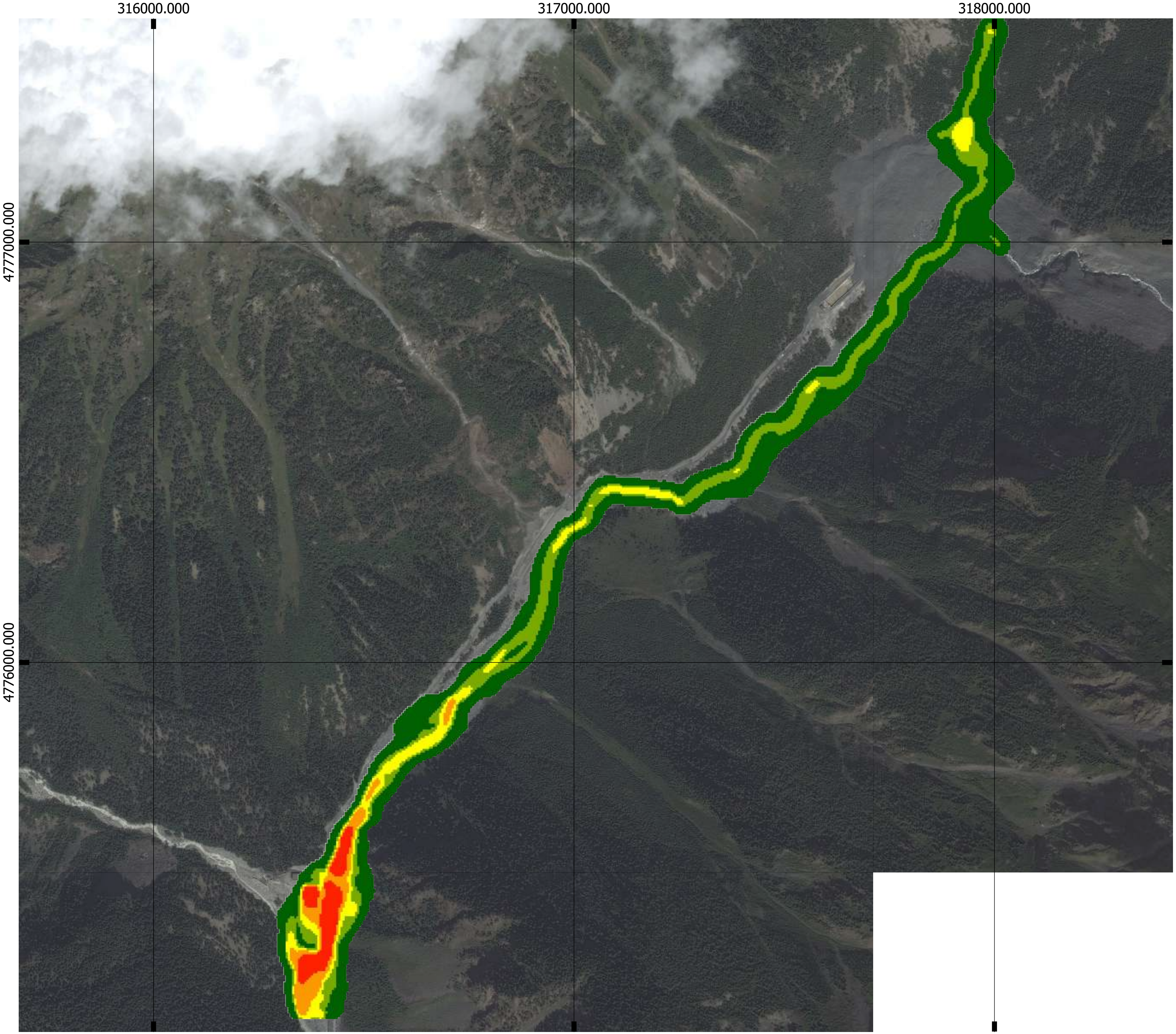
University of Natural Resources and Life Sciences, Vienna

Date: 27.11.2020	**HPP Mestiachala 1** Rock-ice avalanche modelling maps - Murkvami Tributary
Attachment 8.1	
Scale: -	GRPC Georgian Renewable Power Company JSC
Sheet size [cm]: 297/210	

Authors:
Dr. Sven Fuchs, Felix Draesner
Satellite image:
Pléiades 31.08.2019

University of Natural Resources and Life Sciences
A-1180 Vienna

0 250 500 m



Simulation Mestiachala

Debris flow

Maximum flow height over the entire time intervall

1-in-30 year design discharge according to Hydroconsult 2015

Flow height [m]

- <= 0.53
- > 0.53 - 1.63
- > 1.63 - 3.26
- > 3.26 - 5.21
- > 5.21

N

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Baugeologisches Büro Bauer GmbH

University of Natural Resources and Life Sciences, Vienna

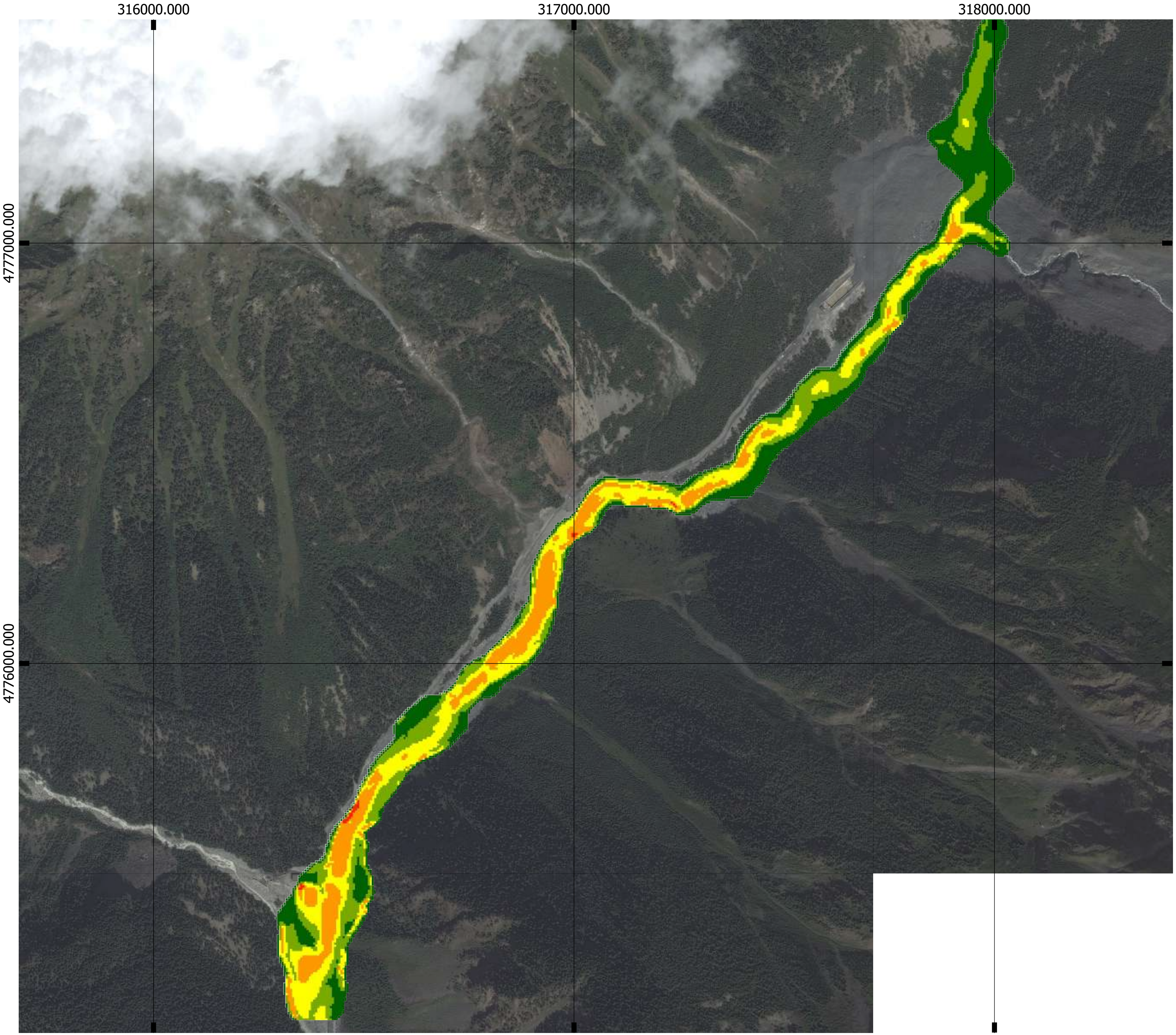
Date: 27.11.2020	**HPP Mestiachala 1**
Attachment 8.2	Debris flow modelling maps - Mestiachala 1-in-30-year event
Scale: -	GRPC Georgian Reneweable Power Company JSC
Sheet size [cm]: 297/210	

Authors:
Dr. Sven Fuchs, Felix Draesner

Satellite image:
Pléiades 31.08.2019

University of Natural Resources and Life Sciences
A-1180 Vienna

0 250 500 m



Simulation Mestiachala

Debris flow

Maximum flow pressure over the entire time intervall

1-in-30 year design discharge according to Hydroconsult 2015

Flow pressure [kN/m²]

<= 22.36

> 22.36 - 55.30

> 55.30 - 89.42

> 89.42 - 183.33

> 183.33

N

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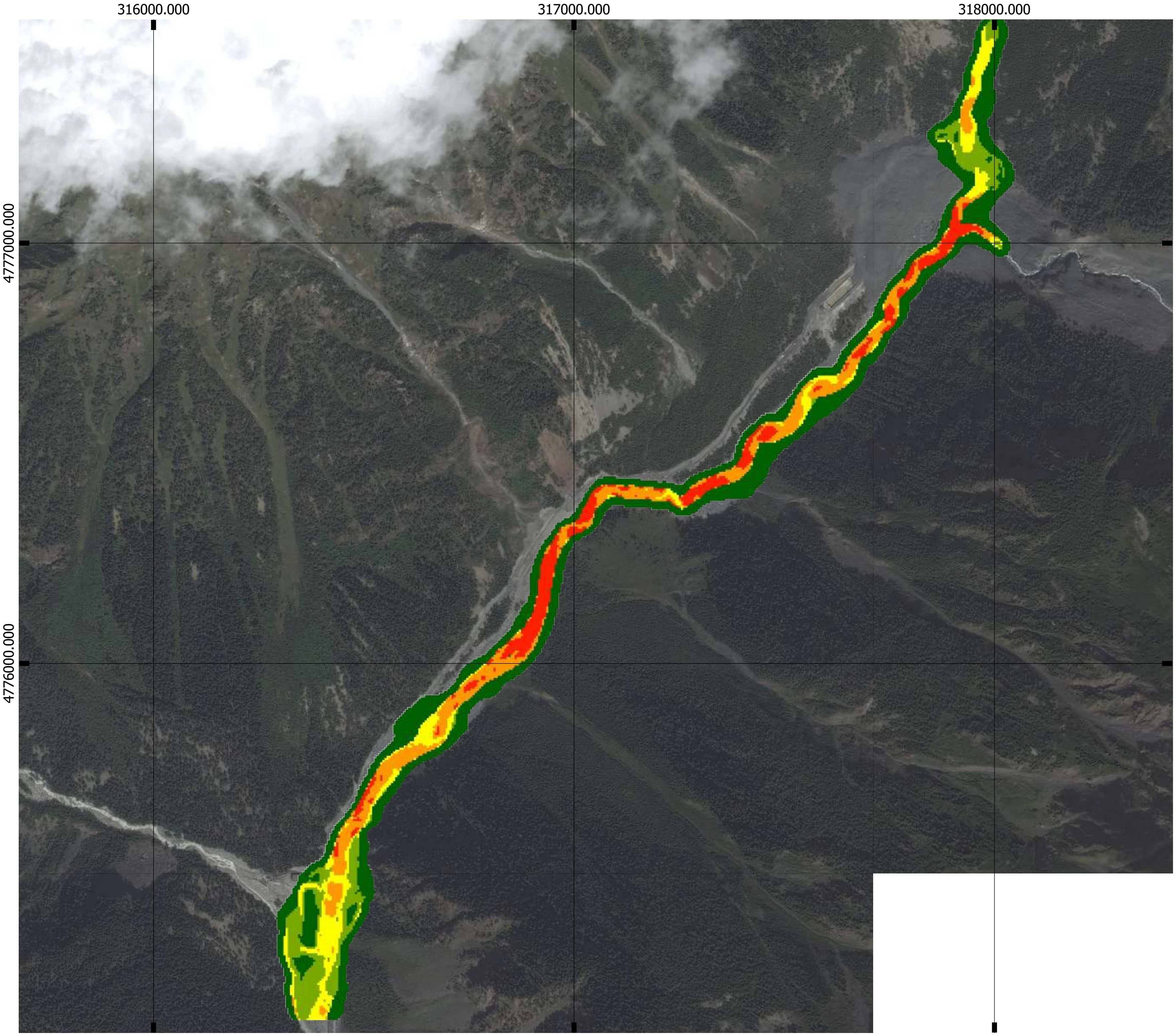
University of Natural Resources and Life Sciences, Vienna

Date: 27.11.2020	HPP Mestiachala 1
Attachment 8.2	Debris flow modelling maps - Mestiachala 1-in-30-year event
Scale: -	GRPC Georgian Reneweable Power Company JSC
Sheet size [cm]: 297/210	

Authors:
Dr. Sven Fuchs, Felix Draesner
Satellite image:
Pléiades 31.08.2019

University of Natural Resources and Life Sciences
A-1180 Vienna

0 250 500 m



Simulation Mestiachala

Debris flow

Maximum flow velocity over the entire time intervall

1-in-30 year design discharge according to Hydroconsult 2015

Flow velocity [m/s]

- <= 1.77
- > 1.77 - 5.13
- > 5.13 - 8.03
- > 8.03 - 10.34
- > 10.34

N

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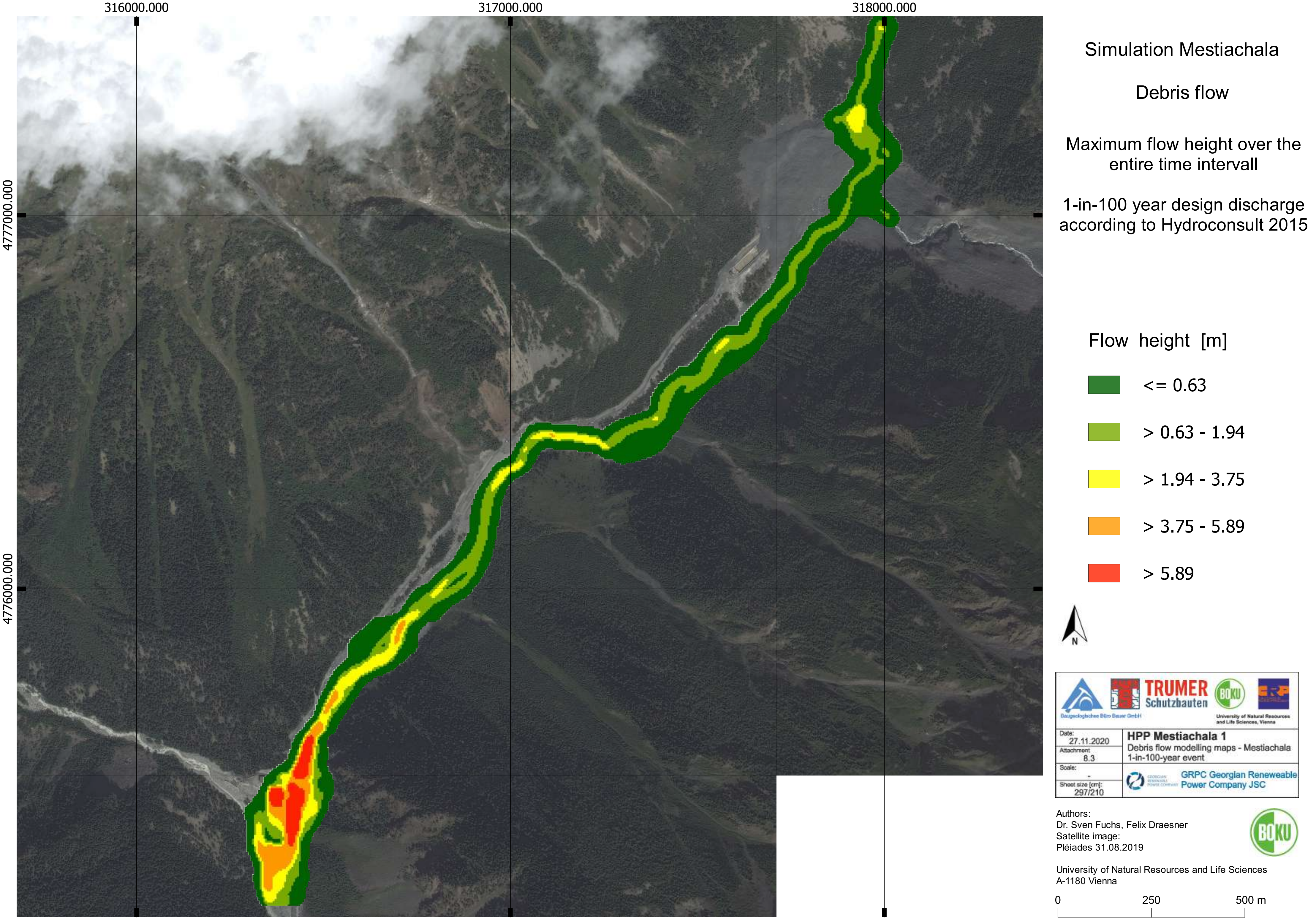
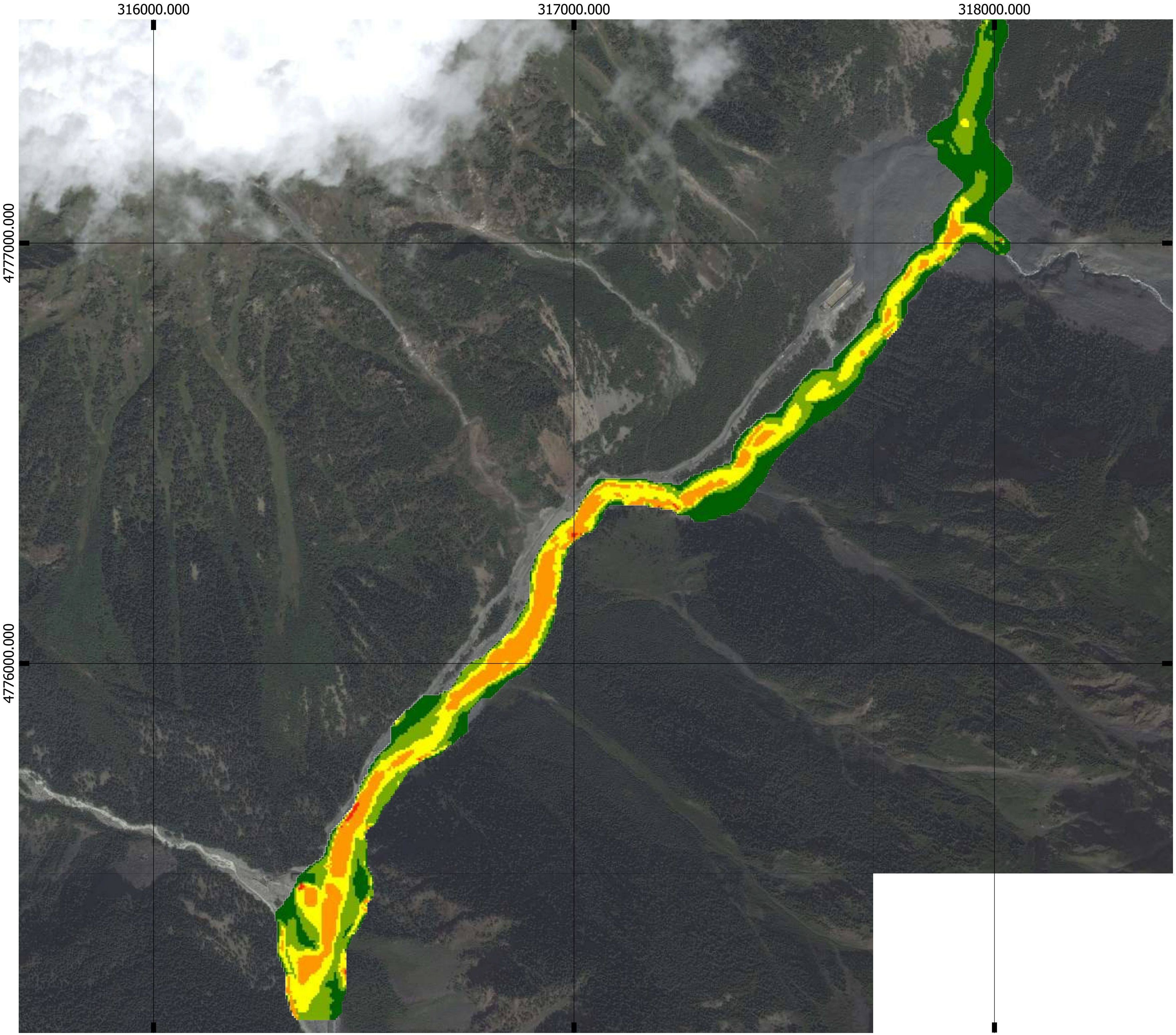
Date: 27.11.2020	**HPP Mestiachala 1** Debris flow modelling maps - Mestiachala 1-in-30-year event
Attachment 8.2	
Scale: -	GRPC Georgian Reneweable Power Company JSC
Sheet size [cm]: 297/210	

Authors:
Dr. Sven Fuchs, Felix Draesner
Satellite image:
Pléiades 31.08.2019

University of Natural Resources and Life Sciences
A-1180 Vienna

0 250 500 m


316000.000
317000.000
318000.000
4777000.000
4776000.000
Simulation Mestiachala
Debris flow
Maximum flow height over the entire time intervall
1-in-100 year design discharge according to Hydroconsult 2015
Flow height [m]
<= 0.63
> 0.63 - 1.94
> 1.94 - 3.75
> 3.75 - 5.89
> 5.89
N
TRUMER Schutzbauten
Date: 27.11.2020
Attachment 8.3
Scale: -
Sheet size [cm]: 297/210
HPP Mestiachala 1
Debris flow modelling maps - Mestiachala
1-in-100-year event
GRPC Georgian Renewable Power Company JSC
Authors:
Dr. Sven Fuchs, Felix Draesner
Satellite image:
Pléiades 31.08.2019
University of Natural Resources and Life Sciences
A-1180 Vienna
0
250
500 m



Simulation Mestiachala

Debris flow

Maximum flow pressure over the entire time intervall

1-in-100 year design discharge according to Hydroconsult 2015

Flow pressure [kN/m²]

- <= 23.54
- > 23.54 - 60.01
- > 60.01 - 96.48
- > 89.42 - 184.71
- > 184.71

N

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Date: 27.11.2020	**HPP Mestiachala 1** Debris flow modelling maps - Mestiachala 1-in-100-year event
Attachment 8.3	
Scale: -	GRPC Georgian Reneweable Power Company JSC
Sheet size [cm]: 297/210	

Authors:
Dr. Sven Fuchs, Felix Draesner
Satellite image:
Pléiades 31.08.2019

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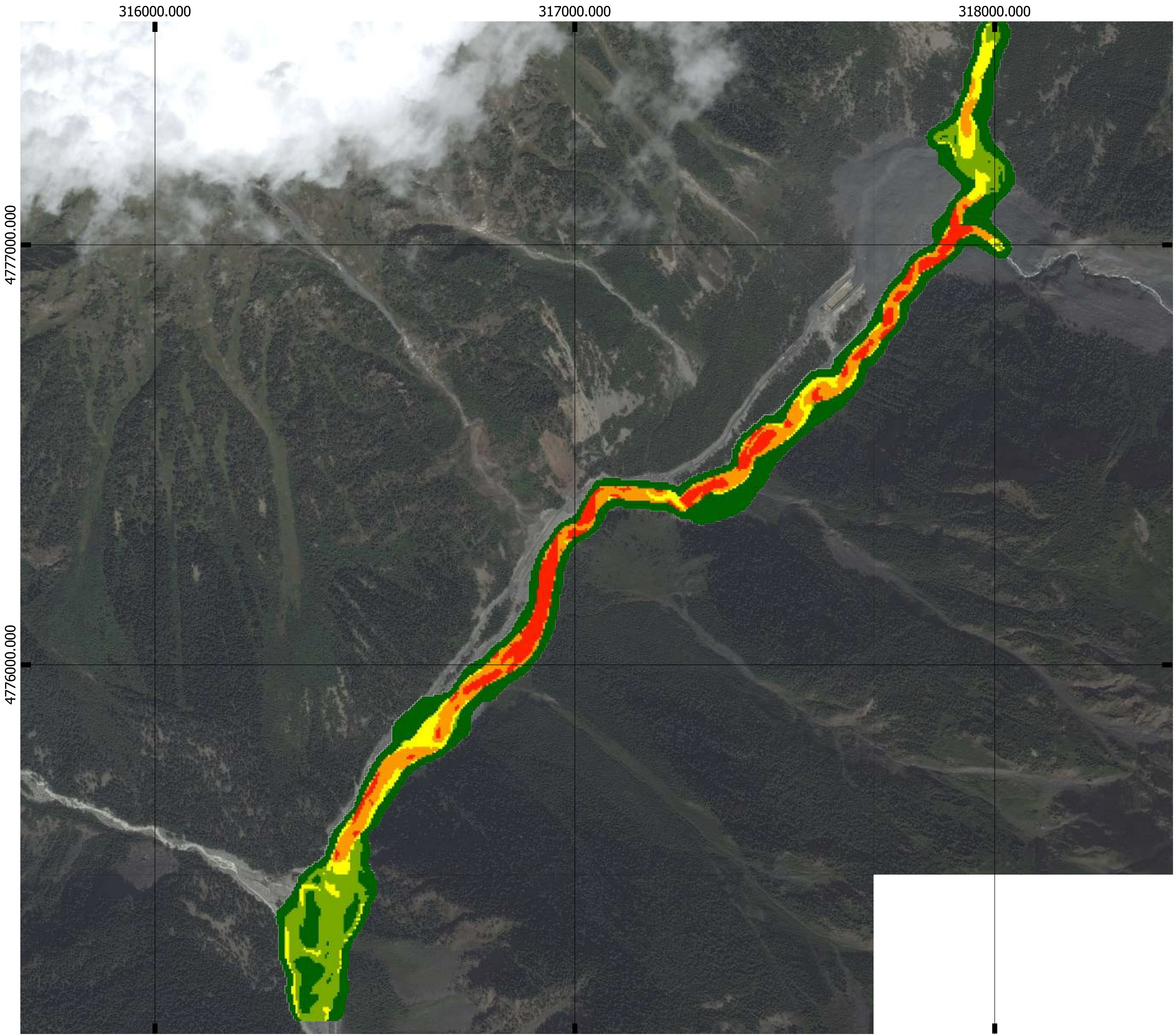
A-1180 Vienna

0 250 500 m



Simulation Mestiachala

Debris flow

Maximum flow velocity over the entire time intervall

1-in-100 year design discharge according to Hydroconsult 2015

Flow velocity [m/s]

(dark green)	<= 1.73
(light green)	> 1.73 - 5.20
(yellow)	> 5.20 - 8.48
(orange)	> 8.48 - 11.08
(red)	> 11.08

N

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Date: 27.11.2020	**HPP Mestiachala 1**
Attachment 8.3	Debris flow modelling maps - Mestiachala 1-in-100-year event
Scale: -	GRPC Georgian Reneweable Power Company JSC
Sheet size [cm]: 297/210	

Authors:
Dr. Sven Fuchs, Felix Draesner

Satellite image:
Pléiades 31.08.2019

University of Natural Resources and Life Sciences
A-1180 Vienna

0 250 500 m

HPP Mestiachala Priority Projects

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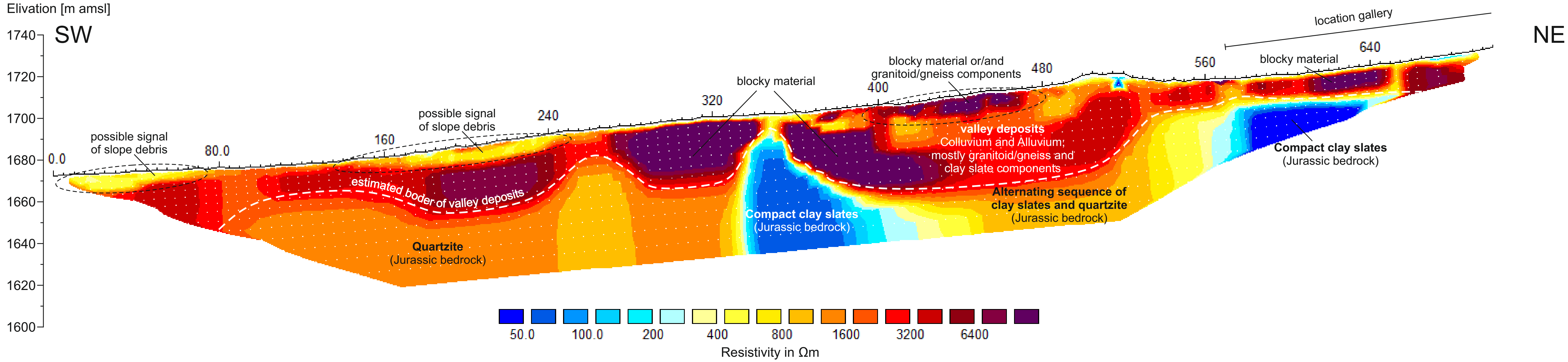
Attachment 9 Electrical Resistivity Tomography (ERT)

Model resistivity with topography
Iteration 8 Abs. error = 2.9

Geoelectrical transect - „Mestiachala, gallery“
Scale 1 : 2,000



Horizontal scale is 10.31 pixels per unit spacing.
Vertical exaggeration in model section display = 1.00.
First electrode is located at 0.0 m.
Last electrode is located at 700.0 m.
Wenner array used.

Unit Electrode Spacing = 5.00 m

Map of research area - „Mestiachala, gallery“
Scale 1 : 6,000

Map basis: Pleiades 50cm,
31st August 2019

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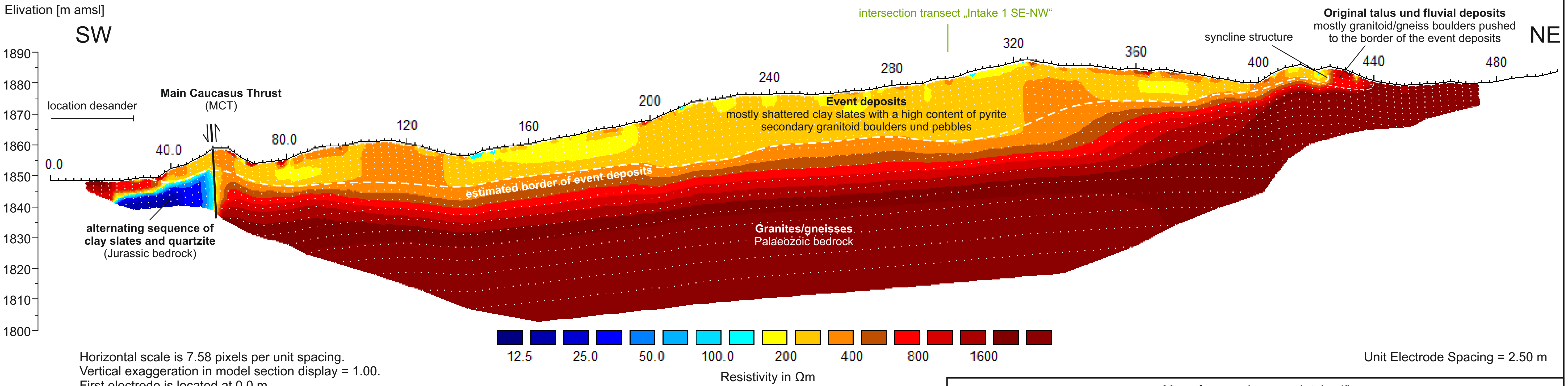
Date: 27.11.2020	**HPP Mestiachala 1** Geoelectrical measurements - Mestiachala gallery
Attachment 9.1	
Scale: 1:2,000 / 1:6,000	GRPC Georgian Reneweable Power Company JSC
Sheet size [cm]: 420/297	

Model resistivity with topography
Iteration 5 Abs. error = 1.6

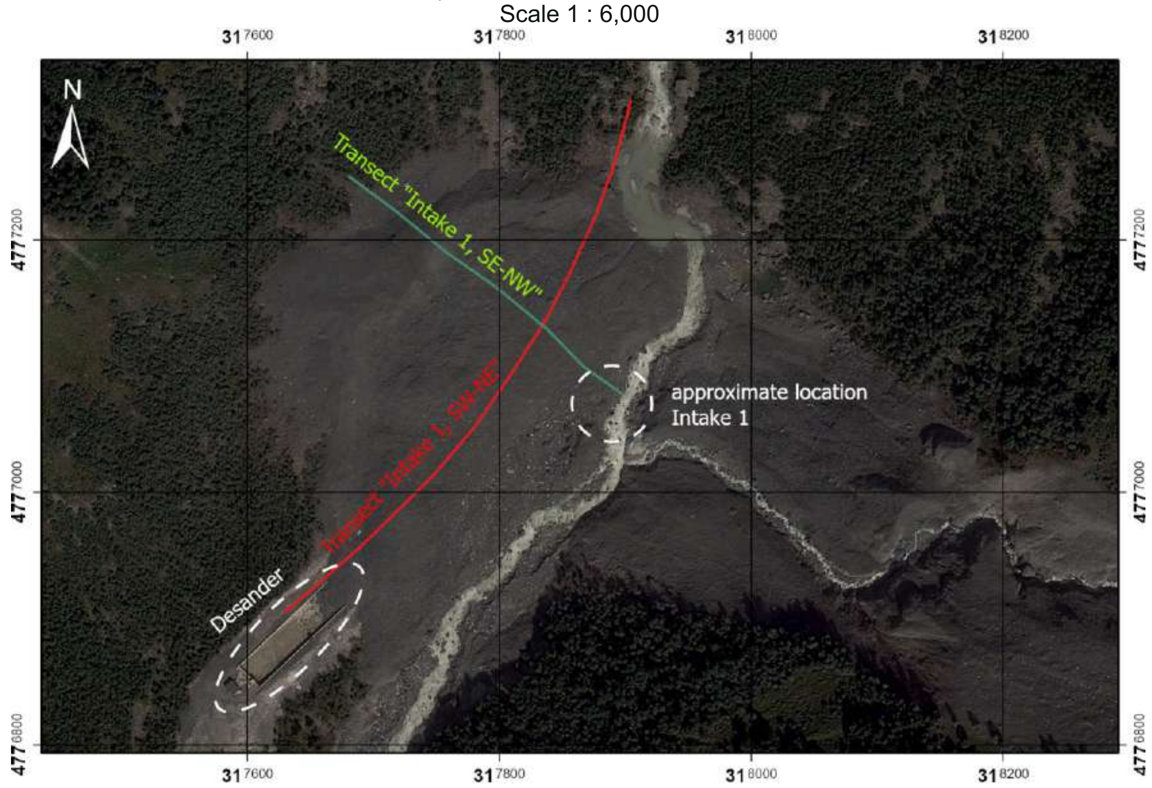
Geoelectrical transect - „Intake 1, SW-NE“
Scale 1 : 1,300



Horizontal scale is 7.58 pixels per unit spacing.
Vertical exaggeration in model section display = 1.00.
First electrode is located at 0.0 m.
Last electrode is located at 500.0 m.
Wenner array used.

Unit Electrode Spacing = 2.50 m

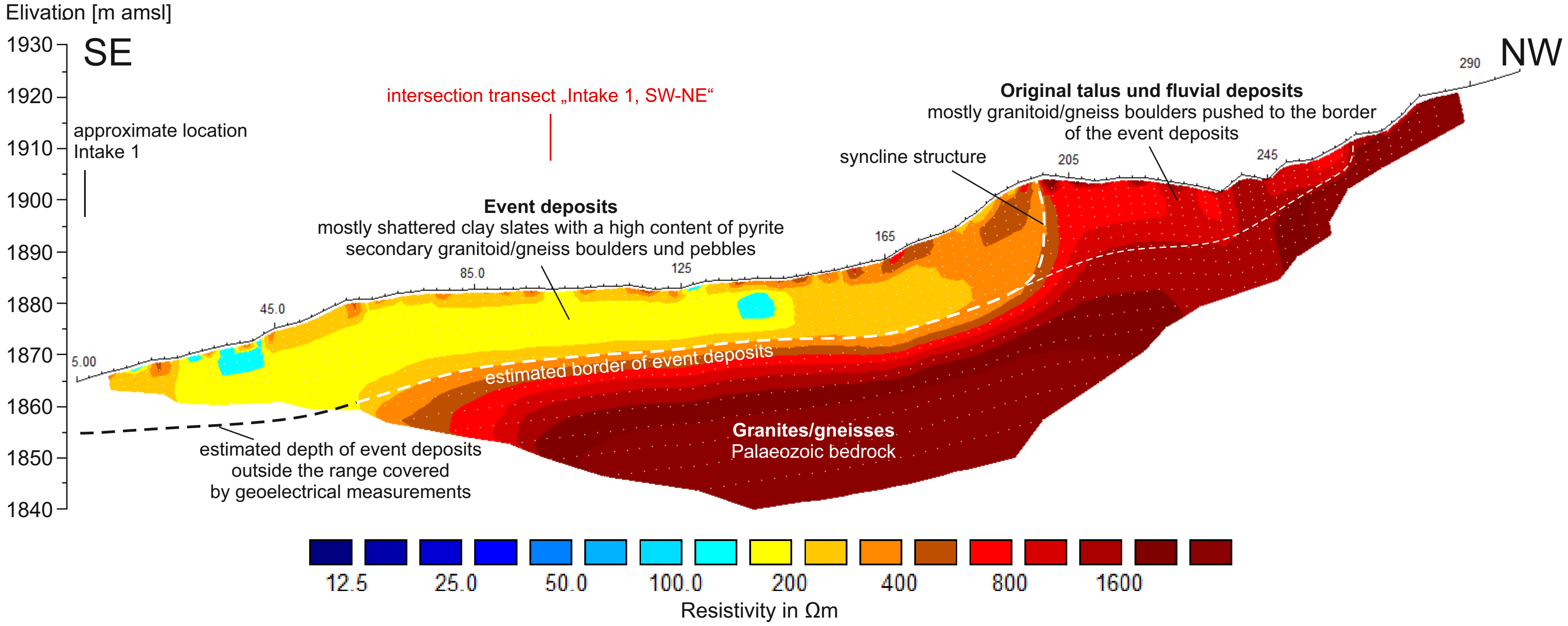
Map of research area - „Intake 1"
Scale 1 : 6,000



Map basis: Pleiades 50cm, 31st August 2019

Model resistivity with topography
Iteration 6 Abs. error = 2.1

Geoelectrical transect - „Intake 1, SE-NW“
Scale 1 : 1,300



Horizontal scale is 12.99 pixels per unit spacing.
Vertical exaggeration in model section display = 1.00.
First electrode is located at 5.0 m.
Last electrode is located at 300.0 m.
Wenner array used.

Unit Electrode Spacing = 2.50 m

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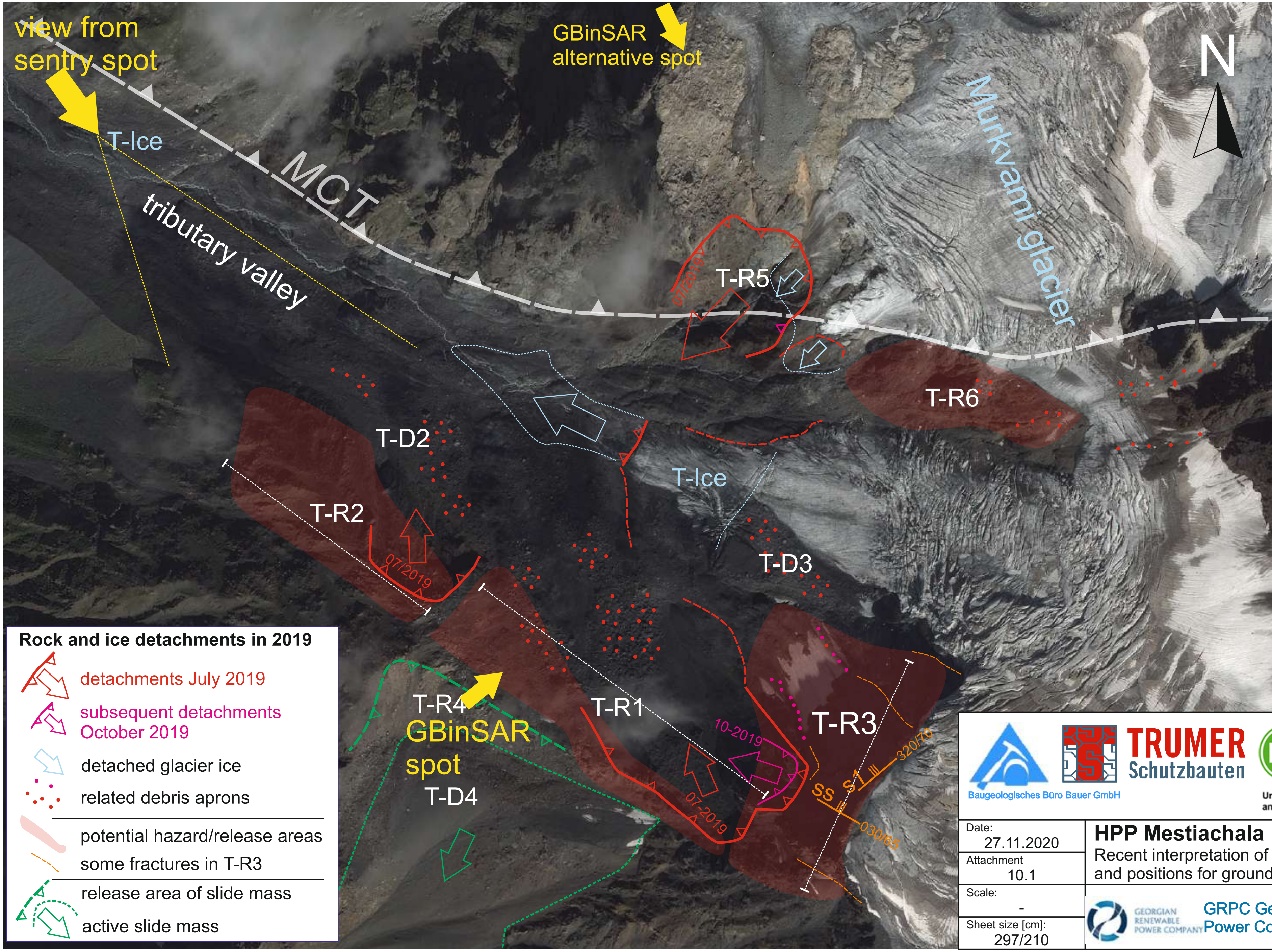
Date: 27.11.2020	**HPP Mestiachala 1**
Attachment 9.2	Geoelectrical measurements - Intake 1
Scale: 1:1,300 / 1:6,000	GRPC Georgian Reneweable Power Company JSC
Sheet size [cm]: 420/297	

HPP Mestiachala Priority Projects

Final report on field research and geohazard assessment 2020

Attachment 10 Monitoring of the July 2019 detachment area



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Date: 27.11.2020	**HPP Mestiachala 1**
Attachment 10.1	Recent interpretation of 2019 detachments and positions for ground-based InSAR
Scale: -	
Sheet size [cm]: 297/210	GEORGIAN RENEWABLE POWER COMPANY GRPC Georgian Reneweable Power Company JSC