Slope Activity Analysis in the Rogun Catchment Area, Tajikistan, using Remote Sensing Techniques

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Eidgenössische Technische Hochschule Zürich
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Slope Activity Analysis in the Rogun Catchment Area, Tajikistan, using Remote Sensing Techniques

MSc Thesis

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ABSTRACT

The stability and lifetime of construction projects in mountain areas is strongly dependent on local slope activity. Hydropower projects in particular are often affected and endangered by landslide damming and floodwave generation due to slope failures, and thus extensive studies of ground surface instability are vital to assess associated hazards. The Rogun Hydropower Project HPP located in Tajikistan in the Vakhsh – Surkhob River network is currently under construction, yet to date no inventory of active slope instabilities in its catchment area exists. The site lies within the seismically active Tien Shan and Pamir Mountain ranges of Central Asia and in particular the Peter the First Range. This region is marked by extreme topography, steep slopes and extensive valley networks and has experienced large and catastrophic slope failures in the past, of which a multitude have been triggered by earthquakes of magnitude $M \geq 4$. Co-seismic failures are thus common in the area and present a high geotechnical hazard.

The following thesis develops an inventory of slope instabilities in the Rogun Dam catchment area based on optical and synthetic aperture radar differential interferometry (DInSAR) remote sensing techniques to understand their distribution and associated hazards. Sentinel-1 multi-temporal differential interferograms are generated for summer periods of 2016 – 2018 and form the basis of active slope detection. These are supported by few ALOS PALSAR-2 differential interferograms. An activity likelihood analysis is developed to understand the state of activity of moving features and provide a semi-quantitative confidence thereof. Slope velocities are estimated based on a comparison between differential interferograms, while different movement types are identified based on a geomorphological classification. The collected data is subsequently integrated to perform spatial and statistical analyses in order to perform a proximity analysis, assess a co-seismic link and evaluate the damming hazard potential to the Rogun HPP. Results show that a clear majority of detected features are located within 10 km of major faults and in zones of high peak ground acceleration (PGA), indicating a potential seismic influence or triggering. Certain active slopes show an increase in surface displacement after a particular earthquake event and equally suggest a potential link. The obtained data is subsequently integrated to develop a damming hazard analysis for slope instabilities detected in Sentinel-1 differential interferograms with an assumed movement probability of 1. It considers the activity likelihood of slope movements, their distance to rivers and faults, as well as estimated volume and velocity per year. The results indicate that a total of 29.6 % of all features constitute a high damming hazard potential in case of catastrophic failure. 4.5 % of all features are located within 1 km of the planned Rogun Dam reservoir and present a high hazard of floodwave generation. The entire study thus clearly highlights the general slope activity in the Rogun Dam catchment area, with a majority of slope movements likely seismically linked and a significant amount presenting a high damming hazard.

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1 INTRODUCTION

Slope instabilities and failures frequently occur in mountain regions worldwide (Nadim *et al.* 2006). They are often induced either by geological or meteorological factors, but also occur as a result of seismic events in regions of high tectonic activity (Evans *et al.* 2009, Havenith & Bourdeau 2010, Fan *et al.* 2019). Such slope instabilities constitute a major geotechnical hazard to the surrounding environment (Nadim *et al.* 2006, Valagussa *et al.* 2019, Strom & Abdrakhmatov 2018) and in particular to hydropower projects, which are numerous in mountainous regions due to extensive river networks and high hydroelectric potential. The main associated hazard here is landslide damming due to slope failure and resulting dam overtopping or river channel blocking (Strom 2010, Strom & Zhirkevich 2013, Korup 2006, Fan *et al.* 2019). One of the most disastrous landslides in history illustrating this is the 1963 Vajont rockslide, which involved approximately 250 Mm³ and created a 140 m high flood wave that breached the newly constructed 260 m high Vajont Dam and claimed up to 2'000 lives (Wolter *et al.* 2014, Ibanez & Hatzor 2018).

In order to develop the necessary hazard assessments of active mountain regions, particularly in context of construction projects, it is crucial to create reliable inventories of detected slope instabilities and analyse their distribution and activity (Dini *et al.* 2019, Harp *et al.* 2011). The following study analyses surface slope activity in a particular region in Central Asia marked by high seismic activity and resulting slope instabilities. The ongoing Himalayan orogeny drives intracontinental collision between the Tien Shan and Pamir Mountain regions, forming high mountains with enormous hydroelectric power due to extreme topography and relief of up to 5'000 m (Hamburger *et al.* 1992, Strecker *et al.* 2003, Strom 2010). The Pamir Mountain range largely lies in the territory of Tajikistan, where the local government and international participants have started construction of the Rogun Hydropower Project (HPP), the worldwide tallest dam at Rogun in the Vakhsh – Surkhob river network (fig.1). Due to ongoing tectonic activity, however, the region frequently experiences earthquakes of magnitude $M > 4$ (Havenith & Bourdeau 2010, Hamburger *et al.* 1992) and resulting slope failures including rockslides and rock avalanches, soil slides, mudslides and loess flows, which may have a considerable damming and floodwave potential (Korup 2006, Strom 2010). Particularly large failure events $\geq 100,000 \text{ m}^3$ are critical here, which have been studied to show a direct dependency on ground motion in seismic events (Valagussa *et al.* 2019, Yuan *et al.* 2013, Fan *et al.* 2019). One such example is the Usoi rockslide in southern Tajikistan, which was triggered by a M7.2 earthquake in 1911 and led to formation of the worldwide tallest natural dam and resulting 500m deep Lake Sarez (Strom 2010). The stability of such landslide dams is uncertain and thus presents a major environmental and geotechnical hazard to the surroundings. Another seismically-induced failure occurred in 1993 in the Obi-Shur Creek downstream of the Rogun Dam site, which breached an existing cofferdam and stopped operation in diversion tunnels (Strom and Zhirkevich 2013).

The examples above and high seismic activity in the Tien Shan and Pamir Mountains highlight the high damming hazard potential in the region, yet to date no assessment of slope activity in the Rogun Dam catchment area in context of the dam construction has been done. Such an analysis is highly important, however, to ensure safe construction and efficient operation upon dam completion. This research gap

presents the major motivation for this thesis, which will aim at filling it by addressing the following scientific questions as part of the IPL-224 Project of the International Program on Landslides:

- 1) What is the general state of slope activity and distribution of unstable slopes in the Rogun Dam catchment area?
- 2) Is there a clear seismic influence on detected slope movement?
- 3) What is the estimated damming hazard potential of detected slope instabilities in relation to the Rogun HPP?

These research questions will be addressed in the following thesis by initially developing an inventory of active slopes. This is done by exploiting remote sensing data, in particular optical and space-borne Synthetic Aperture Radar (SAR) imagery, which is a popular technique in remote and inaccessible yet often active mountain areas worldwide (Strozzi *et al.* 2010, Manconi *et al.* 2018, Dini *et al.* 2019). Subsequently, spatial analyses are performed on the obtained dataset to understand if there is a link to the seismic activity in the area and to develop a damming hazard analysis.

2 STUDY AREA

The exact study area is located within the southern Tien Shan and northern Pamir Mountain ranges of Central Asia roughly between 38°30'N and 39°30'N and 69°30'E and 71°30'E (fig. 1). It extends from Rogun in the southwest up towards the Alai Valley in the northeast and lies largely within the Pamir Peter the First Range (PFR), covering a total area of 9.7×10^3 km². It is marked by mountainous topography with a relief range of >5'000 m from low valleys in the west to high glaciated mountains in the east. Two large river networks define the hydraulic properties of the area. The Surkhob River running roughly NE-SW along the north of the study area and Obikhingou River joining from the south to form the Vakhsh River. The Rogun HPP is being constructed downstream of this network at the town of Rogun and is planned to hold a water reservoir covering an area of approximately 161 km² as indicated in fig. 1. The northern valley comprises the Vakhsh and Surkhob rivers and the southern valley the Obikhingou River, separating from north to south the Kabudkrym (Tien Shan), PFR and northern Pamir Mountain regions (Hamburger *et al.* 1992).

Construction of the Rogun HPP is coordinated by the state-run company OJSC Rogun HPP (Open Joint-Stock Company). Present construction began in 2016 with the involvement of the company Salini Impregilo; upon completion, the dam will generate up to 3'600 MW of hydroelectric energy, thus doubling the country's energy potential. It will be 335 m high with a clay core; its foundations are set at 965 m a.s.l., with a 660 m long and 20 m wide crest at 1'300 m a.s.l. (<https://www.salini-impregilo.com/en/projects/in-progress/rogun-dam.html>, last accessed 18/07/2019). Two diversion tunnels redirect the Vakhsh river network during construction. The first of six turbines started generating electricity on 16th November 2018, with a second producing energy since April 2019.

Figure 1: Study area outline on Google Earth satellite image and location of Rogun Dam and towns of Khait, Gharm and Tavildara along the Vakhsh – Surkhob River and Obikhingou River valleys, respectively. Tajikistan's location to the NW of the Himalayan orogeny in Central Asia is shown in the bottom right, the study is shown in white.

3 REGIONAL BACKGROUND AND PREVIOUS STUDIES

3.1 Tectonics and Geology

The geology and tectonic activity in the study area are strongly influenced by ongoing plate tectonics and convergence between India and the Asian continent. The Cenozoic Tien Shan and Pamir Mountain ranges are products of the rapid Indian indenter motion into the Asian plate at rates of 40-50 mm/a, causing collisional movement at slower rates of 13-19 mm/a towards the north and east (Strecker *et al.* 2003, Molnar *et al.* 1973, Hamburger *et al.* 1992, Lukk *et al.* 1995, Metzger *et al.* 2017). The Pamir and PFR converge northward by 300 km and collide with the Tien Shan along a series of ENE-SWS-striking and 25°-40° S-dipping thrust faults with a (sub-)horizontal NW-SE to N-S oriented maximum compressive stress direction (fig. 2; Yuan *et al.* 2013, Strecker *et al.* 2003, Lukk *et al.* 1995). Strecker *et al.* (2003) estimate a local convergence rate of up to 6 mm/a based on Holocene geological data and deformed landforms, while Lukk *et al.* (1992) suggest a more rapid movement of up to 2 cm/a based on similar Quaternary displacements.

Figure 2: Arcuate thrust trends (red) due to the N-S India - Asia convergence (large arrows) mark the intracontinental collision between the Tien Shan and Pamir Mountain regions. Small arrows show regional compressive stress directions, the study area is roughly located as indicated by the yellow box (adapted from Lukk *et al.* 1995).

The local geology in the Tien Shan and Pamir Mountains broadly consists of Proterozoic and Palaeozoic crystalline bedrock overlain in the PFR by Mesozoic to Palaeogene interbedded shallow and non-marine sediments, containing Jurassic gypsum-rich evaporite layers (Hamburger *et al.* 1992, Molnar *et al.* 1973). These are overlain by Neogene fluvial conglomerates and sandstones found throughout the Tajik Depression and thickening towards the south (Hamburger *et al.* 1992). Triassic volcanism and intrusions are noted throughout the northern Pamir and PFR. The observed units are largely conformable, suggesting a pre-orogenic deposition (Hamburger *et al.* 1992). The geological map in fig. 3 shows units in the study area, which broadly comprise Cretaceous and Miocene sediments together with Quaternary alluvium and terrace deposits in the river valleys. These are supplemented by information obtained from

Russian geological maps provided by Dr. Alexander Strom and adapted as shown in fig. 4. These show more detailed geological units of Carboniferous granites, Proterozoic gneiss including Carboniferous granite intrusion and Upper Devonian to Lower Carboniferous shales, sandstones and limestones in the southern Tien Shan. The Central PFR is dominated by Cretaceous to Neogene, often fractured sediments, including siltstones, sandstones and conglomerates as well as gypsum-rich limestone, clay and marl layers. Towards the southeastern PFR, Jurassic volcanic sediments including lava and tuff deposits as well as sandstones and local coal seams are found.

The PFR in particular was studied in detail by Hamburger *et al.* (1992), who discuss two formation mechanisms. Its convergence with the southward underthrusting Tien Shan either represents a passive continental margin, i.e. extensional system, or more likely the shortening and closing of a foreland basin system, the Tajik Depression to the immediate SW of the study area, as part of an intracontinental collision. Thrust faults extend from the Tajik Depression NE towards the Tien Shan and SE towards the Pamir range along arcuate trends as seen in fig. 2 and are flanked by strike-slip faults (Lukk *et al.* 1995). The main faults here are the Darvaz-Karakul (D-K) strike-slip fault south of the Tajik Depression, running approximately along the Obikhingou River valley, as well as multiple shallow imbricate thrust systems defining the Vakhsh - Surkhob River valley (Tien Shan – Pamir boundary) and occurring within the tightly to isoclinal folded PFR (Hamburger *et al.* 1992). These include the low-angle Vakhsh Thrust and Petrovsky Thrust which link to the Main Pamir Thrust (MPT) further east (fig. 3; Hamburger *et al.* 1992, Lukk *et al.* 2008, Lou *et al.* 2009, Evans *et al.* 2009). Thrusting typically occurs along relatively weak Jurassic gypsum-rich layers as these are often observed on the fault hanging walls, implying a regional décollement horizon (Hamburger *et al.* 1992). The convergence is estimated as Cenozoic in age due to the observed stratigraphy and geological units, creating the present extreme topography with mountain peaks exceeding 7'000 m a.s.l. and river valleys below 2'000 m a.s.l. It is hypothesised that the Himalayan arc migrates northward and leads to progressive closure of a Tajik Depression foreland basin particularly during the Cenozoic, causing deformation and uplift during the Miocene in the Pamir Mountain region (Hamburger *et al.* 1992).

Figure 3: Top: Geological overview map of the Gharm region and PFR. Bottom: Cross-section through profile A-A' crossing from NW to SE the Surkhob River valley and Vakhsh and Petrovsky Thrusts (linking to the MPT further east), the folded PFR, and Obikhingou River, where the Darvaz-Karakul strike-slip fault is roughly located slightly towards the east (from Hamburger et al. 1992).

Figure 4: Rough geological map based on Russian data obtained from Dr. Alexander Strom. Light colour areas along river valleys are likely Quaternary cover, those in mountainous regions unknown.

3.2 Current Seismic Activity

The ongoing tectonic activity and high shortening rates of deformation in the Tien Shan and Pamir Mountain regions due to the India-Asia collision result in high seismicity (Lukk *et al.* 1995, Lou *et al.* 2009, Metzger *et al.* 2017). The so-called Gissar – Kokshaal seismic zone just north of the PFR forming a boundary with the Tien Shan includes up to 50 % of the $M > 6$ earthquakes in Central Asia, while the PFR itself equally shows several shallow to intermediate zones of high seismic activity along the MPT – Vakhsh and D-K fault systems when regarded in plan view and cross-section (fig. 5; Lou *et al.* 2009, Hamburger *et al.* 1992, Lukk *et al.* 1995). A shallow zone of high activity yet overall low magnitude earthquakes is observed at approximately 12 km depth below the PFR, separated by a roughly 5 km deep aseismic section from an additional highly active zone at 17-35 km depth below the surface. The lower zone dips south and can be traced below the Pamir Mountains towards the south and updip towards the Tien Shan suture in the north, suggesting this seismic belt may represent shallow basement thrusts. Lou *et al.* (2009) additionally observe a much deeper seismic zone up to 130 km below the surface, which may represent deformation directly related to or along the collision horizon.

The Gharh region has been extensively studied due to its anomalously high earthquake activity and initiated the Complex Seismological Expedition (CSE) in 1955 after the disastrous 1949 Khait Earthquake (see section 3.3.1). 90'000 earthquakes have been detected since, which has led to the clear definition of two active seismic belts at variable depths below the PFR and Pamir as seen in fig. 5 (Hamburger *et al.* 1992).

Figure 5: Top: Earthquake locations showing two distinct seismic belts, a shallow-intermediate depth zone along the MPT and D-K fault systems in the PFR, and a deeper zone in the Central Pamir Mountains (from Lou et al. 2009). Bottom: Cross-section from NW to SE through the PFR (black profile line in top image) showing shallow earthquake locations due to shallow thrusting (Hamburger et al. 1992).

The CSE includes 15 seismic stations operational until 1992, allowing a detailed record of earthquakes for nearly 40 years and thus enabling earthquake prediction studies (Lukk et al. 1995). Additionally, the Earthquake Model Central Asia (EMCA), operational from 2011 to 2014 as part of the Global Seismic Hazard Assessment Programme (GSHAP), has created seismic maps of peak ground acceleration

(PGA) for a return period of 475 years to study earthquake hazard and risk at a cross-border scale in Central Asia (<http://www.emca-gem.org/>, last accessed 13/07/2019, fig. 6). The results show that the greater Tien Shan and Pamir Mountain region has a PGA $>3.2 \text{ m/s}^2$ and the study area in particular $>4.8 \text{ m/s}^2$, where 0.8 m/s^2 suffice to trigger landslides (Fan *et al.* 2019). Despite this, earthquake statistics are not easily determined for these regions due to the complex tectonic activity. Recurrence times can rarely be approximated; the M7.3 Suusamyr earthquake of 1992 in the Kyrgyz Tien Shan is estimated at a recurrence time of min. 500 years, the expected return period for earthquakes $M>6$, often triggering massive co-seismic failures, in the entire Tien Shan and northern Pamir region is, however, significantly shorter at 10 – 20 years (Abdrakhmatov *et al.* 2003, Havenith & Bourdeau 2010, Metzger *et al.* 2017).

Figure 6: PGA [m/s^2] map for Central Asia with Tien Shan and Pamir region outlined by white box, adapted from EMCA GSHAP ArcGIS data (<http://www.emca-gem.org/>).

3.3 Landslide Hazard and Co-Seismic Failure Events

3.3.1 Slope Instabilities

Slope instabilities worldwide and particularly in the mountains of Central Asia have been found to occur on a range of shallow to steep slopes and cannot be specifically related to geographic occurrences of rainfall- or geomorphologically-induced failures (Havenith & Bourdeau 2010). Due to the extreme topography and high seismic activity in the Tien Shan and Pamir Mountain ranges, a multitude of soil and rockslides, rock falls and loess flows is often directly dependent on earthquakes. Mass movements triggered within seconds or minutes of an earthquake, ranging in size from 10^3 m^3 to 10 km^3 , are termed *co-seismic landslides*, while slope movement and failure post-dating a particular earthquake event are referred to as *post-seismic landslides* (Fan *et al.* 2019). Tajikistan is classified as a landslide hazard hotspot due to the high occurrence frequency of large failure events throughout the 20th century, with some of the highest recorded mortality rates (Nadim *et al.* 2006, Petley 2012). Saponaro *et al.* (2015) determine a very high landslide susceptibility for the Tajik Pamir and study area of this thesis, which coincides with a medium to very high hazard determined by Nadim *et al.* (2006) based on PGA observations (fig. 7). One of the most disastrous earthquakes in Tajikistan in recent history is the M7.4 Khait event of 1949, causing a large rockslide east of Khait and extensive loess flows in the Yasman valley to the west, killing up to 7'000 people and involving more than 320 Mm^3 (Evans *et al.* 2009). Earthquake and landslide hazard surveys were conducted in detail during the Soviet regime until the 1990s but have since ceased (Saponaro *et al.* 2015), yet the ongoing deformation and resulting high seismicity in the area strongly call for increased hazard studies and slope instability mapping.

Past landslides, particularly those related to earthquakes, have been studied in a number of papers (Evans *et al.* 2009, Havenith & Bourdeau 2010, Strom 2010, Yuan *et al.* 2013, Strom & Abdrakhmatov 2018, Fan *et al.* 2019). Massive rockslides and rock avalanches as well as loess earth flows appear to be the predominant failure type in the Tien Shan and Pamir Mountains, which are generally triggered by $M \geq 4$ earthquakes (Havenith & Bourdeau 2010, Keefer 1984). Evans *et al.* (2009) study the 1949 Khait rockslide and describe the local geology and geomorphology along the Surkhob valley, while Havenith & Bourdeau (2010) and Strom & Abdrakhmatov (2018) collect data on several regional events. Certain predisposing factors can be deduced from these studies. Mountains as high as 4'400 m a.s.l. bordering the Surkhob valley, with a relative relief of 2'500m to the valley floor, are typically grass-covered yet contain variably thick layers of loess material with an assumed plasticity index of only 10 (Evans *et al.* 2009). Loess is particularly critical, as this material is highly sensitive to increased moisture content and may rapidly liquefy and initiate flowslides even on very low-angle slopes (Evans *et al.* 2009, Fan *et al.* 2019). Proterozoic bedrock and Palaeozoic – Mesozoic and Neogene sediments are often intensely fractured and foliated, which may influence and increase landslide susceptibility; the relationship between bedding and cross-bedding in sediments is equally important. Landslides are thus typically triggered by a complex interplay of geological, structural, anthropogenic and meteorological predisposing factors coupled with the regional seismicity, where the latter controls the distribution of co-seismic failures (Fan *et al.* 2019).

Figure 7: A medium to high Landslide Hazard is shown for Tajikistan and the study area based on a PGA with a 475 year return period (Nadim *et al.* 2006).

The distribution of co-seismic failures is controlled by a number of factors (Fan *et al.* 2019). The relative location of slope failures to active fault zones and fault rupture orientation is important, where earthquakes related to normal or thrust faults predominantly trigger failures on the hanging wall (e.g. south of the MPT), while movement occurs largely symmetrically around strike-slip faults (e.g. the D – K fault; Fan *et al.* 2019, Valagussa *et al.* 2019, Meunier *et al.* 2007, Strom & Abdrakhmatov 2018). The expected landslide density within certain distances from fault rupture zones and earthquake epicentres is highly dependent on earthquake magnitude and shaking intensity and thus cannot be generalised (Keefer 1984). Topographic amplification of PGA is typically highest near slope crests, thus showing a pre-dominant occurrence of co-seismic movement; this, however, can also be strongly influenced by heterogeneities in the rock mass (Fan *et al.* 2019, Meunier *et al.* 2008, Meunier *et al.* 2007, Havenith & Bourdeau 2010, Strom & Abdrakhmatov 2018). Factors such as slope angle, aspect and curvature as discussed by Saponaro *et al.* (2015) vary among the known events and thus do not indicate a specific susceptibility, yet may influence failure predisposition due to certain block movement orientations and seismic wave propagation (Fan *et al.* 2019). A slight trend towards convex slopes is noted by Havenith & Bourdeau (2010), as well as a strong link between slope gradient and geology. Lithological controls may exist, where larger failures such as rockslides are noted on steeper slopes ($>30^\circ$) and in stronger bedrock, while soft sediments such as Quaternary deposits and loess likely fail in smaller volumes and on shallow slopes (up to $\sim 2^\circ$) as in the Yasman valley (Havenith & Bourdeau 2010, Meunier *et al.* 2007,

Keefer 1984). This behaviour can be expected in the study area based on the local geology and extreme relief.

Based on global case studies, a relationship between landslide area and seismic effects can be established (Valagussa *et al.* 2019, Fan *et al.* 2019, Keefer 1984). Increased ground motion frequency and duration generate larger areas of failure and individual failure sizes, as the shaking intensity can reduce greater rock strengths and overcome cohesion at depth. Landslide volumes are not easily linked empirically to ground motion frequency and strongly depend on an understanding of the pre- and post-failure subsurface geometry (Fan *et al.* 2019). Generally, a decrease in landslide size is observed with increasing distance from the fault trace (Valagussa *et al.* 2019, Havenith & Bourdeau 2010, Saponaro *et al.* 2015).

3.3.2 Landslide Damming

River damming due to landslides is a particular post-failure and potentially post-seismic hazard in the Tien Shan and Pamir Mountain ranges (Fan *et al.* 2019, Strom 2010). The slope failure size necessary to generate damming is dependent on the local relief, geology, meteorology and seismic activity. The mountains act as major glacial, snowmelt and rainfall sources for rivers, comprising large catchment areas feeding the extensive river valley network. The Central Asia region includes numerous landslide dams and resulting lakes, of which at least 100 still contain water and act as reservoirs (Korup *et al.* 2006, Strom 2010, Strom & Abdrakhmatov 2018). The stability of these dams is critical; some remain stable for millennia or centuries, while others have been breached and, in some cases, caused catastrophic outburst floods. Depending on their stability and geological prerequisites, landslide dams may significantly alter valley networks and sediment flux, thus changing entire river landscapes (Fan *et al.* 2019) and presenting a critical geotechnical hazard to hydropower plant construction. A well-known current example in the Tajik Pamir south of the study area is the Usoi rockslide dam, triggered in 1911 by the Pamir M7.2 earthquake in southern Tajikistan (Strom 2010). The 2 km³ large rockslide created the worldwide largest natural dam, whose stability remains critical and which has formed the 500 m deep Lake Sarez. An identified damming site to the east of the study area and directly affecting the Rogun catchment area is a series of landslides and resulting potential river blockages in the Muksu River valley (Strom & Zhirkevich 2013). In general, bedrock failures are more prone to longer-term or permanent damming, while soft sediments and Quaternary deposits typically erode more rapidly and may form large debris flows (Strom 2010). Factors critical to the long-term stability of natural dams and their risk of failure in subsequent earthquake events therefore include geological parameters as well as precipitation and runoff rates, backward erosion of the dam, dam crest or on the lake flanks, and internal deformation within the dam (Strom 2010, Fan *et al.* 2019).

4 METHODOLOGY

The following methods are implemented to address the outlined scientific questions by detecting slope instabilities and understanding their distribution and state of activity. The results are ultimately integrated to perform spatial analyses on the collected database in order to assess a co-seismic link and estimate the damming hazard potential to the Rogun HPP. All data, results and analyses are included in a digital appendix.

4.1 Landslide and Earthquake Inventory

4.1.1 Landslide Inventory

An inventory of past known slope failure events is developed for the study area to understand the temporal and spatial distribution of slope activity and estimate predominant failure types. This allows more effective interpretation of optical images, DEMs and differential interferograms to estimate the current slope activity and hazard to the Rogun HPP. The inventory is created based on existing literature (Strom & Abdrakhmatov 2018) and databases such as NASA's Landslide Viewer (<https://maps.nccs.nasa.gov/arcgis/apps/webappviewer/>, last accessed 16/07/2019). It includes information on failure type and volume, involved rock types, and impacts on humans and the environment in the study area and other regions of the Pamir and Tien Shan. Links to potential trigger mechanisms can be derived from this, based on known meteorological events such as extreme precipitation or snowfall as well as earthquakes that occurred prior to the failure. The inventory will act as a foundation for comparison and cross-validation with results obtained from the slope activity analysis based on remote sensing (section 4.3).

4.1.2 Earthquake Inventory

To understand the earthquake hazard and frequency in the study area, an inventory of known earthquakes is developed based on the existing literature (Evans *et al.* 2009, Havenith & Bourdeau 2010) and databases such as those provided by the USGS and Volcano Discovery (<https://www.volcanodiscovery.com/earthquakes/tajikistan.html> and <https://earthquake.usgs.gov/earthquakes/map/>, both last accessed 16/07/2019). The location, depth and magnitude of earthquakes are noted as these are important to understand their spatial distribution relative to tectonic features as well as their impact on the local geology and slope stability. Havenith & Bourdeau (2010) and Keefer (1984) define an earthquake magnitude threshold of $M \geq 4$ that may trigger slope failures; to ensure a generalised error margin, earthquakes of $M \geq 3.5$ are considered in this study. Combining the earthquake and landslide inventories may allow establishment of a potential link between past slope failures and seismic events and may indicate the role and influence of seismicity for current slope activity.

4.2 Proximity Analysis

4.2.1 Optical Images and DEM

The use of optical images acquired by satellites such as those displayed in Google Earth Pro and of sufficiently high resolution DEMs provides an effective tool in understanding slope geomorphology and

cover (Guzzetti *et al.* 2012, Fiorucci *et al.* 2018, Fan *et al.* 2019). Instabilities may initially be detected based on optical imagery, as loose versus intact material as well as fractures and scarps are typically clearly identified. The use of 3D views in Google Earth Pro additionally helps in understanding the slope dimensions and viewing critical locations from different angles, thus approximating observations otherwise only possible in the field. Combined with radar imagery, a potentially unstable site can be cross-validated and possible geomorphological influences or factors such as vegetation and presence of fractures assessed. The proximity of slope instabilities to such geomorphological features can subsequently be analysed to understand possible links and a predisposition for slope movement. This may be integrated into a complete kinematic analysis assessing preferred slope failure modes and orientations.

DEMs for Tajikistan and covering the study area can be freely downloaded from NASA's Shuttle Radar Topography Mission (SRTM) at a spatial resolution of 90 m and 30 m (<http://srtm.csi.cgiar.org/srtmdata/>, last accessed 14/01/2019). DEMs at finer resolution of 12 m provided by the DLR TanDEM-X data can be purchased for scientific purposes according to an application process; unfortunately, use of these was not granted during the time frame of this master thesis.

4.2.2 Lineament Study

To understand the main tectonic stress regime and structural activity in the study area and thus assess their predisposition influence on slope instability, lineaments in the study area are mapped and their relative location to detected slope movement analysed in a proximity analysis. Linear ground surface features are detected and traced in ArcGIS based on the World Imagery optical basemap and SRTM 30 m DEM. The existing literature on local tectonics and geology as well as an extensive geological map provided by Dr. Alexander Strom are used to determine lineament types. Large scale features defining entire mountain ridges and valleys such as faults, folds and fractures are expected to be well detected, while smaller scale features such as bedding and foliation may not be easily seen or distinguished as such in optical images. Features at the scale of slope faces are an important indicator of slope activity, as they can directly influence the slope's failure predisposition. These may reflect the general tectonic overprint of the region, or can be induced seismically, such as extensive scarps and potential failure planes, possibly indicating very large instabilities on the scale of deep-seated gravitational slope deformations (DSGSD; Havenith & Bourdeau 2010, Strom & Abdrakhmatov 20180). Detected faults will be used in a proximity analysis to understand a potential link between slope movement and seismicity.

4.3 Analysis of Surface Displacement

4.3.1 DInSAR

The main method applied to detect slope instabilities is the use of SAR satellites and Differential SAR Interferometry (DInSAR) in particular; these will form the basis of a surface displacement analysis through activity mapping of potentially unstable features. DInSAR allows detection of relative displacement at a resolution of a few centimetres to millimetres (Manconi *et al.* 2014) and is built on the following principals.

Two SAR images covering largely the same area on Earth, acquired at different times (temporal baseline) and with only a slight orbital offset (spatial baseline) are combined to measure their phase difference, displayed in an *interferogram* (Manconi *et al.* 2014). This includes a *reference* image to which a second *slave* image is co-registered, ensuring that both contain equal properties and cover the same area. The phase offset between the two images reflects elevation along the satellite line of sight (LOS), effectively creating a DEM. By removal of the topographic phase from this interferogram, movement variations along the LOS can be displayed in a *differential interferogram*. This can be done using a DEM or a second interferogram, which does not show any deformation (Bürgmann *et al.* 2000, Wasowski & Bovenga 2014, Sun *et al.* 2015). Differential interferograms show displacement occurring during the period defined by the temporal baseline in fringes. One fringe cycle corresponds to a relative movement of 2π (Strozzi *et al.* 2010). To derive absolute displacement, the interferometric phase is unwrapped and the 2π fringe cycles are converted into absolute values of half the satellite wavelength $\lambda/2$. Here, differential interferograms are named according to the acquisition dates of the reference and slave image following a year-month-day format, e.g. 20160912_20160924 (i.e. the reference image was taken on 12th September 2016 with its slave image counterpart acquired on 24th September 2016, constituting a temporal baseline of 12 days).

Differential interferograms are influenced by certain errors, which can be corrected for during image processing. These include mainly atmospheric and topographic effects and signal noise (Barboux *et al.* 2015, Strozzi *et al.* 2010, Bürgmann *et al.* 2000). The resolution is particularly affected, where e.g. vegetation and snow cover drastically reduce the image *coherence* (Wasowski & Bovenga 2014). Coherence is indicative of the similarity between two SAR images on a range of zero (no coherence and thus decorrelated) to one (measured signals are identical in both images). Images acquired during summer and autumn months thus give more coherent results, while those acquired during winter and spring display information less clearly.

An additional important factor affecting differential interferograms is the location of an unstable feature with respect to the satellite geometry (Manconi *et al.* 2014). Satellites acquire images in numbered ascending and descending orbits in along-track, across-track or repeat track configurations. Differential interferograms display movement in the LOS direction, combining vertical and horizontal components that cannot be distinguished in a single orbit configuration but may be determined if using data from both orbits (Wasowski & Bovenga 2014, Strozzi *et al.* 2010, Barboux *et al.* 2015, Manzo *et al.* 2006). Geometric distortions such as layover or shadowing also frequently influence the phase display (Strozzi *et al.* 2010, Wasowski & Bovenga 2014). Detection of a ground surface feature is thus strongly dependent on its spatial orientation relative to the satellite LOS. To maximise the acquired ground information, ascending and descending orbits are considered for this study.

Equally important to the display of movement in a differential interferogram are temporal and spatial phase aliasing (Wasowski & Bovenga 2014). If a feature movement exceeds a velocity of $\lambda/4$ between subsequent images of the shortest temporal baseline, phase jumps may occur and the coherence can be reduced (Pritchard & Yun 2018, Manconi *et al.* 2014). The amount of fringe cycles covered in this so-called interferometric phase decorrelation cannot be exactly determined and thus no absolute

velocity extracted. The maximum detectable velocities therefore strongly depend on the given temporal and spatial baseline.

Effective temporal baselines are chosen according to the project focus and goal. For construction of the Rogun HPP, both small and large as well as rapid and slow movements must be considered. Fast and thus typically smaller instabilities present the most immediate failure hazard, while large and generally slower features are critical to the Rogun catchment damming hazard potential. The latter typically move at slow rates but may fail rapidly if e.g. triggered by seismic events (Valagussa *et al.* 2019), thus illustrating the importance of local seismicity. Long term activity with movement of few mm/a to cm/a is likely detected at larger temporal baselines of 1 – 2 years. Faster, possibly smaller and seasonally affected features moving few mm/month to cm/month will likely be detected at temporal baselines of 12 days to six months.

This study will process two satellites, the European Space Agency's (ESA) Sentinel-1 and the Japan Aerospace Exploration Agency's (JAXA) ALOS PALSAR-2. Sentinel-1 comprises two satellites (S1A and S1B) acquiring images at C-band (wavelength $\lambda = 5.6$ cm) in repeat track TOPS Interferometric Wide Swath (IW) mode every 12 days over the study area, representing 2.8 cm of movement per fringe cycle in an unwrapped differential interferogram. The ground resolution is roughly 2.3 m in range and 13.6 m in azimuth directions (Manconi *et al.* 2018). The mission started in 2014 with an estimated lifetime of 20 years and will allow systematic and continuous surface deformation monitoring. Ascending orbit number 173 and descending orbit 78 cover the study area as shown in fig. 8, containing available data from 20150322 until present.

ALOS PALSAR-2 satellite with a wavelength of 23.6 cm at L-band and a revisit time of 14 days allows detection of more rapid surface displacements and over longer temporal baselines, with a fringe cycle movement of 11.8 cm in an unwrapped differential interferogram. The mission started in 2014 and acquires images in stripmap mode covering the study area as shown in fig. 8. The descending orbit and frame is 59/2830, ascending orbit and frame 164/770 are split up into a NE and SW image.

4.3.2 Sentinel-1 Data Processing

Differential interferograms are processed using a software developed by GAMMA Remote Sensing and Consulting AG, based in Gümligen, BE Switzerland, and kindly licensed for use in this MSc thesis. Following is a detailed list of the individual processing steps that generate differential interferograms from Sentinel-1 raw data for ascending orbit 173 and descending orbit 78. All used scripts and resulting differential interferograms are supplied in the digital appendix, while those directly used in the surface displacement analysis are listed in App. I.

Raw data download

1. Raw data is acquired from the NASA Alaska Satellite Facility (<https://vertex.daac.asf.alaska.edu/>). The study area for orbit tracks 173 and 78 is specified for which all available images are subsequently listed and downloaded as compressed data using a python script provided by the database.

Figure 8: Ascending (red) and descending (black) configurations for Sentinel-1 orbits 173 and 78 and ALOS PALSAR-2 orbits 164/770 and 59/2830 covering the study area (yellow) and Rogun Dam (white-black dot), overlain on an SRTM 90 m DEM.

Manual pre-processing of the reference image

1. An appropriate reference image is chosen to ensure minimum snow cover and maximum data coherence. For orbit 173, the reference image is 20180809, for orbit 78 it is 20180815.
2. The reference image is unzipped and processed as a single look complex (SLC) file containing three subswath images of 18 bursts each. Relevant bursts covering the study area are selected to minimise data size. The three images are then concatenated to form a single mosaic image with 5 range and 1 azimuth looks, from which a multi look intensity image (MLI) is generated.
3. The concatenated image is geocoded to the available SRTM 30 m DEM.

Automatic processing of slave images

1. Processing of slave images follows the same procedure as for the reference image according to an iterative script. Specified images are unzipped and transformed into SLC format, and concatenated to the selected bursts using the same multi look factors as for the reference image. Here, images acquired from April to November in 2016 to 2018 are used. Winter images show extensive snow cover and thus do not provide sufficiently coherent information for this analysis.
2. The concatenated mosaic image is then co-registered to the pre-processed and geocoded reference image to ensure equal coverage of ground points.

Differential Interferograms

1. To generate differential interferograms, pairs are selected from all co-registered images according to temporal baselines of 12 days, 24 days, 36 days, 48 days, two to six months as well as one year.

2. The selected pairs are then processed automatically in a pre-defined script kindly licensed by GAMMA Remote Sensing AG, using the software's programmes.

2.1 Differential interferograms are generated and saved as raster files.

2.2 Adaptive filtering is applied to reduce phase noise and smooth out 'salt and pepper' appearances in order to better show fringes of movement. This is done in three iterative steps to obtain optimum results.

2.3 The differential interferograms are geocoded to the SRTM 30 m DEM and masked to show areas of layover and shadowing as *no data* areas. These are seen as black in the final images.

Velocity Calculations

The final differential interferograms show movement as a wrapped fringe cycle of 2π , which can be used to estimate velocities of particular surface features. For Sentinel-1, this corresponds to a movement of 2.8 cm during the given temporal baseline. Temporal phase aliasing must be considered here, as movement exceeding a velocity of $\lambda/4$ during this period will be shown as phase jumps and the absolute number of fringes cannot be seen (Wasowski & Bovenga 2014, Pritchard & Yun 2018, Manconi *et al.* 2014). Movement is determined based on a comparison of multi-temporal baseline differential interferograms in which the relevant active slope feature is detected in. The final velocity is calculated from a single differential interferogram that most clearly shows the fringe cycles and is given in App. II.

4.3.3 ALOS PALSAR-2 Data Processing

ALOS PALSAR-2 data is equally processed with the GAMMA software and generally follows the procedure outlined for Sentinel-1, using the same programmes. Here, images acquired from April to November for 2016 – 2019 are considered, for which SLC data is acquired from the JAXA ALOS User Interface Gateway (<https://auig2.jaxa.jp/ips/home>). Ascending orbit 164/770 includes two images covering a relative NE and SW region. For NE, the chosen reference image is 20180728, for SW 20180714, and for orbit 59/2830 20180428. For the latter no summer images are available. The reference images are unzipped and geocoded to the available SRTM 30m DEM. Slave images are equally unzipped and co-registered to the corresponding reference image. Generation of differential interferograms is done as for Sentinel-1 for temporal baselines of 56 days to two years. Shorter temporal baselines are not possible due to lacking data for this particular area of the world. Resulting fringe cycles of 2π represent movement of 11.8 cm during the temporal baseline, which can be used to extract velocities. Again, phase aliasing must be considered.

4.3.4 Surface Displacement Mapping

Mapping of unstable features in the study area is crucial to understand the regional susceptibility to slope failure (Guzzetti *et al.* 2012, Fan *et al.* 2019, Harp *et al.* 2011) and is done in ArcGIS, licensed by ETH Zurich. Landslide mapping done by Dini *et al.* (2019) for the Himalaya in Bhutan and as part of

ESA's GlobPermafrost Initiative for southern Kyrgyzstan (Alfred Wegener Institute, https://maps.awi.de/map/map.html?cu=Globpermafrost_Arctic#mapcontent, last accessed 16/07/2019) will act as foundations for this task. Initial mapping is not based on a distinction between slope movement type, timing or potential triggering factors but largely on movement detection in the DInSAR analysis. The resulting catalogue of slope activity will therefore likely include both seismically and non-seismically induced slope instabilities of various movement types.

Slope surface movement is detected and mapped as polygons based on the generated differential interferograms. The given spread of temporal baselines is important here to increase the number of visible features and cover a range of possible movements. The ArcGIS World Imagery optical basemap and SRTM 30 m DEM additionally aid in detecting features based on geomorphological signals. Particularly large features involving several 100,000 m³ are of interest, as these may present hazards to landslide damming in the study area and breach of the Rogun Dam (Yuan *et al.* 2013). The resulting map will show the general distribution of slope instabilities in the study area, currently regardless of size, type or predisposition, and acts as a foundation for subsequent spatial and statistical analysis (Harp *et al.* 2011, Strom & Abdrakhmatov 2018).

Feature properties are stored in an attribute table as shown in App. II, containing the feature area, volume and mean elevation, the primary source the feature is best visible in including orbit, year, specific image (Source_1 and Source_2) and temporal baseline (Bt). Additionally, its visibility in both satellites (Sat.), the optical image and other differential interferograms (Int.) of potentially variable temporal baselines (Temp.) is denoted as 1 if yes and 0 if no, and the total number of differential interferograms the feature is detected in is given (Total Int. #).

4.3.5 Activity Likelihood Analysis

The level of confidence for a particular detected and mapped slope surface feature can be determined in an activity likelihood analysis (Dini *et al.* 2019). Two main factors count into this process which are shown in the decision tree developed for this particular project (fig. 9). First, the feature count in all Sentinel-1 differential interferograms is determined – the larger the number of differential interferograms a feature is detected in, the larger its confidence. Second, the orbital configuration is important – the confidence increases if the feature is detected in both ascending and descending orbit, and decreases relatively if it is only visible in one orbit configuration. For this project, thresholds of 50 % and 25 % of the total number of Sentinel-1 differential interferograms were selected. The likelihood weighting is denoted by numbers from 1-6, where 1 is low confidence and 6 is high confidence.

4.3.6 Geomorphological Classification of Movement Type

The type of movement is best determined by studying the local geomorphology (Dini *et al.* 2019). The ArcGIS World Imagery optical image, 3D Google Earth Pro views and SRTM 30 m DEM act as foundations for this. This classification is expected to include rock slope deformations, surface soil and debris movement as well as glacial landforms such as rockglaciers. This range is based on results obtained from the landslide inventory as well as existing literature (Strom & Abdrakhmatov 2018, Havenith & Bourdeau 2010, Hungr *et al.* 2014). The following movement types have been defined:

Figure 9: Activity Likelihood Analysis decision tree based on differential interferograms and orbit configuration.

1. Rock slope deformation and rockslides mainly affect large slopes or valley flanks and often show bare and fractured rock (Dini *et al.* 2019). The presence of scarps, fractures as well as debris flows and blocky talus cones may also be indicative (Gschwind & Loew 2016). Convex-concave profiles are typical due to a clear distinction between failure release and deposition areas.
2. Soil creep typically shows slope-parallel lineaments, areas of scree and debris cover and a general variation in slope colour, reflecting areas of small soil slips and failures and deposition (Dini *et al.* 2019). Disturbance in vegetation may also be indicative. Soil slides show a more apparent surface expression of loose soil or larger debris fans and talus cones. The size of soil creep and slides may vary from small local areas to larger slopes.
3. Debris flows are easily detected in the optical image due to their clear flow-like shape and typical occurrence of talus cones and debris fans. They differ from soil slides or rockslides due to their distinct geomorphology.
4. Rockglaciers are creeping landforms related to permafrost and typically follow a very distinct tongue-shaped, lobate and furrowed geomorphology (Humlum 1982; Martin & Whalley 1987, Delaloye *et al.* 2010). They often occur at the foot of steep headlands along cirques or valley walls. It may be difficult to distinguish these from debris-covered glaciers, where a continuous glacial body is assumed, or other ice debris.
5. A certain number of features is expected to be unidentifiable and is thus termed as unknown. These likely include features covered by clouds or snow in the optical image, where no certain geomorphological interpretation is possible.

5 RESULTS

5.1 Landslide and Earthquake Inventory

5.1.1 Landslide Inventory

A total of 30 slope failures are mapped for the last century based on Strom & Abdrakhmatov (2018) and NASA's Landslide Viewer database (<https://maps.nccs.nasa.gov/arcgis/apps/webappviewer/>, last accessed 16/07/2019). These are distributed throughout the entire study area as visible in fig. 10, but are generally observed along the two main river valleys of the Surkhob and Obikhingou Rivers, likely due to better accessibility. Strom & Abdrakhmatov (2018) focus on rockslides and rock avalanches, particularly those triggered by earthquakes, while NASA data includes landslides, mudslides and earthflows, illustrating the range of expected failure types. Absolute failure volumes are only known for four of the rockslide events and show a broad range from $6 \times 10^6 \text{ m}^3$ to $300 \times 10^6 \text{ m}^3$, including the catastrophic 1949 Khait rockslide and loess flows (Strom & Abdrakhmatov 2018, Evans *et al.* 2009; see App. III). Exact failure dates remain unknown apart for features sourced from the NASA Landslide Viewer. Generally, failures are noted in igneous and metamorphic bedrock as well as weak gypsum-bearing sediments and Quaternary loess cover. A minimum of 13 % of the noted events has formed natural dams of unknown stability. Note that the presented inventory is likely only an excerpt of all registered events, which are generally triggered by a complex interplay of seismic, tectonic, meteorological and geological factors (Danneels *et al.* 2008).

5.1.2 Earthquake Inventory

During the 20th and 21st century, >300 earthquakes of $M \geq 3.5$ occurred in and surrounding the study area (fig. 11 and App. IV), as derived from existing literature (Havenith & Bourdeau 2010, Evans *et al.* 2009), the Volcano Discovery database (<https://www.volcanodiscovery.com/earthquakes/tajikistan.html>) and USGS Earthquake database (<https://earthquake.usgs.gov/earthquakes/map/>). Note that earthquakes of lower magnitude are not included here, as these are unlikely to trigger slope failures (Havenith & Bourdeau 2010). The graph in fig. 12 shows the cumulative number of earthquakes in time including markers of known landslide events possibly triggered by earthquakes. Fig. 13 shows a magnitude – frequency plot, clearly highlighting that the majority of earthquakes occur with magnitudes of M_4 to M_5 , while up to 10 % exceed M_5 , matching observations in Havenith & Bourdeau (2010). Based on the time frame of the inventory, estimated recurrence times for earthquakes of magnitude $M \geq 7$ are thus 10 years, for $M \geq 6$ 20 years, for $M \geq 5$ approximately 8 months and for M_4 less than one month. Two main clusters are noted geographically as seen in fig. 11. One collection of earthquakes ranging from $M < 4$ to $M > 5$ occurs along the central PFR and parallel to the NW-SE compression and thus likely occur on the MPT, which crops out along the Vakhsh – Surkhob River valley and dips southward below the PFR (fig. 33 in App. IV). A second cluster of a similarly large magnitude range is located along and south of the Obikhingou River; these likely occur along the D-K strike-slip fault and associated fault splays.

Figure 10: Landslide inventory map showing distribution of known slope failure and rockslide events overlain on SRTM 30 m DEM (light areas are higher, dark areas are lower elevation).

Figure 11: Earthquake locations for $M \geq 3.5$ events recorded by the USGS since the 20th century, on SRTM 30 m DEM.

Figure 12: Cumulative number of earthquakes in time (blue bars) with known past landslide events marked in red, which may have been triggered by contemporary earthquake events.

Figure 13: Magnitude – Frequency plot showing number of earthquakes per magnitude, clearly indicating a high density of M4 to M5 events. The recurrence time per magnitude range as shown by the light blue bars is calculated by considering the number of earthquakes occurring in the main inventory period, i.e. since 2000.

5.2 Proximity Analysis

5.2.1 Lineament Study

Structural and tectonic features identified in the lineament study include major and minor faults, fractures, bedding, fault axes, scarps and lineaments of unknown type. Foliation could not be detected at the mapped scale. Only major faults are presented on the lineament map shown in App. I, as these are used in the proximity analysis; other lineaments are too small to be seen at the presented map scale.

Overall, a clear trend of NE-SW striking arcuate lineaments defining the valley and ridge topography is visible, reflecting the predominant tectonic activity in the region and an approximately N-S oriented maximum compressive stress direction due to the ongoing India-Asia collision (Hamburger *et al.* 1992, Lukk *et al.* 1995). These large features represent major tectonic faults and are cross-referenced with the available geological maps. Smaller faults show both the main N-S compression but also run obliquely to this at approximately NE-SW compression, these are also seen in the geological maps and may reflect a later deformational phase. Fractures are noted both parallel to the main regime as well as oblique in a number of orientations, again reflecting subsequent deformational phases. Fractures and bedding lineaments are not always easily distinguished at the mapped scale. Identified bedding appears largely parallel to the main tectonic trace; as this seems unlikely due to the intense deformation history, these lineaments should be treated with a potential error and may in fact represent fractures. Few fold axes are identified, reflecting complex stress regimes with a general N/NW-S/SE compression orientation. Scarps are identified on mountain ridges and parallel to slope flanks and typically coincide spatially with identified active slopes. No complete lineament map is shown as the individual features cannot be seen at a map scale covering the entire study area. Lineaments at locations of detected slope instabilities, which may have a predisposition influence are considered in the analysis in section 6.2.

5.3 Analysis of Surface Displacement

A total of 227 active surface features are identified in the study area (fig. 14) based on 46 differential interferograms, showing that DInSAR is an overall effective tool for the detection and mapping of slope instabilities in the study area. Particularly Sentinel-1 presents a valuable source; 189 of all features are detected based on 32 Sentinel-1 differential interferograms, forming the bulk of the developed database. This is supplemented with 33 features detected in 14 ALOS PALSAR-2 differential interferograms. 36 of all 227 features are clearly visible in both satellites. Five features are detected based solely on optical images in ArcGIS and Google Earth Pro. Sentinel-1 differential interferograms covering July, August and September are most effective in clearly showing slope movement, due to reduced snow cover and resulting high correlation. Here, features are detected in temporal baselines ranging from 12 – 48 days, including one of 372 days, yet 81 % of all features are best detected in 12 days temporal baselines. Few differential interferograms were generated for 6 months temporal baselines covering winter from November to May; these, however, cannot be used for purposes of analysis as they are highly decorrelated due to extensive snow cover. ALOS PALSAR-2 differential interferograms show less systematic coverage over the study area for summer periods during 2016 – 2019, with very few of 56 – 84 days (2 – 3 months). Temporal baselines of 1 – 2 years with low decorrelation show best results. All

generated differential interferograms are supplied in the digital appendix while those used in the surface displacement analysis are listed in App. I.

5.3.1 Geomorphological Classification and Activity Likelihood Analysis

The classification of the feature type according to the description in section 4.3.6 is based largely on a geomorphological analysis using optical images in ArcGIS and Google Earth Pro. The results are shown in fig. 14 and include a majority of 39.65 % rock slope deformations and rockslides and 40.52 % soil creep and slides. 2.7 % debris flows are noted, 11.9 % rock glaciers and ice debris and 5.28 % features of unknown type. Single processes could not always be distinguished in each detected slope instability and thus a combination of processes may be possible. This applies to certain rockslides which likely occur in a larger rock slope deformation, as well as soil creeping and sliding features. Mapping based on ALOS PALSAR-2 led to the detection of rock slope deformations, rockslides and soil creep only.

The activity likelihood of the detected slope instabilities is based on the developed decision tree according to the methodology outlined in section 4.3.5 and is shown in fig. 15. It is applied to the total 189 features detected in Sentinel-1 differential interferograms. 4.2 % of all features occur in >50 % of the used differential interferograms, while 54 % of all features are seen in 25-50 %. Table 1 below shows the percentage per likelihood class as well as of each grouped movement type. The results show that >50 % of rock slope deformations and rockslides, soil creep and soil slides as well as features of unknown type are seen in 25-50 % of all differential interferograms and thus have a high likelihood of true activity. Debris flows are largely only seen in optical images and else in <25 % of all differential interferograms, thus showing a lower likelihood of activity. >50 % of all rockglaciers and ice debris are visible in >25 % of all differential interferograms, with 18.5 % detected in >50 % in ascending and descending orbit, thus rendering a very high likelihood of activity.

Table 1: Activity Likelihood Analysis results for a total 189 features and per movement type.

Likelihood	% Total Features	% Rock slope deformation/ Rockslide	% Soil Slide/ Creep	% Debris Flow	% Rockglacier/ Ice Debris	% Unknown
1	35.4	36.4	36	16.7	29.6	33.3
2	6.4	4.1	5.3	16.7	7.4	16.7
3	37.6	39.2	44	0	14.8	41.7
4	16.4	16.1	13.4	0	29.6	8.3
5	0.5	1.4	0	0	0	0
6	3.7	1.4	1.3	0	18.5	0

Figure 14: Distribution of detected active slope features according to movement type based on a geomorphological classification and overlain on the SRTM 30 m DEM.

Figure 15: Distribution of active slopes based on Activity Likelihood Analysis overlain on SRTM 30 m DEM. Active slopes marked in white as N/A are detected based on ALOS PALSAR-2 and not included in the likelihood analysis.

The area size distribution per feature type is listed in table 2, ranging in total from minimum $4.7 \times 10^3 \text{ m}^2$ to maximum 2.49 km^2 and covering only 0.78 % of the entire study area. Rock slope deformations and rockslides clearly form the largest slope instabilities in terms of mean area, followed by soil creep, debris flows, rockglaciers and ice debris and soil slides. Unknown type movements include a wide range of area sizes, indicating that these may cover a number of different movement types. Movements identified as *Rockslides/Rock slope deformations* are grouped as rockslides, *Soil Creep/Slide* as soil creep.

Table 2: Area size distribution per movement type.

Movement Type	Min. Area [m ²]	Max. Area [m ²]	Mean. Area [m ²]
Rock slope deformation	54'825	2'488'975	541'122
Rockslide	37'290	1'556'003	401'963
Soil Slide	80'895	134'487	103'603
Soil Creep	38'064	1'389'814	270'541
Debris Flow	4'711	689'153	145'707
Rockglacier	89'740	253'078	139'799
Ice Debris	26'552	317'641	118'380
Unknown	48'708	1'274'775	307'497

Volumes cannot be determined from the DInSAR analysis directly due to lacking knowledge of the depth and location of failure planes. Empirical relations may be used, however, to estimate possible volume ranges for the detected slope instabilities; these have been developed in several studies (Korup 2005, Guzzetti *et al.* 2008, Strom & Abdrakhmatov 2018). The results vary greatly, where the choice of the most representative relationship is difficult and introduces uncertainty. As Strom & Abdrakhmatov (2018) study 551 bedrock landslides in Central Asia, including the Tien Shan and Pamir Mountain ranges in Tajikistan, their empirical relationship of $V = 26.875A^{1.419}$ is applied in this study. These results are larger by three orders of magnitude compared to those obtained from Korup (2005) and Guzzetti *et al.* (2008) and represent a worst case scenario. The volume ranges per movement type are shown in table 3 and listed in detail in App. II. Note that these remain approximated estimates of true slope instability volumes, with a possible error of up to 50 % (Strom & Abdrakhmatov 2018).

Table 3: Estimated volume distribution per movement type using Strom & Abdrakhmatov's (2018) equation.

Movement Type	Min. Volume [m ³]	Max. Volume [m ³]	Mean Volume [m ³]
Rock slope deformation	1.43E+08	3.20E+10	2.01E+09
Rockslide	8.25E+07	1.64E+10	1.01E+09
Soil Slide	2.48E+08	5.09E+08	3.32E+08
Soil Creep	8.49E+07	1.40E+10	8.19E+08
Debris Flow	4.38E+06	5.18E+09	9.86E+07
Rockglacier	5.09E+07	1.72E+09	3.79E+08
Ice Debris	2.87E+08	2.87E+08	4.12E+08
Unknown	1.21E+08	1.24E+10	5.06E+08

Average feature heights are extracted from the SRTM 30 m DEM and shown in fig. 16 and in App. VI. Their distribution allows a distinction between glacially and non-glacially influenced movements. Rock slope deformations and rockslides, soil slides and soil creep, and debris flows each show a wide range of elevation, suggesting that these particular slope instabilities in the study area are not necessarily dependent on topographic height and associated parameters such as snow or vegetation cover. Mean elevations are lowest for rock slope deformations and soil creep, which may fall below 2'500 m a.s.l. Rockglaciers and ice debris occur at highest mean elevations, which is clearly influenced by the occurrence of isolated or sporadic permafrost in this part of the study area (Alfred Wegener Institute, https://maps.awi.de/awimaps/projects/public/?cu=globpermafrost_central_asia#mapcontent, last accessed 16/07/2019). Features classified as unknown type are equally distributed across variable elevations with a high mean elevation of >3'200 m a.s.l., thus confirming findings from the area size distribution indicating multiple different movement processes.

Figure 16: Elevation range per movement type showing minimum and maximum ranges and mean elevation.

5.3.2 Velocity Calculations

General surface displacements are derived from the differential interferograms according to the methodology briefly outlined in section 4.3.2. It is based on a comparison of the differential interferograms a feature is detected in, where the absolute velocity is calculated from a single most representative differential interferogram. The majority of features are best visible in temporal baselines of 12 days for Sentinel-1 and 336 – 364 days for ALOS PALSAR-2, from which velocities were extrapolated linearly per 12 days, per four months (120 days) to represent summer velocities (e.g. June – September) as well as per year to indicate long-term displacements, as shown in fig. 17 and fig. 18. Summer velocities may be treated as a roughly representative approximation of average summer displacement, while velocities per year indicate a worst case scenario and are most likely not

representative of true surface displacement as slope movements are not expected to occur linearly. Displacement is rather expected to vary according to seasonal influences including precipitation and snow and vegetation cover, and may thus be variable in multi-temporal baseline differential interferograms depending on the associated acquisition period (Strozzi *et al.* 2010). This cannot be confirmed for winter months, however, as the generated differential interferograms are decorrelated and do not allow good visualisation of fringes. A more detailed implication and solution to this particular limitation is outlined in section 6.4. A full compilation of the results is given in App. II, while App. VII provides a summarised table of velocity ranges per 12 days, per four months and per year.

Debris flows and rockglaciers form the overall fastest slope movements as seen in fig. 17, which is expected due to their movement mechanisms. Rock slope deformations and rockslides equally show generally high mean velocities of 1.225 – 1.77 cm/12d, followed by ice debris, soil creep and soil slides. Unknown features fall in between these ranges. Mean velocities are generally high enough to lead to temporal aliasing in the majority of detected features in both satellites (Wasowski & Bovenga 2014). Use of Sentinel-1 thus clearly limits the detectable maximum displacement rate. This should ideally be supplemented with the longer wavelength satellite ALOS PALSAR-2, its unsystematic coverage and resulting available long temporal baselines of 1 – 2 years, however, lead to similar results of aliasing. Overall, ALOS PALSAR-2 rather shows slower movements averaging 15 cm/a. For both satellites, the observed displacement falls within the ‘extremely slow’ velocity category defined by Keefer (1984) and the ‘slow’ to ‘very slow’ velocity classes defined by Hungr *et al.* (2014). Considering that this study analyses general slope activity and potentially long-term movement and not features imminently prone to failure, this result is expected.

Figure 17: Linear extrapolation of velocities per 12 days, 4 months and 1 year for each slope movement type.

Figure 18: Velocity ranges per 12 days, 4 months and 1 year for each slope movement type, with mean velocities indicated in red.

6 ANALYSIS AND DISCUSSION

6.1 Distribution of Active Slopes and Associated Seismic Link

Understanding the distribution of detected active slopes and their characteristics enables a distinction between slope instability predisposition and movement induced by seismic activity in the study area. The strong tectonic overprint of the region and dense fracture network at the scale of slope faces provide conditions allowing for general high slope activity. Through this existing predisposition, additional strain can be exerted on active slopes through triggering factors. A likely triggering influence in the study area are earthquakes due to the recorded high seismic activity in the entire region. This potential link to seismicity is assessed in the following discussion through various analyses. These include an assessment of feature distribution, size and location relative to seismogenic faults, e.g. in a proximity analysis, as well as studying certain slope instabilities in relation to particular earthquake events. The latter is done for examples presented in section 6.2. Shallow and intermediate depth earthquakes in the Pamir and PFR region are typically associated with the MPT, forming a southward concave arc and running along the Vakhsh – Surkhob Rivers, and D-K strike-slip fault, roughly defining the Obikhingou River and south of the study area (Lou *et al.* 2009). These two systems are thus treated as the major seismogenic faults in the study area (App. IV and V).

6.1.1 Overall Spatial Distribution of Active Slopes

Co-seismic slope movement typically occurs on the hanging wall of thrust faults and is distributed symmetrically around strike-slip fault traces (fig. 19; Fan *et al.* 2019, Valagussa *et al.* 2019, Meunier *et al.* 2007). This pattern is observed for the study area (App. VI). Slope instabilities detected and mapped based on DInSAR and optical images show a widespread distribution throughout the entire study area, both along the river valleys and in high mountainous areas. A clear trend roughly parallel to the main NW-SE compression direction and major fault traces is noted. High feature densities along the central PFR and close to the Rogun Dam likely reflect slope activity influenced by seismic and tectonic activity associated with the MPT dipping south underneath this mountain range. A second high density area runs along the Obikhingou River, which likely corresponds to movement influenced by the D-K strike-slip fault. This distribution of detected features is thus a first indicator of seismically-induced slope activity.

6.1.2 Density Distribution of Active Slopes

The density of expected landslides or slope movements with respect to the fault trace is an additional indicator of seismic influence and is a function of earthquake magnitude, frequency and duration of ground shaking, topographic amplification and orientation of the fault rupture itself (Keefer 1984, Fan *et al.* 2019, Valagussa *et al.* 2019, Meunier *et al.* 2007, Strom & Abdrakhmatov 2018). This can be assessed in a proximity analysis. Meunier *et al.* (2007) derive a general distance of 50 km perpendicular to fault traces for 80 % of all landslides triggered in three global earthquake event case studies, where 10 % of the observed failures occurred within 5 km parallel to the associated fault zone. Keefer (1984) study data from 40 global earthquakes and resulting induced landslides and have developed an empirical relationship between magnitude and distance from fault rupture zones as shown in fig. 20,

leading to a similar result. For magnitudes up to M6 as observed for the majority of the study area based on the earthquake inventory (see section 5.1.2), movement including rock- and soil slides and falls as well as debris flows may occur within a distance of approximately 50 km of the involved fault trace, increasing exponentially with increasing magnitudes.

Figure 19: Sketch diagrams showing expected high density of slope activity along the PFR on the hanging wall of the MPT and symmetrically along the D-K strike-slip fault (adapted from Fan et al. 2019).

Figure 20: Relationship between earthquake magnitude and distance of landslides to fault rupture zone. The dashed line indicates disrupted slides and falls, the dash-double-dot line coherent slides and falls, and the dotted line lateral spreads and flows (Keefer 1984).

Fig. 21 shows the cumulative amount of mapped features that occur at certain distances to seismogenic faults identified in the lineament study (App. VI). The results show that all detected slope instabilities are located within 24 km of major faults and thus may be seismically influenced according to the distance range defined by Keefer (1984) observations. Of these, approximately 90 % clearly occur within 10 km of faults. Cumulatively, 4.4 % occur within 50 m, 12.7 % within 500 m and 21.14% within 1 km. This observation strongly suggests that observed slope instabilities are likely influenced or triggered by seismic activity along major fault traces in the study area. Whether active slope features are influenced co- or post-seismically cannot be determined, as, apart from few examples discussed in section 6.2, changes in their displacement rate are not studied in relation to particular earthquake events.

Figure 21: Cumulative percentage of total detected active slope features per distance to major seismogenic faults.

6.1.3 Area Size Distribution of Active Slopes

Analysing the size of detected features relative to fault traces equally allows an estimation of seismic influence. Valagussa *et al.* (2019) and Fan *et al.* (2019) observe a decrease in landslide size with increasing distance to the seismogenic fault trace. This trend can also be roughly observed for the study area when considering the area of each detected slope instability (fig. 22). The relationship indicates that larger active slope features occur within a close proximity of 5 km of major faults, and feature area and volume decrease with increasing distance from these faults, suggesting a tectonic and seismic influence on slope instability size. Two outliers of areas $>10^6 \text{ m}^3$ at large distances are noted, which represent large rock slope deformations observed north of the MPT towards the NE of the study area.

6.1.4 Elevation Distribution of Active Slopes

To additionally understand the relationship between seismic activity and the distribution of observed slope instabilities, the location of features relative to valleys and ridges is studied. Fig. 23 shows that active slope features located at high elevations occur at a range of distances to seismogenic faults, while features at low elevations generally occur close to said faults. Additionally, PGA ranges are

influential. PGA amplification occurs at slope crests, thus movements observed here are likely influenced seismically (Fan *et al.* 2019, Meunier *et al.* 2008). More than half of all detected features (51.2 %), are observed at slope crests, excluding rockglaciers and ice debris, whose formation is strongly controlled by topography and permafrost distribution (Delaloye *et al.* 2010). This equally implies a seismic link to feature distribution. Note that all analyses presented above, however, do not exclusively imply a seismic influence; the detected slope movements may also have been induced by other factors including precipitation, annual melting cycles, topographic influences and geological predisposition.

Figure 22: Distribution of detected active slope feature area relative to distance from seismogenic faults.

Figure 23: Distribution of detected active slope feature elevation relative to distance from seismogenic faults.

6.2 Geomorphological Analysis

The analysis in section 6.1 clearly highlights a likely seismic influence on slope movement in the entire study area controlled by the regional tectonic and structural predisposition for unstable slopes. This seismic influence can additionally be studied in relation to particular types of slope movement, which have been classified based on a geomorphological analysis of detected features using the available optical images. Velocity accelerations are observed for particular examples of identified features, which may hypothetically be triggered by specific earthquake events. This is assessed in the following discussion, including an analysis of the observed velocity ranges and locations relative to faults and rivers for examples of detected slope instabilities according to classified movement type. Note that the given coordinates in each example refer to the centre of the presented scene.

6.2.1 Rock Slope Deformations and Rockslides

Rock slope deformations and rockslides are detected spanning along the central and northern PFR and just south of the Obikhingou River in both Sentinel-1 and ALOS PALSAR-2 (see fig. 14). Only 13 % are noted north of the MPT in the southern Tien Shan, suggesting a strong relation to the MPT and D-K fault activity. The majority of these movements have a high activity likelihood and are visible in more than 25 % of all Sentinel-1 differential interferograms. This good detection in summer is likely related to overall relatively high mean velocities of 1.225 – 1.77 cm/12d or 14 – 15.52 cm/120d, showing clear fringes yet also temporal aliasing. They form some of the largest detected features, with areas up to 2.49 km². Together with soil slides, they constitute the highest abundance of movement type, which correlates with findings from Keefer (1984). This is likely due to their general rock mass heterogeneity, where expected fractures, joints and scarps provide the necessary predisposition to allow amplification of seismic PGA and thus may lead to preferential co-seismic movement at low earthquake magnitudes of M4 (Keefer 1984, Fan *et al.* 2019, Meunier *et al.* 2007). Rock slope deformations and rockslides often contain more than one single mapped polygon, which implies that these particular slope instabilities undergo complex movement involving several parts of the slope moving differently at varying rates. Two such slope movements are shown in fig. 24 and 25.

Fig. 24 shows a largely vegetated complex rock slope deformation 3.3 km² large and including four distinct movements found in the far east of the study area. Scarps on the surrounding slopes indicate some movement at depth and suggest an overall larger slope instability than mapped. Movement is best seen in an ascending orbit 173 August differential interferogram as indicated, where velocities are approximately 5.6 cm/12d and thus subject to temporal aliasing. This is relatively high considering only few rockslides and scree slopes in this complex are visible in optical images, yet disturbances in the vegetation and the high phase decorrelation support high movement rates. ALOS PALSAR-2 data does not cover this feature and thus more exact displacements cannot be determined. To determine whether areas of temporal aliasing reflect true surface movement or are influenced by periodic snow cover or atmospheric influences, a coherence analysis could be done. This compares coherence within and surrounding the area of aliasing in multiple differential interferograms; if coherence is low only where phase decorrelation occurs, it is likely related to fast movement unable to be detected by the applied sensor.

Figure 24: A complex rock slope deformation including rockslides and extensive scarps (white lines) seen in the Google Earth Pro optical image and in ascending orbit 173. Its location in the study area is shown by the red dot in the top left, Rogun Dam is marked by the black dot and rivers are shown in blue.

Fig. 25 equally shows a complex rockslide and rock slope deformation covering an area of 1.7 km² including three distinct features and clearly involving surface movement as expressed by scree and debris-covered slopes. Overall movement is best seen in a descending orbit 78 August – September differential interferogram and reaches velocities up to 1.575 cm/12d. The central feature is more clearly visible in ascending orbit 173, and moves more slowly at an estimated 1.05 cm/12d. ALOS PALSAR-2 images indicate slower movement of 0.79 cm/12d for the central feature based on a 56d differential interferogram, and 8.8 cm/a for the central and larger feature based on a 364d temporal baseline. This clearly illustrates 1) a high dependency on satellite type and data quality and quantity when estimating average movement velocities, and 2) a high variability of processes within one large slope instability, likely due to variable slope angle and steepness and involved rock types and structural features.

An additional example is presented in fig. 26; this particular rockslide is located on a SE-facing slope in fractured Cretaceous sand- and siltstones and conglomerate, where the fractured nature of the rock may provide a general predisposition to movement. This slope instability is included in the landslide inventory as feature number 'Tajik 145' (App. III). It shows an exposed fresh surface implying a relatively recent failure (Strom & Abdrakhmatov 2018). Within this, two distinct parts are visible based on the DInSAR analysis and extracted velocities. A lower part, likely the accumulation zone, moves faster than the release area upslope, indicating ongoing movement within parts of the rockslide deposit. Additionally, slope-parallel extensive scarps and cracks are observed upslope of the rockslide; this area does not, however, show movement based on DInSAR. These may indicate the presence of a larger rock slope deformation and typically form as a result of seismic activity (Fan *et al.* 2019). Strom & Abdrakhmatov (2018) suggest that the failed rockslide may have been triggered by the 1949 Khait earthquake along the MPT; the visible scarps could therefore be a co- or post-seismic result of the same or a later earthquake, possibly also occurring along the D-K fault system which runs at a distance of only 1 km. The location of this rock slope deformation on a river directly contributing to the Obikhingou River network highlights a relatively high damming potential should it fail (Fan *et al.* 2019, see also section 6.3).

Figure 25: Rock slope deformation and rockslide complex showing three distinctly moving features in Sentinel-1 ascending orbit 173 and descending orbit 78 and ALOS PALSAR-2 ascending orbit 164 NE.

Temporal variations in displacement of a detected slope instability may indicate a direct seismic influence on its movement rate and are possibly triggered by specific earthquake events. The two distinct parts in the rockslide in fig. 26 clearly show variable movement, which is also noted when comparing ascending Sentinel-1 summer images from 2016, 2017 and 2018. During August of 2016 and 2017, the upper part of the failed feature continues to move rapidly yet constantly at an estimated velocity of 1.925 cm/12d. This decelerates slightly to 1.75 cm/12d in September 2016 and 2017, suggesting a decrease in motion towards autumn, possibly due to reduced pore pressure or onset of snowfall in certain regions. The slope clearly accelerates in June – July 2018 up to a velocity of 2.8 cm/12d. ALOS PALSAR-2 renders an even higher velocity of 3.8 cm/12d. The reason of this acceleration is unknown but may be related to 1) the general structural predisposition of the region and meteorological events, 2) the generally high seismicity in the region and likely seismic influence as discussed in section 6.1, or 3) a specific earthquake event triggering faster slope movement.

Figure 26: Rockslide in a contributing river valley to the Obikhingou River seen in Sentinel-1 ascending orbit 173 and ALOS PALSAR-2 ascending orbit 164 NE. The fresh surface indicates recent failure, where a distinction between a slower upper and faster lower part can be made. Scarps upslope are marked in white and indicate a larger rock slope deformation.

The known high predisposition and seismic activity are expected to influence movement acceleration, while particular earthquake events are less indicative. One such possible event is the M4.3 earthquake that occurred on 04/06/2018 along the D-K fault 70 km to the SW (App. VIII). For the given magnitude,

however, this event falls outside the distance range estimated by Keefer (1984). Another earthquake of M4.3 occurred on 15/12/2017 only 11 km to the SW along the D-K fault, thus 6 months prior to the noted velocity acceleration but nonetheless may have induced post-seismic movement within the studied rockslide. The faster lower feature equally accelerates in 2018 relative to 2016, possibly due to the same seismic event, and also shows a velocity decrease in September relative to August 2018. Velocities for 2017, however, cannot be clearly determined due to very strong interferometric phase decorrelation; here a coherence analysis could be done to correctly identify this effect. It likely implies a movement acceleration that exceeds the possibility of visual estimation, which could be related to earthquake events prior to or in summer 2017 that did not affect the larger slope instability. Both movements slow down in late August – September 2018, suggesting that a co-seismic acceleration due to a specific earthquake occurred temporarily and did not influence the assumed larger rock slope deformation indicated by extensive scarps.

6.2.2 Soil Slides and Soil Creep

Soil sliding and creeping is observed throughout the study area and particularly along river valleys. This is expected as soil cover is unlikely to extend to the higher mountain regions within the southern Tien Shan, PFR and northern Pamir Mountains, but may still suggest a seismic influence on soil movement occurring in the MPT hanging wall and along the D-K fault. As for rock slope deformations and rock slides, the majority of movement in soil is observed in >25 % of all Sentinel-1 differential interferograms, rendering a high confidence of activity. Mean summer velocities are slightly lower at 0.765 – 1.05 cm/12d or 7.22 – 10.5 cm/120d. The area of moving features varies greatly, from 0.038 km² to 0.95 km², suggesting that their formation depends strongly on the general slope size and topographic influences, as well as geological properties. According to Fan *et al.* (2019), the size of active features may be directly linked to the heterogeneity of the present rock types. Smaller movements typically occur in homogeneous and unconsolidated soil material, while larger movements and failures are often found in fractured and structurally influenced bedrock.

The example in fig. 27 shows an active slope along the Surkhob River in the east of the study area within Cretaceous sand- and siltstones and conglomerate and Quaternary material. It illustrates that a distinction between soil sliding and creeping is not always possible, as these two processes may be linked. Both soil deposits and freshly exposed surfaces due to sliding are visible as well as slope-parallel scarps further upslope. The latter indicate a larger creeping motion at slower rates not detected by the applied satellites, initiating small surface failures as a result (Dini *et al.* 2019). Two separate movements are mapped; the larger is visible in both Sentinel-1 and ALOS PALSAR-2 differential interferograms, the smaller only in the latter. ALOS PALSAR-2 indicates overall low velocities based on a 308d and 672d differential interferogram, showing movement of only 13.87 cm/a or 0.9 cm/24d for the larger feature and 3.6 cm/a for the smaller feature. Sentinel-1 indicates faster movement, where the larger feature shows a change in summer velocities between 2016 and 2018 as indicated in fig. 27. Descending Sentinel-1 differential interferograms covering 24d temporal baselines in August visualise the movement best. A clear increase in velocity from minimum 2.1 cm/24d to 3.325 cm/24d is noted between 2016 and 2017 and a subsequent decrease in summer 2018 to 1.75 cm/24d. Note that these velocities are derived

from fringe cycles influenced by temporal aliasing and are thus minimum values. The acceleration of this particular soil sliding and creeping complex may be related to various factors as discussed for rock slope deformations in section 6.2.1. Based on the known tectonic predisposition and general seismic influence in the region, it may again be hypothesised that the acceleration is additionally triggered by a particular earthquake event occurring along the MPT fault, which roughly runs along the Surkhob valley and thus within 1 - 2 km to the north of the studied moving soil complex. An earthquake event of M4.2 occurred 67 km to the WSW along the MPT on 05/08/2017, which may be responsible for this increased velocity directly afterwards (App. VIII). This, however, again lies outside the distance range for M4-5 earthquakes as found by Keefer (1984). Another earthquake of M4.3 on 02/12/2017 occurred only 8.7 km SE, equally on the MPT. This event happened 8 months prior to the observed velocity acceleration, but may induce post-seismic slope movement due to its close proximity.

Figure 27: Soil creeping and sliding occurs on a N-facing slope in the Surkhob River Valley as seen in Sentinel-1 descending orbit 78 and ALOS PALSAR-2 ascending orbit 164 NE. Scarps are indicated in white.

6.2.3 Debris Flows

Debris flows are typically too fast to detect with DInSAR due to high movement rates. Only few debris flows have thus been identified in the study area, of which two are visible in differential interferograms. They include some of the smallest detected features with a mean area of 0.145 km² and thus constitute only a minor part of the observed slope activity in the study area. 4 of the 6 mapped debris flows occur on lower parts of the slope and thus may imply rainfall-induced movement, these are only seen in optical images and thus do not appear to be moving significantly. The other two occur on slope crests and in one case as part of a more complex rockslide, suggesting a possible seismic influence (Fan *et al.* 2019, Meunier *et al.* 2008). These have an overall low likelihood of activity and a moderate to high mean velocity of 1.05 cm/12d or 18.8 cm/120d. Fig. 28 shows a debris flow in Palaeogene – Neogene gypsum-rich limestone and/or clay and marl units in a tributary river valley east of the Obikhingou River. It includes a continuously moving release area and lower deposit, which has been re-populated indicating a relatively historic failure event.

This particular debris flow has a low likelihood of activity of 1 as it is only seen in 5 Sentinel-1 differential interferograms. Summer velocities range from 0.7 – 1.4 cm/24d, with a higher velocity of 1.925 cm/24d observed in July - August 2017 as shown in fig. 28. Again, this may possibly be related to a particular earthquake event. The debris flow has a distance of <10 km to the MPT; no earthquakes immediately prior to the acceleration are noted here. The closest in timing occurred two weeks before the noted acceleration on 26/06/2017 with M5 along the D-K fault 33 km to the SE, thus lying roughly within the expected distance range (App. VIII; Keefer 1984). It may have triggered co- or post-seismic faster movement, yet, as for the rock and soil examples discussed above, this remains highly uncertain and is solely aimed at presenting a possible triggering mechanism for the observed velocity accelerations.

Figure 28: This debris flow release area (black) is seen in Sentinel-1 descending orbit 78, its deposit as marked by red lines is clearly visible in the optical image.

6.2.4 Rockglaciers and Ice Debris

Rockglaciers and ice debris are observed particularly in the far SE of the study area, where elevations may exceed 5'900 m a.s.l., yet these features are only noted up to elevations of 4'054 m a.s.l. Isolated and sporadic permafrost is encountered here, which lays the necessary prerequisites for the formation of rockglaciers (Delaloye *et al.* 2010). These particular slope movements are not considered as hazardous to the Rogun Dam construction, a detailed discussion of their occurrence and movement rates is thus provided in App. IX, together with examples of three rockglaciers detected with Sentinel-1.

6.3 Damming Hazard

Whether slope instabilities and resulting failures have the potential to form landslide dams and impact ongoing hydropower construction projects such as the Rogun HPP depends on a number of factors. These include landslide properties such as rock mass characteristics, landslide volume and mobility, geomorphological properties such as slope steepness, valley floor topography and distance to river networks, and, if seismically-induced, earthquake properties such as frequency and duration (Fan *et al.* 2019, Strom 2010). Where and when dams form cannot be predicted, however, a hazard map can be developed for the study area indicating the damming hazard potential for the detected slope instabilities. The hazard analysis presented in the following discussion integrates data obtained from spatial analyses to develop an estimation of the damming hazard potential of mapped slope movement.

6.3.1 Distances to Rivers

A direct first indication of whether a detected slope movement may be hazardous to river damming is given by its relative location to the local river network. This is obtained by calculating its shortest distance to the closest rivers. According to studies discussed in Fan *et al.* (2019), a landslide is *connected* to a river network if its point of lowest elevation touches or intersects a river channel, corresponding to a distance of zero. Such a location of detected slope instabilities in the study area relative to the Vakhsh – Surkhob River and Obikhingou River networks feeding the Rogun HPP thus automatically constitutes a damming hazard. Active features upslope along the relevant river valleys must also be considered in this analysis, however, as particularly loose rock and soil slides and creep as well as debris flows may become (re-)mobilised in the case of a triggering event and influence the river network. Rockglaciers and ice debris are not considered here, as such moving landforms are not expected to constitute a damming hazard due to their locations at generally high altitudes and in permafrost regions. A total of 200 features are thus included in the following analysis.

The critical distance between an active slope movement and closest river to constitute a damming hazard is highly dependent on multiple factors and cannot be generalised. The Khait failure of 1949 in the north of the study area illustrates this; the Khait rockslide travelled approximately 7.4 km downslope until reaching and crossing the river valley (see App. III), while loess flows in the Yasman valley travelled up to 20 km, highlighting the dependency on rock type (Evans *et al.* 2009). Table 4 includes a summarising analysis of inclined distances between slope instabilities and the main rivers and planned Rogun Dam reservoir, calculated from the height difference between detected slope features and the closest river point.

Table 4: Percentage of active features per distance to main rivers and planned reservoir.

Distance to Rivers	% total mapped features	Distance to Reservoir	% total mapped features
<50 m	3.5	<50 m	2.5
50 - 500 m	8	50 - 500 m	0.5
500 m - 1 km	7.5	500m - 1 km	1.5
1 - 5 km	41	1 - 5 km	7.5
5 - 10 km	25.5	5 - 10 km	11.5
>10 km	14	>10 km	76.5

All mapped features lie within 20 km of major rivers contributing to the Rogun Dam catchment area (see complete list in App. II). More than half of all detected slope instabilities occur within 5 km of the main river network and 19 % within 1 km. Note that these distances do not incorporate the topographic relief between a slope movement and closest river, which clearly influences its potential influence on the river network. A slope instability may be within a critical distance to a river, but this distance can contain a number of ridges and valleys separating the feature from that particular river catchment and thus reducing its potential hazard.

The detected slope features can be initially classified into three damming hazard categories based solely on their distance to rivers (fig. 29). 19 % of all features, excluding rockglaciers and ice debris, are located within 1 km to a major river and are classified into a high hazard category. 66.5 % lie within 1 – 10 km and are classified into a medium hazard category. 14 % are located >10 km from major rivers and are classified into a low hazard category. Regardless of their distances to rivers, 10 % of all features appear topographically separated from the contributing river catchments and are therefore given an estimated low hazard. Note that these initial hazard potentials remain estimates, slopes covered in loess and very loose debris, for example, are expected to travel longer distances upon failure due to higher mobility than rock slopes (Evans *et al.* 2009).

Only 4.5 % of the analysed features lie within 1 km of the planned Rogun HPP reservoir and 19 % within 1 -10 km. These are expected to form high and medium secondary hazards of floodwaves, respectively. The remaining features are distributed at larger distances. This overall lower amount of potentially hazardous features is expected, as the reservoir covers only a limited area of the major rivers in the west of the study area.

Figure 29: Damming hazard analysis for detected slope instabilities based only on their distance to major rivers.

6.3.2 Integrated Hazard Analysis

The hazard assessment based solely on the distance between slope movement and rivers as presented in section 6.3.1 gives a first indication of the potential landslide damming hazard in the study area but cannot be considered representative. For a more precise and effective damming hazard assessment, all available data must be integrated. According to the FOEN guidelines for Protection against Mass Movement Hazards (Federal Office for the Environment, 2016), hazard maps are calculated according to known probability and intensity factors of slope failure. The probability of slope movement in this study is 1, as detected features are expected to move based on the DInSAR analysis. An integrated hazard analysis is thus applied for *permanent landslides*, based only on intensity. The intensity integrates relevant data obtained in this thesis as listed below. Note that rockglaciers and ice debris are again excluded from the analysis as in section 6.3.1, as well as all features detected based solely on optical images or ALOS PALSAR-2 differential interferograms, leaving a total of 162 features as listed in App. X. The final hazard per detected slope instability is calculated by adding weighted intensity inputs according to $Hazard = w_1\sigma_1 + w_2\sigma_2 + w_3\sigma_3 + w_4\sigma_4 + w_5\sigma_5$ (Yang *et al.* 2013). σ_n represents the input data, w_n an associated weighting factor, which here is chosen qualitatively.

- 1) σ_1 : The minimum distance of a detected slope instability to the rivers defining the Rogun Dam catchment area presents a first approximation of the possibility of said feature to form a landslide dam. A short distance constitutes a higher hazard (see section 6.3.1). This input is expected to have the highest influence on the damming hazard potential of detected slope features and is thus assigned a relative weighting of $w_1 = 3$. Features separated from the river network by topographic relief are treated as features of low hazard, i.e. with distances >10 km.
- 2) σ_2 : The confidence of whether a detected slope feature truly exists and moves is given by the likelihood of activity and has an expected high influence on the potential of landslide damming. The higher the likelihood class, the higher the confidence of movement and thus a related hazard, with an assigned weighting of $w_2 = 2$. If considered separately, a rough classification gives likelihood classes 5 and 6 a high hazard, 3 and 4 a medium hazard and 1 and 2 a low hazard.
- 3) σ_3 : The estimated volume of detected slope instabilities is also important. Large features are expected to increase the overall hazard to landslide damming as they involve larger failure energies and thus increase the potential of damming a river (Strom & Abdrakhmatov 2018). The volume in this study is estimated based on empirical relationships and thus cannot be considered as truly representative, therefore giving a weighting of $w_3 = 1$.
- 4) σ_4 : The velocity per year of detected features reflects their general movement rate and mobility. Faster moving features may be more prone to failure and involve higher energies compared to slower features. Note that velocities of cm/a are extrapolated linearly in a worst case scenario which is likely not representative of true surface displacement rates. A weighting of $w_4 = 1$ is thus assigned to reflect this uncertainty.
- 5) σ_5 : The distance to seismogenic faults gives a rough indication of the seismic influence in the study area and likelihood of a feature to fail due to earthquake events. A shorter distance

suggests a potentially higher probability for landslide failure upon an earthquake event compared to larger distances. Note that this must be treated with uncertainty as PGA values remain unknown, which would allow for a more precise estimation of the seismic triggering influence. The weighting is therefore $w_5 = 1$.

All intensity inputs are normalised to a scale of 0 to 1 based on their highest relative value according to the equation $\frac{X-min}{max-min}$, where 1 reflects a high hazard. For distances to rivers and faults, however, shorter distances constitute a higher hazard and thus an invert of the normalisation is applied according to $1 - \frac{X-min}{max-min}$. The assigned weighting reflects the expected influence of an input on the integrated damming hazard. The calculated hazard is again normalised to the highest value to give a range of 0 to 1 as shown in fig. 30. A complete list of all results is given in App. X.

Figure 30: Histogram of normalised integrated hazard range.

Based on the histogram range in fig. 30, hazard classes are defined, reflecting a 30 % – 30 % – 40 % distribution. Note that this classification is simplified and biased. All features with a normalised hazard value of <0.3 are classified as having a low hazard of landslide damming, all features of $0.3 - 0.6$ as medium hazard, and all features >0.6 as high hazard. This distribution also reflects the sum of the two main defining intensity inputs only, given by the distance to rivers σ_1 and activity likelihood σ_2 and their respective weightings, as shown in the hazard matrix in fig. 31. If this classification is applied, 29.6 % of all features have a high damming hazard, 53.7 % a medium hazard and 16.7 % a low hazard (fig. 32).

Figure 31: Hazard matrix based on the addition of σ_1 and σ_2 inputs under consideration of their pre-defined hazard classes and respective weighting in the integrated hazard analysis.

When compared with the initial hazard analysis in section 6.3.1, the integrated hazard analysis map shows a significantly higher number of slope movements with an identified high damming hazard and lower number of features with a medium damming hazard, presenting a more conservative result. The amount of features with an expected low hazard is similar in both analyses. This result indicates that an integration of several intensity inputs reflecting the characteristics of slope movement rather than using only one attribute, here the distance to rivers, potentially better reflects the true damming hazard in the study area by representing a worst case scenario. All available data which may impact the damming potential of slope instabilities must thus be considered to improve the accuracy of the hazard analysis. The integrated analysis can therefore act as a foundation for further studies and more accurate hazard analyses, e.g. incorporating detailed data on slope volumes, rock mass characteristics and seismic influences such as local PGA.

Both hazard analyses highlight the significant amount of slope instabilities presenting a high damming hazard upon failure in the study area. Rough scenarios affecting the Rogun Dam construction and lifetime can be specified based on the distance to seismogenic faults and assumed recurrence time of earthquakes along these faults. All detected slope movements are located within 24 km of seismogenic faults and thus lie within the possible distance to be triggered by an earthquake of magnitude $M \geq 4$ according to Keefer (1984), which constitutes the magnitude threshold for seismically-induced slope failures (Havenith & Bourdeau 2010). Earthquakes of M4-5 have a recurrence time of <1 month and thus the potential to trigger frequent slope failures in the Rogun Dam catchment area, presenting a worst case scenario. Earthquakes of M5-6 have a recurrence time of approximately 8 months and may lead to annual slope failures. Both scenarios can cause failures during dam development that directly affect and damage the ongoing construction works. Particularly features classified with a high damming hazard should therefore be studied in more detail, including analyses of volume, possible failure plane locations and rock mass characteristics, enabling a more precise and reliable hazard analysis. M6 and M7 earthquakes have estimated recurrence times of 10 – 20 years, strongly affecting the area and lifetime of the Rogun Dam and reservoir but presenting a less significant hazard to the construction itself.

Figure 32: Integrated damming hazard analysis considering multiple intensity inputs.

6.4 Limitations

Limitations are largely set by the available data and project time frame. This applies mainly to the satellite radar data, including the DEM resolution and DInSAR satellite properties, as well as the extent of the developed inventory and subsequent analyses.

The available SRTM 30 m DEM resolution is generally too low for slope deformation analyses as undertaken in this project. Surface features may be detected and better interpreted geomorphologically if properly visualised in the DEM, which could not be done here. Distances to rivers and faults should ideally be calculated considering topography, for which a better resolution DEM is also required. A higher resolution of 12 m as provided by the TerraSAR-X DEM is thus necessary for detailed studies on the mapped active surface features, but unfortunately this particular DEM was not granted for the project.

Depending on the use of DInSAR enabled satellites, analysis results may vary. ALOS PALSAR-2 typically shows good correlation and allows detection of fast movements; due to limited image availability covering the study area, however, this was not possible in the presented analysis. Sentinel-1 satellites are very effective in systematic surface analyses as they provide a dense coverage of Earth of 12 days between subsequent images. Despite this, the detection of active surface features in the study area is limited as Sentinel-1 shows only a certain movement range of cm/a due to the short wavelength at C-band. Fast movements exceeding 1.4 cm per temporal baseline typically show interferometric phase decorrelation due to temporal aliasing and thus their absolute velocities cannot be determined (Wasowski & Bovenga 2014, Manconi *et al.* 2014). Sentinel-1 is thus poorly suited to detect rapid movement such as that occurring immediately after ground motion (Fan *et al.* 2019), but sufficiently shows areas of general slope movement. Vegetation and snow cover reduce the image coherence and are shown as decorrelation, which additionally reduces the amount of obtained information on surface movement (Wasowski & Bovenga 2014). Layover and shadowing are common effects when studying steep mountainous terrain with DInSAR, and equally reduce the amount of available information (Dini *et al.* 2019, Strozzi *et al.* 2010). These characteristics associated with satellite image acquisition limit the extent of detectable features and thus the final catalogue, which influences the application of spatial and statistical analyses on the collected dataset and may lead to partly unrepresentative results.

An additional limitation to the interpretation of the developed catalogue is the determination of velocities of active slope features. Velocities are calculated based on a comparison between all differential interferograms of one satellite that a particular feature is detected in, while the absolute velocity is based on a single differential interferogram, thus introducing uncertainty. For purposes of analysis, velocities are extrapolated linearly per year, which is likely not representative of true surface displacement. Surface movement is expected to accelerate or decelerate depending on seasonal variations, where the corresponding velocity estimation is dependent on the quality of the differential interferograms used. To avoid this limitation and calculate a more representative approximation of true surface displacements, the velocities of all differential interferograms a feature is detected in must be averaged. This can be done either manually, requiring large amounts of time, or by stacking e.g. in the GAMMA software, and is suggested to apply in further studies of this project. Stacking requires unwrapping of the interferometric phase from relative to absolute values and generation of a displacement map. This,

however, is very difficult in rugged terrain as it may introduce errors and produce incorrect results, and is thus typically only done for small areas of interest previously specified (Strozzi *et al.* 2010).

The lack of fieldwork as part of this study provides limited geotechnical, geological and structural information on the study area necessary for a detailed 3D study of particular active features of interest such as those presented in section 6.2. Fieldwork generally allows for a better estimation of feature size and associated volumes, the presence of extensive scarps and potential failure planes as well as the involved geological units and soil cover. These factors are important when assessing the state of activity of a detected slope deformation to more precisely estimate its potential failure and damming hazard, as the size and height of a potential landslide dam are crucial to understand its influence on river blockages and the hydraulic properties of the affected valley and river network (Strom & Zhirkevich 2013).

7 CONCLUSION

The discussed data and analyses show that the implementation of optical and DInSAR remote sensing techniques is an effective tool to detect and map slope instabilities in the Rogun Dam catchment area in order to develop a coherent dataset for subsequent spatial and hazard analyses. Results show a widespread distribution of a total 227 rock slope deformations, rockslides, soil creep and slides, debris flows, rockglaciers and ice debris throughout the study area. The likelihood of activity is moderate to high for the majority of features, as these are visible in >25 % of all Sentinel-1 differential interferograms. Velocities greatly vary between <5 - >90 cm/120d during summer; winter velocities cannot be determined due to extensive snow cover and decorrelation. No detected feature appears imminently prone to failure, however, and all movements fall within the 'extremely slow' and 'slow to very slow' velocity categories defined by Keefer (1984) and Hungr *et al.* (2014), respectively. Due to the limitations of Sentinel-1 satellites discussed in section 6.4, velocities exceeding approximately 1.4 cm per temporal baseline cannot be determined accurately due to interferometric phase decorrelation. Use of ALOS PALSAR-2 did not fulfil its aspired solution to this limitation due to low image availability of otherwise correlated data.

Spatial and statistical analyses on the collected database indicate a clear link between surface slope movement and seismic activity in the Tien Shan and Pamir Mountain regions. The majority of detected slope instabilities occur either on the MPT hanging wall or roughly symmetrically around the D-K strike-slip fault, suggesting a dependency on earthquake events occurring on these two major seismogenic fault systems (Fan *et al.* 2019). More than 80 % of all features are located within a distance of 10 km to these and are often found on slope crests where PGA is topographically amplified (Meunier *et al.* 2008). A general increase in feature area and volume with fault proximity is also observed, additionally providing supporting evidence for a seismic influence (Valagussa *et al.* 2019, Fan *et al.* 2019). This can be directly assessed when comparing differential interferograms prior to and after earthquake events and comparing displacement rates for particular features. For an example soil creep/slide complex, rockslide and debris flow, an increase in velocity within 12 days or 24 days temporal baselines after specific earthquake events can be observed, implying a co- or post-seismically induced acceleration of surface displacement. This appears to be temporarily linked to the seismic event, however, and does not increase surface velocities over longer annual time scales.

The data obtained in the spatial and statistical analyses and especially derived from the lineament study and proximity analysis acts as a foundation for a comprehensive kinematic analysis. The general orientation of lineaments can be presented in a stereoplot to assess their influence on the orientation of slope movement and their preferred failure modes, and may be linked to the known structural predisposition and seismic influence. This was not done as part of the presented thesis but should be included in future work on this study.

The damming hazard potential of detected slope instabilities is defined in two hazard analyses. An initial analysis considers only one intensity input relating to the distance between slope instabilities and closest rivers, while the second integrates all relevant obtained data as a combined intensity with a probability of 1, more accurately representing true slope characteristics and thus hazard potentials. This includes

feature distance to rivers and faults as well as their activity likelihood, estimated volumes and extrapolated velocities per year and is applied to all slope movements excluding rockglaciers and ice debris detected with Sentinel-1. The added normalised intensity inputs allow classification into three hazard categories. 29.6 % of the analysed detected slope instabilities present a high damming hazard, 53.7 % a medium hazard and 16.7 % a low hazard. These results indicate a worst case scenario when compared to the initial hazard analysis, with an overall significant amount of high hazard features, which may impair the Rogun Dam construction and HPP lifetime depending on scenarios for seismic triggers and earthquake recurrence times. Note that the developed analysis represents an approximation of the hazard distribution in the study area and is strongly dependent on the available data quality. 4.5 % of all features excluding rockglaciers and ice debris have a high and 19 % a medium secondary hazard of floodwave generation in the Rogun Dam reservoir.

In conclusion, the study area shows considerable surface slope activity of various movement types in rock and soil. This surface activity is likely largely induced by seismic activity in the Tien Shan and Pamir Mountain regions; to more accurately determine this, an inventory of co-seismic landslides triggered by a particular earthquake should be developed and their morphology and displacement discussed. Structural and rock mass controls cannot be assessed but are equally expected to influence the overall stability of active slopes. Nearly a third of all features are estimated to have a high river damming and floodwave potential and may impact ongoing dam construction.

7.1 Outlook

As outlined in section 6.4, the developed catalogue is limited due to certain data limitations associated with the use of Sentinel-1. Application of other satellites with varying band wavelengths is expected to increase the extent of visible features and provide a more complete dataset. The available ALOS PALSAR-2 data unfortunately does not allow detection of faster movements in the study area, yet this should be extended, potentially with the use of older images or other long wavelength satellites. Suitable satellites are ESA's ENVISAT, which also acquires images at C-band but has been operational from 2002 to 2010 and therefore allows a longer-term analysis of surface movement, and the X-band TerraSAR-X satellite, which may detect slower movements due to a shorter wavelength of only 3.1 cm.

Additionally, Sentinel-1 data from 2019 should be processed to expand the catalogue of active features. This has not been done for this thesis as results presented in section 5.3 show that images covering July, August and September acquisition periods are best suited to detect slope movement in the study area, and data processing was largely completed before this.

To better understand surface displacement and increase the likelihood confidence of detected active features, two analyses can be applied. First, an analysis of coherence statistics for areas of temporal aliasing can be done. If the surrounding region has a generally low coherence, this is likely related to implicating atmospheric and meteorological effects. If only the area of aliasing shows low coherence, the effect likely reflects true surface movement too fast for detection and thus increases the confidence of detected slope activity. An additional technique is to develop a time series through stacking. This integrates several interferograms over time to find areas constantly showing deformation for a given

period and can better indicate particular seasonal variations, influences by meteorological or seismic events or an association to ground deformation, in some cases permitting early warning systems (Wasowski & Bovenga 2014, Manconi *et al.* 2018). Time series also allow derivation of horizontal (east-west) and vertical movement components from the LOS displacement when using both ascending and descending orbits, which provides more representative information on the expected deformation (Manzo *et al.* 2006). Ultimately, this method may allow more precise detection of unstable sites critical to the Rogun HPP in terms of damming hazard in order to set up monitoring systems.

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10 DECLARATION OF ORIGINALITY

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11 APPENDIX

11.1 Appendix I: List of Analysed Differential Interferograms

Table 5: List of all generated Sentinel-1 and ALOS PALSAR-2 differential interferograms used in the surface displacement analysis.

Satellite	Orbit	Temporal Baseline	Differential Interferogram	Orbit	Temporal Baseline	Differential Interferogram	
Sentinel-1	173	12	20160819_20160831	78	12	20170727_20170808	
			20160912_20160924			20170820_20170901	
			20170814_20170826			20180710_20180722	
			20170907_20170919			20180827_20180908	
			20180622_20180704			24	20160813_20160906
			20180809_20180821				20170808_20170901
			20180821_20180902				20180803_20180827
		24	20160819_20160912		36	20170808_20170913	
			20170709_20170802		48	20170727_20170913	
			20170728_20180821			20180815_20181002	
		36	20160807_20160912		180	20170422_20171019	
			20170721_20170826			20180429_20181026	
		48	20160807_20160924			20161117_20170516	
			20180809_20180926			20171112_20180511	
		180	20170416_20171013		360	20170727_20180722	
			20180411_20181008		372	20170820_20180827	
			20161111_20170510		732	20160813_20180815	
			20171106_20180505				
		357					
		372					
		732					
ALOS PALSAR-2	164/770 SW	56	20180519_20180714	164/770 NE	56	20180602_20180728	
		70	20160716_20160924		308	20180728_20190601	
		84	20170826_201711118		364	20160730_20170729	
		336	20160924_20170826	672	20160730_20180602		
			20180714_20190615		20170729_20190601		
		406	20160716_20170826	59/2830	364	20170419_20180428	
		728	20160716_20180714		728	20170429_20190427	

11.2 Appendix II: Complete Table of Active Features and Attributes

Table 6: Complete attribute table of detected slope instabilities.

Attribute Number	Movement Type	Ohrt	Year	Source 1	Source 2	Br	Optical	Int.	Temp.	Sat.	Total Int. #	Likelihood	Area [m2]	Area Volume [m3]	Elevation [m a.s.l.]	cm/Br	cm/12d	cm/20d	cm3	Aliasing	Geological Unit	Distance to River [m]	Distance to Fault [m]	Distance to Hazard [m]	Integrated Hazard	Dominant Hazard		
60	Debris Flow	173	2017	20170709	20170802	24	1	1	1	0	5	1	689153	0.8891527	5.15E+09	2775	1.525	0.863	9.63	29.3	1	Palaeognath/Miocene Sediments	3750.19	9.65	18273.15	medium	high	
71	Debris Flow/Rockslide	78, 173	2017	20170820	20170901	12	1	1	1	1	6	2	46786	0.0467869	1.14E+08	154	3.43	2.800	28.00	85.1	1	Proterozoic Gneiss	923.45	0.00	31727.27	medium	high	
204	Debris Flow/Sol Slide						1	1	1	0	0	0	58893	0.058893	1.57E+08	1817						Cretaceous Sediments	0.00	11.86	57560.47	high	high	
205	Debris Flow/Sol Slide						1	1	1	0	0	0	4711	0.004711	4.38E+06	1789						Quaternary	0.00	11.89	57546.47	high	high	
206	Debris Flow/Sol Slide	173, 78	2018	20180808	20180821	12	1	1	1	0	6	2	37575	0.0375747	8.34E+07	2014	1.050	1.050	10.50	31.9	1	Quaternary	284.79	11.76	56501.92	high	high	
68	Debris Flow/Sol Slide	173, 78	2018	20180821	20180802	12	1	1	1	0	6	2	252078	0.2520784	1.25E+09	4004	1.050	1.050	10.50	31.9	1	Cretaceous Sediments	13911.48	6.26	32092.26	high	high	
170	Debris	173, 78	2018	20180821	20180802	12	1	1	1	0	18	6	119866	0.1198662	4.12E+08	3565	2.625	2.625	26.25	79.8	1	Unknown	10447.05	9.19	81322.63	high	high	
775	Debris	173, 78	2018	20170727	20170802	48	1	1	1	0	3	1	134357	0.1343574	5.09E+08	3565	1.575	0.394	3.94	11.9		Palaeognath/Miocene Sediments	14230.37	8.78	25396.61	high	high	
186	Debris	173, 78	2018	20180821	20180802	12	0	1	1	1	4	1	106564	0.1065646	5.06E+08	3543	1.650	1.650	16.50	31.9		Unknown	4523.42	7.55	69798.67	high	high	
191	Debris	173, 78	2018	20180821	20180802	12	0	1	1	1	4	1	88474	0.0884739	5.06E+08	3543	1.525	0.325	3.25	15.9		Unknown	4523.42	7.55	69798.67	high	high	
3	Rock slope deformation	173	2016	20160812	20160824	12	0	1	1	1	0	8	3	885114	0.8851139	1.72E+09	2463	1.750	1.750	17.50	53.2	1	Palaeognath/Miocene Sediments	1657.51	3.33	39748.61	high	medium
4	Rock slope deformation	173	2016	20160812	20160824	12	0	1	1	1	0	8	3	885114	0.8851139	1.72E+09	2463	1.750	1.750	17.50	53.2	1	Palaeognath/Miocene Sediments	1657.51	3.33	39748.61	high	medium
6	Rock slope deformation	173	2016	20160812	20160824	12	0	1	1	1	0	8	3	885114	0.8851139	1.72E+09	2463	1.750	1.750	17.50	53.2	1	Palaeognath/Miocene Sediments	1657.51	3.33	39748.61	high	medium
8	Rock slope deformation	173	2016	20160812	20160824	12	0	1	1	1	0	8	3	885114	0.8851139	1.72E+09	2463	1.750	1.750	17.50	53.2	1	Palaeognath/Miocene Sediments	1657.51	3.33	39748.61	high	medium
31	Rock slope deformation	173	2017	20170709	20170802	24	0	1	1	0	4	1	1015367	1.0153673	8.97E+08	2353	1.400	1.400	14.00	42.6	1	Divergent/Carboniferous Sediments	4772.80	2.16	64890.23	medium	high	
35	Rock slope deformation	173	2017	20170709	20170802	24	0	1	1	0	7	1	255366	0.2553663	1.27E+08	1248	2.450	1.225	12.25	37.3	1	Cretaceous Sediments	985.63	0.00	13118.29	medium	high	
46	Rock slope deformation	173	2017	20170807	20170819	12	0	1	1	1	0	5	1	55379	0.055374	1.46E+08	2163	0.500	0.500	5.00	15.2		Unknown	1369.26	12.19	7081.99	medium	high
47	Rock slope deformation	173	2017	20170807	20170819	12	0	1	1	1	0	5	1	129646	0.1296463	4.89E+08	2170	1.400	1.400	14.00	42.6		Cretaceous Sediments	6047.44	4.26	4866.55	medium	medium
48	Rock slope deformation	173	2017	20170812	20160824	12	0	1	1	1	12	3	694359	0.6943595	5.23E+09	1878	1.925	1.925	19.25	58.5		Cretaceous Sediments	4577.41	2.47	2887.89	high	medium	
53	Rock slope deformation	173	2017	20170814	20170826	12	0	1	1	1	0	11	3	127889	0.1278893	4.74E+08	1709	1.575	1.575	15.75	47.9	1	Cretaceous Sediments	3358.81	2.42	2169.13	medium	medium
56	Rock slope deformation	173	2017	20170814	20170826	12	0	1	1	1	0	9	3	115039	0.1150392	4.08E+08	2165	1.400	1.400	14.00	41.6	1	Palaeognath/Miocene Sediments	5268.88	7.11	31035.08	medium	medium
57	Rock slope deformation	173	2018	20170807	20170819	12	0	1	1	1	0	11	3	468178	0.4681785	2.98E+09	2088	1.925	1.925	19.25	58.5	1	Cretaceous Sediments	5197.86	0.00	9187.43	medium	medium
62	Rock slope deformation	173	2018	20180821	20180802	12	0	1	1	1	12	3	248733	0.2487335	1.22E+09	1482	1.750	1.750	17.50	53.2	1	Cretaceous Sediments	1798.39	2.91	604.70	high	high	
64	Rock slope deformation	78	2018	20180827	20180818	12	1	1	1	0	4	1	451013	0.4510133	2.84E+09	2683	1.575	1.575	15.75	47.9		Proterozoic Gneiss	14475.73	2.73	26833.04	low	high	
65	Rock slope deformation	173	2018	20180827	20180818	12	1	1	1	1	0	4	1	1119989	1.1199891	1.00E+10	1938	1.225	1.225	12.25	37.2		Palaeognath/Miocene Sediments	268.03	1.35	40188.06	high	high
66	Rock slope deformation	173	2017	20170814	20170826	12	1	1	1	1	10	3	131210	1.312104	1.02E+10	1938	2.450	2.450	24.50	74.5	1	Palaeognath/Miocene Sediments	242.40	1.25	40188.06	high	high	
81	Rock slope deformation	173	2018	20180829	20180821	12	0	1	1	1	13	3	160681	0.1606817	6.35E+08	1876	1.750	1.750	17.50	53.2	1	Palaeognath/Miocene Sediments	205.96	3.15	4203.42	medium	high	
83	Rock slope deformation	173	2018	20180829	20180821	12	0	1	1	1	13	3	248682	0.2486822	1.62E+09	2471	1.925	1.925	19.25	58.2	1	Palaeognath/Miocene Sediments	206.61	2.20	5342.91	medium	medium	
89	Rock slope deformation	173	2018	20180829	20180821	12	0	1	1	1	13	3	399892	0.3998929	2.30E+09	3235	2.100	2.100	21.00	63.9	1	Palaeognath/Miocene Sediments	4406.94	2.12	64200.00	medium	medium	
100	Rock slope deformation	173	2017	20170814	20170826	12	1	1	1	1	0	9	3	597010	0.5970101	4.17E+09	3535	1.225	1.225	12.25	37.3		Unknown	5406.45	0.00	82391.21	medium	medium
114	Rock slope deformation	173	2017	20170814	20170826	12	0	1	1	1	0	8	3	489257	0.4892567	3.20E+09	2110	1.400	1.400	14.00	42.6		Quaternary	1131.71	2.08	77840.44	high	high
118	Rock slope deformation	173	2017	20170821	20180802	12	0	1	1	1	0	8	3	61040	0.0610399	1.69E+08	2227	1.575	1.575	15.75	47.9	1	Cretaceous Sediments	2432.17	0.15	84576.95	medium	medium
119	Rock slope deformation	173	2017	20170814	20170826	12	0	1	1	1	0	12	3	150798	0.1507977	5.99E+08	3889	2.100	2.100	21.00	63.8	1	Cretaceous Sediments	3630.60	1.77	93975.04	medium	medium
121	Rock slope deformation	173	2018	20180808	20180821	12	0	1	1	1	0	8	3	445450	0.4453989	2.81E+09	2747	1.750	1.750	17.50	53.2	1	Carboniferous Granite	6551.65	0.00	13017.86	low	low
132	Rock slope deformation	173	2016	20160819	20160831	12	1	1	1	0	7	1	68433	0.0684333	1.97E+08	2852	0.875	0.875	8.75	26.6	1	Cretaceous Sediments	6680.87	0.31	13025.64	high	low	
133	Rock slope deformation	173	2017	20170814	20170826	12	1	1	1	1	0	13	3	454389	0.4543893	2.87E+09	1880	1.750	1.750	17.50	53.2	1	Palaeognath/Miocene Sediments	2276.30	2.44	7854.31	high	medium
140	Rock slope deformation	173	2017	20170814	20170826	12	1	1	1	1	0	11	3	200013	0.2000125	8.94E+08	1839	1.750	1.750	17.50	53.2	1	Cretaceous Sediments	3057.77	2.07	8755.86	medium	medium
141	Rock slope deformation	173	2017	20160812	20160824	12	1	1	1	1	0	13	3	150333	0.1503333	5.97E+08	1601	1.050	1.050	10.50	31.9		Cretaceous Sediments	1389.84	3.32	723.80	medium	medium
142	Rock slope deformation	173	2017	20170814	20170826	12	1	1	1	1	0	11	3	58425	0.0584254	1.43E+08	1649	0.700	0.700	7.00	21.3		Cretaceous Sediments	2071.86	3.21	7742.86	low	medium
143	Rock slope deformation	173	2016	20160812	20160824	12	1	1	1	1	0	6	1	358953	0.3589527	2.00E+09	2215	1.225	1.225	12.25	37.2	1	Cretaceous Sediments	7869.53	1.74	12589.52	low	medium
147	Rock slope deformation	173	2017	20160819	20160831	12	0	1	1	1	0	9	3	268487	0.2684871	1.33E+09	1667	1.750	1.750	17.50	53.3	1	Cretaceous Sediments	6024.65	0.59	22916.02	medium	high
155	Rock slope deformation	78	2017	20170820	20170831	12	0	1	1	1	0	2	1	138365	0.1383653	5.13E+08	1067	1.750	1.750	17.50	53.3	1	Palaeognath/Miocene Sediments	0.00	0.00	7277.58	medium	high
156	Rock slope deformation	78	2017	20170820	20170831	12	0	1	1	1	0	2	1	138365	0.1383653	5.13E+08	1067	1.750	1.750	17.50	53.3	1	Cretaceous Sediments	1495.78	0.19	2273.21	medium	high
157	Rock slope deformation	78, 173	2018	20180827	20180808	12	0	1	1	1	13	4	231937	0.2319373	1.41E+09	2441	3.175	3.175	31.75	89.2	1	Cretaceous Sediments	7085.43	0.99	766.99	high	high	
159	Rock slope deformation	78, 173	2017	20180827	20180808	12	0	1	1	1	0	8	4	201197	0.2011968	1.46E+08	1413	2.275	2.275	22.75	68.2		Cretaceous Sediments	0.00	0.00	766.99	high	high
162	Rock slope deformation	78	2017	20170808	20170813	36	0	1	1	1	0	3	1	162030	0.1620309	6.53E+08	2234	1.750	1.750	17.50	53.2	1	Carboniferous Granite	6464.69	0.43	5256.39	medium	medium
164	Rock slope deformation	78	2017	20170727	20170808	12	0	1	1	1	0	5	1	316266	0.3162655	1.77E+09	2298	2.800	0.933	9.33	28.3	1	Palaeognath/Miocene Sediments	2015.10	10.21	19326.05	medium	medium
165	Rock slope deformation	78	2017	20170727	20170808	12	0	1	1	1</																		

Attribute Number	Movement Type	Orbit	Source 1	Source 2	Bit	Optical	Int.	Temp.	Sat.	Total Inc. #	Likelihood	Area [m ²]	Area [km ²]	Volume [m ³]	Elevation [m a.s.l.]	cm/Bit	cm/12d	cm/120d	cm/s	Aliasing	Geological Unit	Distance to Rivers [m]	Distance to Faults [km]	Distance to Reservoir [m]	Integrated Damming Hazard	Damming Hazard (River Distance)	
231	Rock slope deformation	164	2016	20160730	20180602	672	0	1	1	0	3	N/A	599971	0.599971	4,25E+09	2947	8.850	0.158	1.58	4.8	1	Cretaceous Sediments	1084.337	0.71	41406.58	low	
232	Rock slope deformation	164	2018	20180728	20190601	308	0	1	1	0	3	N/A	372039	0.372039	2,16E+09	2684	7.380	0.288	2.88	8.7	1	Cretaceous Sediments	9399.30	0.07	41815.71	medium	
236	Rock slope deformation	164, 59	2016	20160730	20180602	672	0	1	1	0	4	N/A	2310974	2.310974	2,88E+10	2417	11.800	0.211	2.11	6.4	1	Paleogene-Neogene Sediments	1388.332	0.54	41512.71	medium	
237	Rock slope deformation	164	2016	20160730	20170728	364	0	1	1	0	3	N/A	559791	0.559791	3,85E+09	2945	6.640	0.249	2.49	6.7	0	Jurassic Volcanic Sediments	1119.06	10.21	86197.66	medium	
106	Rockslacer	173, 78	2017	20170814	20170926	12	1	1	1	0	16	6	174041	0.174041	7,34E+08	3804	2,450	2,450	21.00	74.5	1	Unknown	1209.65	12.44	84140.32	low	
107	Rockslacer	173, 78	2018	20180821	20180902	12	1	1	1	0	23	6	317641	0.317641	1,72E+09	3828	1,750	1,750	17.50	63.2	1	Unknown	1003.36	12.20	84202.90	low	
108	Rockslacer	173, 78	2017	20170812	20180924	12	1	1	1	0	9	4	96062	0.096062	2,91E+08	2954	2,800	2,800	28.00	65.1	1	Unknown	1019.45	12.63	82355.22	low	
109	Rockslacer	173, 78	2018	20180912	20180924	12	1	1	1	0	7	2	135958	0.135958	5,17E+08	3939	1,925	1,925	19.25	58.5	1	Unknown	1019.45	9.77	81355.22	low	
111	Rockslacer	173, 78	2016	20160912	20180924	12	1	1	1	0	1	3	259243	0.259243	1,29E+09	3769	2,450	2,450	24.50	74.5	1	Unknown	4400.90	9.89	76290.76	low	
112	Rockslacer	173, 78	2018	20180827	20180908	12	1	1	1	1	22	6	143215	0.143215	4,57E+08	3696	1,575	1,575	15.75	47.9	1	Unknown	5019.36	9.69	76290.76	low	
113	Rockslacer	173, 78	2017	20170808	20170901	24	1	1	1	1	14	3	115602	0.115602	4,11E+08	4054	2,100	1,050	10.50	31.9	1	Unknown	14158.82	9.67	76290.76	low	
115	Rockslacer	173, 78	2017	20170907	20170919	12	1	1	1	0	10	6	28552	0.028552	5,09E+07	3621	0,700	0,700	7.00	21.3	1	Jurassic Volcanic Sediments	3682.81	11.75	85716.72	low	
122	Rockslacer	173, 78	2017	20170907	20170919	12	1	1	1	0	18	6	120689	0.120689	4,37E+08	3872	2,100	2,100	21.00	63.8	1	Unknown	5432.56	2.15	83817.80	low	
123	Rockslacer	173, 78	2018	20170820	20170901	12	1	1	1	0	9	4	36734	0.036734	7,77E+07	3866	2,275	2,275	22.75	69.2	1	Unknown	7884.21	1.40	84648.09	low	
150	Rockslacer	173, 78	2016	20160912	20160924	12	1	1	1	0	3	4	96528	0.0965275	2,90E+08	3680	1,400	1,400	14.00	42.6	1	DevoianCarboniferous Sediments	9653.89	0.97	81376.90	low	
184	Rockslacer	173, 78	2017	20170820	20170901	12	1	1	1	0	14	4	104286	0.104286	5,47E+08	3794	2,800	2,800	28.00	65.1	1	Unknown	5092.59	4.34	64337.94	low	
185	Rockslacer	173, 78	2017	20170727	20170908	12	1	1	1	0	8	4	141524	0.141524	5,47E+08	3711	1,400	1,400	14.00	42.6	1	Unknown	6984.96	5.98	67664.78	low	
187	Rockslacer	173, 78	2017	20170820	20170901	12	0	1	1	0	7	1	64185	0.064185	1,78E+08	3611	1,750	1,750	17.50	53.2	1	Cretaceous Sediments	10619.82	23.28	84440.42	low	
188	Rockslacer	173, 78	2018	20180803	20180927	24	1	1	1	0	11	4	61400	0.0613999	1,85E+08	3601	1,575	0,788	7.88	23.9	1	DevoianCarboniferous Sediments	10022.76	0.43	78454.19	low	
189	Rockslacer	173, 78	2018	20180710	20180722	12	1	1	1	0	2	1	135263	0.065702	1,85E+08	3751	2,100	2,100	21.00	63.8	1	DevoianCarboniferous Sediments	5197.97	0.89	78454.19	low	
190	Rockslacer	173, 78	2017	20170727	20170908	12	1	1	1	0	3	1	65770	0.065702	1,85E+08	3871	1,400	1,400	14.00	42.6	1	Jurassic Volcanic Sediments	8602.64	1.10	84404.48	low	
194	Rockslacer	173, 78	2017	20170820	20170901	12	0	1	1	0	13	4	207864	0.207864	9,45E+08	3853	1,750	1,750	17.50	53.3	1	Cretaceous Sediments	9041.81	3.28	95505.69	low	
195	Rockslacer	173, 78	2017	20170820	20170901	12	0	1	1	0	10	3	61052	0.0610536	1,66E+08	3871	2,100	2,100	21.00	63.8	1	Jurassic Volcanic Sediments	10311.16	3.76	95597.14	low	
196	Rockslacer	173, 78	2017	20170820	20170901	12	0	1	1	0	5	1	122273	0.1222731	4,45E+08	3916	2,800	2,800	28.00	65.1	1	Cretaceous Sediments	10447.63	2.57	10835.29	low	
169	Rockslacer (Inactive)	173, 78	2017	20170820	20180927	372	0	1	1	0	2	1	74489	0.074489	2,20E+08	3511	1,750	0,875	8.75	26.6	1	Cretaceous Sediments	10237.46	2.26	10847.67	low	
207	Rockslacer (Inactive)	173, 78	2017	20170820	20180927	372	0	1	1	0	2	1	58254	0.0582542	1,55E+08	3395	0,225	0,007	0.07	0.2	1	DevoianCarboniferous Sediments	1248.92	0.00	10847.67	low	
25	Rockslide	173, 78	2016	20170709	20170902	24	1	1	1	0	11	4	194819	0.1948197	8,62E+08	1135	2,100	1,050	10.50	31.9	1	Cretaceous Sediments	10795.69	10.42	31725.88	low	
43	Rockslide	173, 78	2018	20180821	20180902	12	1	1	1	0	1	9	21677	0.0216772	9,69E+08	2679	2,100	2,100	21.00	63.8	1	Paleogene-Neogene Sediments	10933.37	2.29	43331.81	low	
69	Rockslide	173, 78	2017	20170814	20170926	12	1	1	1	0	14	3	854811	0.8548113	7,03E+09	2840	1,925	1,925	19.25	58.5	1	Proterozoic Gneiss	3746.32	3.22	56841.11	low	
87	Rockslide	173, 78	2018	20180821	20180902	12	1	1	1	0	9	3	121578	0.121578	4,41E+08	2440	0,875	0,875	8.75	26.6	1	Cretaceous Sediments	161.03	0.23	5790.34	low	
98	Rockslide	173, 78	2017	20170907	20170919	12	0	1	1	1	10	3	210829	0.2108288	9,64E+08	2194	1,050	1,050	10.50	31.9	1	Cretaceous Sediments	6674.35	0.99	5790.34	low	
134	Rockslide	173, 78	2017	20170907	20170919	12	0	1	1	0	7	1	143724	0.1437246	5,60E+08	2886	2,100	2,100	21.00	63.9	1	Cretaceous Sediments	10830.34	7.53	15891.34	low	
135	Rockslide	173, 78	2016	20160819	20160912	24	1	1	1	1	4	1	37280	0.0372906	8,25E+07	1971	0,875	0,438	4.38	13.3	1	Paleogene-Neogene Sediments	10633.36	4.88	18392.25	low	
138	Rockslide	173, 78	2016	20160819	20160912	24	1	1	1	1	6	1	86886	0.0868957	2,70E+08	3391	2,275	1,138	11.38	34.6	1	Cretaceous Sediments	10880.34	5.64	21192.36	low	
145	Rockslide	173, 78	2016	20170820	20170901	12	0	1	1	0	13	4	309455	0.3094531	1,66E+09	2904	2,100	1,050	10.50	31.9	1	Cretaceous Sediments	986.50	2.78	9578.25	low	
146	Rockslide	173, 78	2017	20170820	20170901	12	0	1	1	0	3	1	19791	0.197912	8,76E+08	1580	1,750	1,750	17.50	53.3	1	Cretaceous Sediments	2947.16	1.34	11252.36	low	
154	Rockslide	173, 78	2017	20170820	20170901	12	0	1	1	0	3	1	27576	0.2775761	1,42E+09	2237	1,400	1,400	14.00	42.6	1	Cretaceous Sediments	11509.45	5.65	23375.24	low	
155	Rockslide	173, 78	2017	20170820	20170901	12	0	1	1	0	3	1	516468	0.5164678	3,46E+09	3175	1,575	1,575	15.75	47.9	1	Cretaceous Sediments	8821.94	1.39	91879.19	low	
172	Rockslide	173, 78	2017	20170727	20170908	12	1	1	1	1	7	2	281843	0.281843	1,46E+09	2932	1,750	0,438	4.38	13.3	1	Paleogene-Neogene Sediments	3727.34	1.28	64545.18	low	
176	Rockslide	173, 78	2017	20170820	20170901	12	1	1	1	1	8	4	224359	0.2243586	1,05E+09	2015	2,100	2,100	21.00	63.8	1	Paleogene-Neogene Sediments	153.50	0.11	65114.39	low	
180	Rockslide	173, 78	2017	20170820	20170901	12	1	1	1	0	4	1	177238	0.1772383	7,53E+08	2015	2,100	2,100	21.00	63.8	1	Paleogene-Neogene Sediments	1289.77	1.58	10722.23	low	
182	Rockslide	173, 78	2017	20170820	20170901	12	1	1	1	0	4	1	288866	0.288866	1,51E+09	2125	3,150	3,150	31.50	95.8	1	Cretaceous Sediments	0.00	0.94	57693.91	low	
210	Rockslide	173, 78	2018	20180909	20180921	12	1	1	1	0	10	4	61490	0.06149	1,68E+08	1954	3,690	0,527	5.27	16.0	0	Paleogene-Neogene Sediments	2639.19	2.14	2912.56	low	
213	Rockslide	173, 78	2017	20170824	20171118	84	1	1	1	1	2	N/A	984517	0.9845169	8,58E+09	2323	1,750	1,750	17.50	53.2	1	Cretaceous Sediments	751.64	7.75	39611.32	low	
12	Rockslake/Rock slope deformation	173, 78	2018	20170814	20170926	12	0	1	1	1	12	4	1586003	1.5860031	1,64E+10	1849	2,100	2,100	21.00	63.9	1	Unknown	7322.91	11.58	44888.94	low	
16	Rockslake/Rock slope deformation	173, 78	2017	20170808	20170919	12	0	1	1	1	5	2	1278767	1.278767	1,24E+10	2072	1,575	0,525	5.25	15.9	1	Proterozoic Gneiss	5429.31	4.95	72380.06	low	
72	Rockslake/Rock slope deformation	173, 78	2017	20170814	20170926	12	0	1	1	0	9	3	92333	0.0923326	2,98E+08	3691	1,225	1,225	12.25	37.2	1	Cretaceous Sediments	12168.95	0.71	91239.04	low	
83	Rockslake/Rock slope deformation	173, 78	2017	20170814	20170926	12	0	1	1	0	1																

Attribute Number	Movement Type	Obkr	Year	Source	Source	Bl	Optical	Int.	Temp.	Set	Total Int. #	Likelihood	Area [m2]	Area	Volume [m3]	Elevation [m a.s.l.]	cm/ft	mm/12d	cm/12d	cm/a	Altering	Geological Unit	Distance to Rivers [m]	Distance to Reservoir [m]	Distance to Dam [m]	Integrated Damming Hazard	Damming Hazard (River Dist.)	
29	Soil Creep	173	2017	20170907	20170919	12	0	1	1	0	10	3	130961	0.1309612	4.930E+08	1783	2.275	2.275	22.75	69.2	1	Palaeogene/Neogene Sediments	2599.84	2.72	6515.19	medium	medium	
30	Soil Creep	173	2017	20170907	20170919	12	0	1	1	0	10	3	398697	0.3986967	1.262E+09	2574	1.975	1.975	15.75	47.9		Cretaceous Sediments	7192.39	7.15	12701.04	medium	low	
32	Soil Creep	173	2017	20170907	20170926	12	0	1	1	0	9	3	217704	0.2177041	1.01E+09	2592	1.975	1.975	15.75	47.9	1	Cretaceous Sediments	5364.72	5.37	1768.95	medium	low	
33	Soil Creep	173	2017	20170907	20170926	12	0	1	1	0	11	3	97529	0.0975291	3.423E+08	2033	1.030	1.030	10.30	31.9		Cretaceous Sediments	3567.68	3.05	3583.17	medium	low	
36	Soil Creep	173	2017	20170907	20170926	12	0	1	1	0	8	3	168359	0.1683589	6.10E+08	1954	0.875	0.875	6.75	26.6		Palaeogene/Neogene Sediments	17163.28	1.66	1551.46	low	low	
38	Soil Creep	173	2017	20170907	20170926	12	0	1	1	0	6	3	61425	0.0614251	9.922E+08	2100	1.030	1.030	10.30	31.9	1	Palaeogene/Neogene Sediments	16867.95	14.10	26953.50	low	low	
40	Soil Creep	173	2017	20170907	20170926	24	0	1	1	1	7	1	110544	0.1105439	3.66E+08	2294	2.275	1.138	11.38	34.5		Cretaceous Sediments	16292.62	10.23	15134.01	low	low	
41	Soil Creep	173	2017	20170909	20170926	12	0	1	1	0	8	3	176219	0.1762191	7.472E+08	2204	2.600	1.400	14.00	42.6	1	Cretaceous Sediments	16657.93	10.02	16919.17	low	low	
44	Soil Creep	173	2017	20170914	20170926	12	0	1	1	1	0	7	1	196392	0.1963921	8.172E+08	1273	1.400	1.400	14.00	42.6		Quaternary	331.76	1.60	0.00	high	high
49	Soil Creep	173	2017	20180909	20180926	12	0	1	1	1	0	7	1	55043	0.0550431	4.162E+08	1613	1.030	1.030	10.30	31.9	1	Cretaceous Sediments	742.64	2.64	645.37	medium	high
54	Soil Creep	173	2017	20180914	20170926	12	1	1	1	1	0	7	1	261422	0.2614217	1.31E+09	2004	1.750	1.750	17.50	53.2		Palaeogene/Neogene Sediments	5450.56	0.99	10826.59	medium	medium
67	Soil Creep	173	2017	20180909	20180926	12	0	1	1	1	0	4	1	142978	0.1429781	5.555E+08	1974	0.875	0.875	6.75	26.6		Proterozoic Gneiss	972.57	0.59	3926.15	low	high
73	Soil Creep	173	2017	20180921	20170919	12	0	1	1	1	0	8	3	87629	0.0876285	2.77E+08	2208	1.225	1.225	12.25	37.2	1	Proterozoic Gneiss	6360.08	3.20	36214.80	low	low
74	Soil Creep	173	2017	20180921	20180926	12	0	1	1	1	0	8	3	175983	0.1759831	7.46E+08	3174	1.030	1.030	10.30	31.9		Proterozoic Gneiss	10857.11	4.54	32261.14	low	low
75	Soil Creep	173	2017	20180921	20180926	12	0	1	1	1	0	9	3	52718	0.0527179	1.35E+08	2393	0.875	0.875	6.75	26.6	1	Quaternary	11050.11	4.48	31364.94	medium	low
76	Soil Creep	173	2017	20180921	20180926	12	1	1	1	1	0	6	1	30604	0.0306036	8.49E+07	3772	1.030	1.030	10.30	31.9		Palaeogene/Neogene Sediments	10034.60	9.52	39439.60	low	low
77	Soil Creep	173	2017	20180919	20170919	12	1	1	1	1	0	6	1	63437	0.0634369	1.75E+08	1854	0.525	0.525	5.25	15.9		Cretaceous Sediments	2084.27	1.93	45247.63	low	medium
78	Soil Creep	173	2017	20180921	20170919	12	1	1	1	0	0	2	1	57759	0.0577592	1.53E+08	1967	0.350	0.350	3.50	10.6		Quaternary	7170.96	4.24	40471.63	low	medium
79	Soil Creep	173	2017	20180921	20180926	12	0	1	1	0	0	11	3	373122	0.3731219	2.17E+09	2289	2.100	2.100	21.00	63.8	1	Cretaceous Sediments	1154.88	1.09	54868.79	high	medium
82	Soil Creep	173	2017	20180919	20180921	12	0	1	1	1	0	10	3	91330	0.0913303	2.94E+08	2101	1.400	1.400	14.00	42.6		Cretaceous Sediments	4681.35	4.25	46853.58	medium	medium
84	Soil Creep	173	2017	20180919	20170926	12	0	1	1	1	0	10	3	482064	0.4820642	3.12E+09	2068	1.925	1.925	19.25	56.5	1	Unknown	1876.92	7.37	55512.90	medium	medium
88	Soil Creep	173	2017	20180919	20170926	12	0	1	1	1	0	11	3	106699	0.1066986	3.67E+08	2266	1.750	1.750	17.50	53.2	1	Unknown	4951.10	5.90	59679.68	medium	medium
89	Soil Creep	173	2017	20180919	20170919	12	0	1	1	1	0	12	3	50460	0.0504602	1.27E+08	2365	1.030	1.030	10.30	31.9	1	Unknown	5298.33	5.41	59880.39	medium	medium
92	Soil Creep	173	2017	20180919	20170919	12	0	1	1	1	0	11	3	67065	0.0670651	1.90E+08	2363	0.525	0.525	5.25	15.9		Quaternary	731.88	11.61	74806.71	medium	high
94	Soil Creep	173	2017	20180914	20170926	12	0	1	1	1	0	10	3	163032	0.1630321	6.69E+08	2294	1.030	1.030	10.30	31.9		Unknown	1007.97	5.25	71931.38	medium	medium
96	Soil Creep	173	2017	20180914	20170926	12	0	1	1	1	0	8	3	102751	0.1027516	3.48E+08	2750	0.875	0.875	8.75	26.6		Unknown	359.93	0.07	65984.24	high	high
97	Soil Creep	173	2017	20180919	20170926	12	0	1	1	1	0	9	3	81258	0.0812576	2.46E+08	2761	0.875	0.875	8.75	26.6		Palaeogene/Neogene Sediments	2014.10	8.00	73922.66	medium	high
99	Soil Creep	173	2017	20180919	20180921	12	1	1	1	1	0	8	3	186832	0.1868321	8.14E+08	3731	2.800	2.800	28.00	85.1	1	Cretaceous Sediments	1956.34	0.78	69912.65	high	medium
101	Soil Creep	173	2017	20180919	20170926	12	0	1	1	1	0	5	1	484192	0.4841922	3.14E+09	1956	1.575	1.575	15.75	47.9		Cretaceous Sediments	1518.66	3.09	69742.67	medium	medium
102	Soil Creep	173	2017	20180919	20170926	12	0	1	1	1	0	8	3	222680	0.2226799	1.04E+09	2984	1.400	1.400	14.00	42.6		Devonian/Carboniferous Sediments	10701.39	9.62	75657.39	low	low
104	Soil Creep	173	2017	20180921	20180921	12	1	1	1	0	0	3	1	235944	0.2359437	6.50E+08	2823	0.875	0.875	8.75	26.6		Cretaceous Sediments	589.94	4.84	7565.47	medium	medium
117	Soil Creep	173	2016	20160819	20160902	12	1	1	1	1	0	8	3	159659	0.1596587	1.53E+09	1915	1.575	0.768	7.68	24.0	1	Cretaceous Sediments	8897.41	9.66	4027.49	medium	medium
131	Soil Creep	173	2016	20160819	20160912	24	1	1	1	1	0	14	3	235944	0.2359437	1.13E+09	1915	1.575	0.768	7.68	24.0		Cretaceous Sediments	4368.66	15.60	23729.75	low	medium
136	Soil Creep	173	2016	20160819	20160912	24	1	1	1	1	0	4	1	124635	0.1246352	4.57E+08	2787	1.225	0.613	6.13	18.6		Proterozoic Gneiss	7547.00	4.83	50748.26	medium	medium
148	Soil Creep	173	2016	20160807	20160912	36	1	1	1	1	1	8	4	532380	0.5323803	3.60E+09	3540	1.225	0.408	4.08	12.4		Cretaceous Sediments	5100.97	1.66	2897.74	medium	medium
158	Soil Creep	173	2016	20160827	20160912	36	1	1	1	0	1	3	1	246227	0.2462273	1.20E+09	1888	2.800	2.800	28.00	85.0	1	Unknown	1789.47	3.34	5517.79	medium	medium
160	Soil Creep	173	2017	20170727	20170913	48	0	1	1	1	0	1	7	279569	0.2795671	1.44E+09	1527	2.100	0.525	5.25	15.9		Quaternary	1298.50	9.85	9517.33	medium	medium
161	Soil Creep	173	2017	20180827	20180908	12	0	1	1	1	0	4	1	59639	0.0596386	1.61E+08	2187	1.400	1.400	14.00	42.6	1	Cretaceous Sediments	5574.71	0.37	16809.30	medium	medium
161	Soil Creep	173	2017	20180827	20180908	12	0	1	1	1	0	5	1	130601	0.1306014	4.89E+08	2356	1.225	0.613	6.13	18.6		Palaeogene/Neogene Sediments	7571.66	5.03	50653.65	medium	medium
181	Soil Creep	78, 173	2017	20180710	20180722	12	0	1	1	1	0	8	4	119400	0.1193995	4.30E+08	3275	1.750	1.750	17.50	53.2	1	Quaternary	427.39	1.12	8692.40	high	high
183	Soil Creep	78, 173	2017	20170820	20170901	12	0	1	1	1	0	10	4	108633	0.1086314	1.32E+09	2012	1.030	1.030	10.30	31.9		Cretaceous Sediments	346.41	1.02	8692.40	high	high
201	Soil Creep	78, 173	2017	20170727	20170908	12	0	1	1	1	0	11	4	283611	0.2836111	1.32E+09	2012	1.750	0.875	8.75	26.6	1	Quaternary	321.97	1.30	87918.17	medium	high
202	Soil Creep	78, 173	2017	20170808	20170901	12	0	1	1	1	0	6	2	340477	0.3404768	1.62E+09	1924	2.800	0.700	7.00	21.3		Cretaceous Sediments	2033.62	2.52	0.00	medium	medium
212	Soil Creep	164	2018	20170824	20171118	84	0	1	1	1	1	3	N/A	277039	0.2770391	1.42E+09	1915	3.680	0.526	5.26	16.0		Carboniferous Granite	2785.81	1.83	1689.70	medium	medium
214	Soil Creep	164	2018	20180519	20180714	56	0	1	1	1	0	6	N/A	93734	0.0937341	3.05E+08	1522	8.120	17.40	17.40	52.9		Palaeogene/Neogene Sediments	4225.26	3.09	3011.52	medium	medium
215	Soil Creep	164	2018	20180519	20180714	56	0	1	1	1	0	6	N/A	93625	0.0936251	1.54E+09	2157	7.370	1.423	14.23	43.3	1	Jurassic Volcanic Sediments	5179.46	3.71	4942.75	medium	medium
216	Soil Creep	164	2018	20180519	20180714	56	0	1	1	1	0	3	N/A	293641	0.2936411	1.54E+09	2157	7.370	15.79	15.79	48.0		Palaeogene/Neogene Sediments	1412.21	16.63	1803		

Attribute Number	Movement Type	Orbit	Year	Source_1	Source_2	Bit	Optical	Int.	Temp.	Sat.	Total Int. #	Likelihood	Area [m ²]	Volume [m ³]	Elevation [m a.s.l.]	cm/Bit	cm/2d	cm/20d	cm/a	Aliasing	Geological Unit	Distance to Rivers [m]	Distance to Faults [km]	Distance to Reservoir [m]	Integrated Damming Hazard	Damming Hazard (River Distance)	
14	Soil Creep/Side	78, 173	2016	20170808	20170913	36	0	1	1	1	1	2	422986	0.4229863	2.95E+09	1.335	2.450	0.817	8.17	24.8		Cretaceous Sediments	861.74	0.98	0.00	medium	high
17	Soil Creep/Side	78, 173	2017	20170820	20170901	12	1	1	1	1	19	6	793724	0.7937242	6.32E+09	1.940	1.925	1.925	19.25	58.5	1	Quaternary	523.56	1.99	69452.02	high	high
18	Soil Creep/Side	78, 173	2017	20170820	20170901	48	1	1	1	1	8	4	173156	0.1731562	7.29E+08	1.834	2.800	0.700	7.00	86.1	1	Quaternary	689.16	1.46	76993.53	high	high
19	Soil Creep/Side	78, 173	2017	20170820	20170901	12	0	1	1	1	13	4	489122	0.4891217	3.26E+09	1.981	1.750	1.750	17.50	53.2	1	Quaternary	464.43	1.05	76992.32	high	high
26	Soil Creep/Side	78, 173	2017	20170907	20170919	12	0	1	1	1	10	3	367813	0.3678132	2.12E+09	2.236	1.575	1.575	15.75	47.9		Cretaceous Sediments	1044.55	9.89	15222.01	medium	low
27	Soil Creep/Side	78, 173	2017	20170907	20170919	12	0	1	1	1	9	1	182006	0.1820065	7.82E+08	2.961	1.225	1.225	12.25	37.3		Cretaceous Sediments	10165.20	9.42	15647.35	low	low
37	Soil Creep/Side	78, 173	2017	20170907	20170919	12	0	1	1	1	7	2	78220	0.0782195	2.36E+08	3.901	1.050	1.050	10.50	31.9		Quaternary	3792.02	13.44	14730.15	medium	medium
51	Soil Creep/Side	78, 173	2017	20170814	20170826	12	1	1	1	1	7	1	248869	0.2488693	1.32E+09	2.155	1.925	1.925	19.25	58.5	1	Cretaceous Sediments	441.93	0.75	78262.78	medium	high
55	Soil Creep/Side	78, 173	2017	20170814	20170826	12	1	1	1	1	5	1	481753	0.4817527	3.11E+09	1.836	2.800	28.00	88.0		Proterozoic Gneiss	2044.59	5.55	15046.39	medium	low	
58	Soil Creep/Side	78, 173	2017	20160819	20160831	12	1	1	1	1	7	1	420198	0.4201982	2.86E+09	1.988	1.225	1.225	12.25	37.2		Palaeogene/Neogene Sediments	1133.01	1.69	40411.95	medium	medium
63	Soil Creep/Side	78, 173	2017	20160819	20160831	12	0	1	1	1	10	3	160057	0.1600572	6.52E+08	2.907	1.575	1.575	15.75	47.9		Jurassic Volcanic Sediments	6492.17	0.00	54440.99	medium	medium
80	Soil Creep/Side	78, 173	2017	20170814	20170826	12	1	1	1	1	3	1	71407	0.0714074	2.07E+08	3.530	1.050	1.050	10.50	31.9		Unknown	6158.82	0.33	76011.99	medium	medium
116	Soil Creep/Side	78, 173	2017	20170820	20170901	12	1	1	1	1	14	4	213761	0.2137605	9.83E+08	3.528	4.200	4.200	42.00	127.7	1	Jurassic Volcanic Sediments	1098.65	0.44	91371.60	high	medium
125	Soil Creep/Side	78, 173	2017	20170820	20170901	12	0	1	1	1	9	2	108771	0.1087709	3.82E+08	3.938	2.450	2.450	24.50	74.5		Jurassic Volcanic Sediments	1364.25	0.19	91723.22	high	medium
126	Soil Creep/Side	78, 173	2017	20170820	20170901	12	0	1	1	1	4	2	3560173	0.35601734	3.82E+08	2.951	0.700	0.700	7.00	21.3	1	Jurassic Volcanic Sediments	4291.92	0.00	92509.73	medium	medium
129	Soil Creep/Side	78, 173	2018	20180821	20180902	12	1	1	1	1	15	4	170573	0.1705725	7.14E+08	2.299	0.700	0.700	7.00	21.3		Palaeogene/Neogene Sediments	5204.64	10.39	25634.40	medium	medium
137	Soil Creep/Side	78, 173	2017	20170907	20170919	12	1	1	1	1	11	3	227789	0.2277895	7.14E+08	2.954	1.400	1.400	14.00	42.6	1	Cretaceous Sediments	1746.42	0.81	23706.82	medium	medium
146	Soil Creep/Side	78, 173	2017	20160819	20160831	12	0	1	1	1	7	1	200343	0.2003427	8.97E+08	2.154	1.925	1.925	19.25	58.5		Palaeogene/Neogene Sediments	1920.41	9.96	59864.42	medium	medium
149	Soil Creep/Side	78, 173	2016	20160912	20160924	12	0	1	1	1	1	1	134487	0.134487	5.09E+08	2.988	1.050	1.050	10.50	31.9		Cretaceous Sediments	6603.04	0.14	72816.83	medium	medium
5	Soil Slide	78, 173	2017	20170814	20170826	12	1	1	1	1	6	7	104285	0.1042849	3.55E+08	2.288	1.050	1.050	10.50	31.9		Cretaceous Sediments	8089.45	1.72	53963.14	low	medium
86	Soil Slide	78, 173	2017	20170727	20170913	48	1	1	1	1	2	1	94735	0.0947353	3.10E+08	2.017	1.225	1.225	12.25	37.2		Cretaceous Sediments	6823.79	1.72	3553.32	low	medium
167	Soil Slide	78, 173	2017	20170727	20170913	48	0	1	1	1	4	1	80895	0.0808951	2.48E+08	3.007	1.225	1.225	12.25	37.2	1	Unknown	7166.34	0.49	81893.68	low	medium
192	Soil Slide	78, 173	2017	20180809	20180821	12	0	1	1	1	9	3	137133	0.1371327	5.24E+08	3.541	1.225	1.225	12.25	37.2		Unknown	6823.92	7.72	11710.96	medium	low
45	Unknown	78, 173	2018	20180809	20180821	12	0	1	1	1	0	3	509486	0.5084863	3.96E+09	3.443	1.925	1.925	19.25	58.5	1	Palaeogene/Neogene Sediments	4146.71	8.35	13975.97	medium	high
50	Unknown	78, 173	2018	20180622	20180704	12	0	1	1	1	1	2	1274775	1.2747753	1.24E+10	1.741	1.400	1.400	14.00	42.6		Proterozoic Gneiss	106.00	0.48	35014.60	high	high
59	Unknown	78, 173	2018	20180809	20180821	12	0	1	1	1	0	2	700727	0.700727	5.30E+09	3.505	2.275	2.275	22.75	69.2	1	Palaeogene/Neogene Sediments	12619.13	0.28	22754.43	medium	low
61	Unknown	78, 173	2018	20180809	20180821	12	1	1	1	1	3	3	136068	0.1360063	5.17E+08	3.521	1.050	1.050	10.50	31.9		Palaeogene/Neogene Sediments	10038.30	9.89	30050.95	low	low
70	Unknown	78, 173	2018	20170814	20170826	12	1	1	1	1	10	3	387359	0.3873594	2.28E+09	3.965	2.625	2.625	26.25	79.8	1	Devonian/Carboniferous Sediments	9283.45	20.39	67444.26	low	low
93	Unknown	78, 173	2018	20180809	20180821	12	1	1	1	1	3	3	48708	0.0487079	1.21E+08	3.616	1.050	1.050	10.50	31.9		Jurassic Volcanic Sediments	10016.15	8.95	89940.78	low	low
124	Unknown	78, 173	2018	20180809	20180821	12	0	1	1	1	6	2	131878	0.1318782	4.95E+08	2.177	1.750	1.750	17.50	53.2	1	Palaeogene/Neogene Sediments	7034.77	1.86	98465.58	medium	medium
166	Unknown	78, 173	2017	20170808	20170913	36	0	1	1	1	1	6	106729	0.1067288	3.07E+08	3.544	0.525	0.525	5.25	17.5	1	Proterozoic Gneiss	9677.83	2.56	98465.67	low	medium
170	Unknown	78, 173	2017	20170808	20170913	36	0	1	1	1	7	2	94142	0.0941422	3.07E+08	2.292	2.275	2.275	22.75	69.2	1	Cretaceous Sediments	2097.81	3.11	42150.06	medium	medium
174	Unknown	78, 173	2017	20170820	20170901	12	0	1	1	1	1	1	88689	0.0886889	2.82E+08	3.963	1.400	1.400	14.00	42.6	1	Cretaceous Sediments	12539.56	5.43	98416.68	low	low
197	Unknown	78, 78	2016	20160912	20160924	12	0	1	1	1	1	4	75337	0.0753373	2.24E+08	3.982	0.700	0.700	7.00	21.3		Proterozoic Gneiss	12643.04	4.93	99149.98	medium	low

11.3 Appendix III: Landslide Inventory.

Table 7: Landslide inventory data table containing rockslides mapped by Strom & Abdrakhmatov (2018) and catalogued in NASA's Landslide Viewer.

Geographical Data						Comments	Landslide Body Characteristics				Source
Failure Type	Rough Geographical Location	Latitude	Longitude	Feature Number if available	Date of Failure		Total area affected (headscarp + deposits) (km ²)	Total volume (10 ⁶ m ³)	Total hor. distance from crown to deposit tip (km)	Total ver. distance from crown to deposit lowest point (km)	
Rockslide (DSGSD)	Darai-Namak	38.7711	69.9311	Tajik 001		neotectonic thrust fault and arcuate scarps; difficult relation btw neotectonism and adjacent sliding bodies					Strom & Abdrakhmatov 2018
Rockslide		39.2011	70.9133	Tajik 037		rejuvenated older landslide dam upstream from Khait	1.10	6.0	1.96	0.540	Strom & Abdrakhmatov 2018
Rockslide	Khait	39.1869	70.8814	Tajik 038	July 1949	Most disastrous slope failure	5.70	100.0	7.41	1.350	Strom & Abdrakhmatov 2018
Rockslide	Kutugansu-mouth	39.4415	71.4160	Tajik 049			3.80	300.0	3.10	0.950	Strom & Abdrakhmatov 2018
Rockslide		39.3481	71.2811	Tajik 050							Strom & Abdrakhmatov 2018
Rockslide		39.1697	70.3603	Tajik 051							Strom & Abdrakhmatov 2018
Rockslide	Honaihol	38.6530	69.8200	Tajik 083							Strom & Abdrakhmatov 2018
Rockslide	Djurudj	38.6533	69.8013	Tajik 084							Strom & Abdrakhmatov 2018
Rockslide (DSGSD)		39.1100	71.3000	Tajik 117		giant thrust, HW with DSGSD, fresh scarps and ongoing def.					Strom & Abdrakhmatov 2018
Rockslide (DSGSD)		39.1200	71.2000	Tajik 118		giant thrust, HW with DSGSD, fresh scarps and ongoing def.					Strom & Abdrakhmatov 2018
Rockslide		38.9200	70.1800	Tajik 119		graben-like subsidence					Strom & Abdrakhmatov 2018
Rockslide		38.7660	71.0527	Tajik 142		natural damming of unnamed valley, potential glacial origin or debris flow					Strom & Abdrakhmatov 2018
Rockslide		38.7591	71.0408	Tajik 143		natural damming of unnamed valley, potential glacial origin or debris flow					Strom & Abdrakhmatov 2018
Rockslide		38.7906	71.0724	Tajik 144		natural damming of unnamed valley, potential glacial origin or debris flow					Strom & Abdrakhmatov 2018
Rockslide	Ragnow-mouth	38.9213	70.9642	Tajik 145		likely no more than a century old; possibly also triggered by 1949 Khait EQ; natural dam has breaching potential; similar to Satsu rockslide in Muksu Valley					Strom & Abdrakhmatov 2018
Rockslide		38.8915	70.9622	Tajik 146		parallel to Jurassic layers strike		200.0			Strom & Abdrakhmatov 2018
Rockslide		38.9405	70.9985	Tajik 147		scarps potentially along/inherits bedding					Strom & Abdrakhmatov 2018
Rockslide		38.8823	70.8988	Tajik 148							Strom & Abdrakhmatov 2018
Rockslide		38.8555	70.7826	Tajik 149							Strom & Abdrakhmatov 2018
Rockslide		38.7885	70.8211	Tajik 150		deposits overlay low dam from previous landslide					Strom & Abdrakhmatov 2018
Rockslide		38.7890	70.4060	Tajik 151		easily erodible, thus source of debris flow material					Strom & Abdrakhmatov 2018
Rockslide		38.7605	70.3696	Tajik 152							Strom & Abdrakhmatov 2018
Rockslide		39.2508	71.3482	Tajik 204							Strom & Abdrakhmatov 2018
Rockslide		39.2906	71.4042	Tajik 205							Strom & Abdrakhmatov 2018
Landslide	12 km W of Gharm	39.01	70.20		March 2007	500m blocked road, 8 dead		small			NASA Landslide Viewer
Mudslide	Gharm	39.02	70.37		July 2017	extensive damage to infrastructure		medium			NASA Landslide Viewer
Mudslide	Rasht Valley, 6km NE of Gharm	39.07	70.43		July 2015	929 homeless families, 272 houses destroyed		medium			NASA Landslide Viewer
Landslide	Jirgatol	39.22	71.19		April 2007	3 houses destroyed, 1 dead		medium			NASA Landslide Viewer
Mudslide	Rasht Valley, 6km SE of Jirgatol	39.20	71.28		May 2017			large			NASA Landslide Viewer
Earthflow	Ozodagon, Rasht Valley, 25km NE of Jirgatol	39.34	71.51		April 2017	6 houses destroyed		medium			NASA Landslide Viewer

11.4 Appendix IV: Earthquake Inventory

Figure 33: Earthquake locations and D-K and MPT fault traces, indicating the seismogenic nature of these faults.

11.5 Appendix V: Lineament Map of Major Seismogenic Faults

Figure 34: Major seismogenic faults in the study area and distribution of detected slope activity.

11.6 Appendix VI: Elevation Range per Slope Movement Type

Table 8: Elevation range per movement type.

Movement Type	Min. Elevation [m a.s.l.]	Max. Elevation [m a.s.l.]	Mean Elevation [m a.s.l.]
Rock slope deformation	1'067	3'889	2'422
Rockslide	1'135	3'842	2'655
Soil Slide	2'017	3'307	2'647
Soil Creep	1'273	3'772	2'258
Debris Flow	1'584	3'433	2'501
Rockglacier	2'954	4'054	3'760
Ice Debris	3'423	4'004	3'726
Unknown	1'741	3'982	3'225

11.7 Appendix VII: Velocity Ranges per Slope Movement Type

Table 9: Velocity ranges per movement type per 12 days, 4 months (120 days) and per year. Velocities per 4 months represent summer velocities and may be treated as approximate true velocities. Velocities per year are linearly extrapolated and cannot be considered as truly representative of surface movement, this is expected to be slower due to typically observed deceleration in winter.

Movement Type / Velocities	Rock slope deformation	Rock slide	Soil Slide	Soil Creep	Debris Flow	Rock glacier	Ice Debris	Unknown
Min cm/12d	0.16	0.438	0.306	0.118	0.96	0.7	0.394	0.175
Max cm/12d	5.6	5.6	1.05	4.2	2.8	2.8	2.625	2.625
Mean cm/12d	1.77	1.225	0.765	1.05	1.88	1.75	1.05	1.313
Min cm/120d	1.6	4.375	3.06	1.18	9.625	7	3.93	1.75
Max cm/120d	56	56	10.5	42	28	28	26.25	26.25
Mean cm/120d	14	15.52	7.22	10.5	18.8	17.38	11.29	12.95
Min cm/a	4.8	10.6	9.3	3.61	29.3	21.3	80	75
Max cm/a	>170	>170	31.9	127.7	85.1	85.1	79.8	79.8
Mean cm/a	42.6	47.6	21.92	33.2	57.2	52.85	34.28	39.4

11.8 Appendix VIII: Potentially Seismically-Induced Active Slopes

11.9 Appendix IX: Rockglaciers and Ice Debris

Rockglaciers and ice debris are observed in the SE of the study area at elevations up to 4'054 m a.s.l. They form typical lobate and tongue-shaped landforms as expected (fig. 35). Mean velocities in summer are 1.05 – 1.75 cm/12d or 11.29 – 17.38 cm/120d. Due to these relatively high velocities and the distinct morphology, rockglaciers and ice debris have a high likelihood of activity including the highest percentage of all detected features in >50 % of the differential interferograms. Average velocities per year are likely lower, as displacement during winter is expected to be slower due to increased snow and ice cover. This cannot be confirmed, however, due to a lack of sufficiently correlated winter differential interferograms. Fig. 35 includes three rockglaciers observed in Sentinel-1 ascending orbit 173, where the central feature has a likelihood class of 6 and thus very high confidence of true activity due to its generally high velocity of min. 2.8 cm/12d as observed here in one full fringe cycle. Features to the right and left have a lower activity likelihood and are often too decorrelated to estimate displacement rates due to snow cover at higher elevations of ~3'900 m a.s.l.

Figure 35: Three rockglaciers observed in high permafrost mountains in Sentinel-1 ascending orbit 173.

11.10 Appendix X: Integrated Damming Hazard Analysis

Table 10: Complete table of data relevant to calculate the integrated damming hazard.

Slope Instability Number and Type				Slope Instability Parameters					Geological and Geomorphological/Spatial Characteristics					Hazard Parameters						30-30-40 Classification
Attribute Number	Movement Type	Bt	Likelihood	Area [m ²]	Volume [m ³]	Elevation [m a.s.l.]	Velocity cm/a	Distance to Rivers [m]	Distance to Faults [m]	Distance to Reservoir [m]	Norm. Likelihood	Norm. River (Invert)	Norm. Fault (Invert)	Norm. Velocity	Norm. Volume	Hazard	Normalised Hazard			
60	Debris Flow	24	1	689153	5.18E+09	2775	29.300	3750.19	9650.23	18273.15	0.000000	0.798246	0.526754	0.123267	0.238330	2.97359	0.354944	medium		
171	Debris Flow/Rockslide	12	2	46786	1.14E+08	3433	85.100	9899.18	4971.92	17727.89	0.200000	0.467441	0.756178	0.409861	0.005143	2.97351	0.301714	medium		
3	Rock slope deformation	12	3	863114	7.12E+09	2483	53.200	1657.51	3334.88	38749.61	0.400000	0.910829	0.836458	0.246020	0.321819	5.2586	0.700413	high		
4	Rock slope deformation	12	1	1918957	2.21E+10	3183	53.200	3796.89	2183.42	63028.56	0.000000	0.795734	0.892925	0.246020	1.000000	5.52615	0.747093	high		
6	Rock slope deformation	12	1	646679	4.73E+09	2853	42.600	4757.90	2154.42	46060.23	0.000000	0.744033	0.894347	0.191577	0.213647	3.74532	0.436378	medium		
8	Rock slope deformation	12	1	1015367	8.97E+09	2353	42.600	0.00	16654.31	88312.64	0.000000	1.000000	0.183275	0.191577	0.405255	4.18536	0.513156	medium		
31	Rock slope deformation	24	1	256346	1.27E+09	1288	37.300	985.63	0.00	13118.29	0.000000	0.946975	1.000000	0.058485	0.057472	4.12022	0.501791	medium		
35	Rock slope deformation	12	1	55379	1.45E+08	2163	15.200	1369.26	12191.04	7081.99	0.000000	0.926336	0.402153	0.050547	0.006533	3.24507	0.349096	medium		
46	Rock slope deformation	12	1	129646	4.83E+08	2170	42.600	6047.44	4255.26	4966.55	0.000000	0.674658	0.791322	0.191577	0.021844	3.05056	0.315158	medium		
47	Rock slope deformation	12	3	694359	5.23E+09	1876	58.500	4577.41	2467.67	2567.68	0.400000	0.753743	0.878986	0.273241	0.236341	4.68614	0.600530	high		
48	Rock slope deformation	12	3	127889	4.74E+08	1709	47.900	3358.61	2416.49	2169.13	0.400000	0.819312	0.881496	0.218798	0.021425	4.40108	0.550794	medium		
53	Rock slope deformation	12	3	115039	4.08E+08	2165	41.600	5268.88	7106.29	31035.08	0.400000	0.716543	0.651508	0.186441	0.018436	3.82445	0.450185	medium		
56	Rock slope deformation	12	3	465178	2.96E+09	2098	58.500	5197.86	0.00	9187.43	0.400000	0.720364	1.000000	0.273241	0.133870	4.50207	0.568415	medium		
57	Rock slope deformation	12	3	248733	1.22E+09	1492	53.200	798.39	2913.02	6064.70	0.400000	0.957048	0.857146	0.246020	0.055065	4.88444	0.635130	high		
62	Rock slope deformation	12	1	451013	2.84E+09	2623	47.900	14475.73	2733.24	26933.06	0.000000	0.221231	0.865962	0.218798	0.128122	1.87657	0.110323	low		
64	Rock slope deformation	12	1	1119999	1.03E+10	2018	37.200	268.03	1354.17	40188.06	0.000000	0.985581	0.933592	0.163842	0.465769	4.51994	0.571533	high		
66	Rock slope deformation	12	3	1311210	1.29E+10	1938	74.500	242.40	1247.33	40108.63	0.400000	0.986959	0.938331	0.355419	0.582515	5.63764	0.766547	high		
81	Rock slope deformation	12	3	245683	1.20E+09	2471	58.800	2098.61	2220.46	53442.91	0.400000	0.887098	0.882090	0.274782	0.054109	4.68228	0.599856	medium		
85	Rock slope deformation	12	3	143826	5.60E+08	3610	42.600	7040.08	4300.89	52965.27	0.400000	0.621266	0.789085	0.191577	0.025311	3.66974	0.423191	medium		
100	Rock slope deformation	12	3	398921	2.39E+09	3235	63.900	4906.94	2120.92	64200.00	0.400000	0.736015	0.895990	0.300976	0.107889	4.313	0.535426	medium		
114	Rock slope deformation	12	3	587010	4.12E+09	3535	37.300	5408.45	0.00	82491.21	0.400000	0.709035	1.000000	0.164355	0.186225	4.27769	0.529264	medium		
118	Rock slope deformation	12	3	491257	3.20E+09	2110	42.600	1331.71	2081.88	76040.44	0.400000	0.928357	0.897905	0.191577	0.144643	4.81919	0.623746	high		
119	Rock slope deformation	12	1	61040	1.66E+08	2227	47.900	2432.17	147.79	84376.95	0.000000	0.869154	0.992752	0.218798	0.007501	3.82651	0.450545	medium		
121	Rock slope deformation	12	3	150798	5.99E+08	3889	63.800	3630.60	1774.09	93875.04	0.400000	0.804680	0.912999	0.300462	0.027089	4.45457	0.560127	medium		
132	Rock slope deformation	12	3	448540	2.81E+09	2747	53.200	6561.65	0.00	13017.86	0.400000	0.647532	1.000000	0.246020	0.127127	4.11574	0.501009	medium		
133	Rock slope deformation	12	1	68433	1.95E+08	2852	26.600	6980.67	311.72	13225.64	0.000000	0.625528	0.884713	0.109399	0.008822	2.97952	0.302763	low		
139	Rock slope deformation	12	3	454399	2.87E+09	1860	53.200	2276.30	2444.63	7954.31	0.400000	0.877539	0.880116	0.246020	0.129489	4.68824	0.600897	high		
140	Rock slope deformation	12	3	200013	8.94E+08	1839	53.200	3057.77	2069.77	7713.80	0.400000	0.935497	0.893499	0.246020	0.040414	4.49142	0.586557	medium		
141	Rock slope deformation	12	3	150553	5.97E+08	1601	31.900	1388.84	3317.53	7213.80	0.400000	0.925229	0.837309	0.136620	0.026556	4.57657	0.581414	medium		
142	Rock slope deformation	12	3	54825	1.43E+08	1649	21.300	2071.86	3207.45	7742.86	0.400000	0.888537	0.842707	0.082178	0.006441	4.39694	0.550071	medium		
143	Rock slope deformation	12	1	359503	2.08E+09	2215	37.200	7869.53	1737.71	12598.52	0.000000	0.578633	0.914783	0.163842	0.092869	2.90139	0.580131	low		
147	Rock slope deformation	12	3	264987	1.33E+09	3556	37.200	6024.65	590.12	25916.02	0.400000	0.675884	0.971061	0.163842	0.060240	4.0228	0.484792	medium		
155	Rock slope deformation	12	1	136155	5.18E+08	1067	53.300	0.00	0.00	7277.58	0.000000	1.000000	1.000000	0.246533	0.023417	4.26995	0.527915	medium		
156	Rock slope deformation	36	1	778350	6.15E+09	1591	35.500	1308.78	1180.85	5223.21	0.000000	0.929580	0.942091	0.155110	0.277912	4.16388	0.509409	medium		
157	Rock slope deformation	12	4	332862	1.84E+09	2491	95.800	7082.43	873.89	7861.48	0.600000	0.618978	0.957145	0.464818	0.083257	4.56215	0.578898	medium		
159	Rock slope deformation	12	4	281197	1.45E+09	1413	62.200	0.00	991.35	0.00	0.600000	1.000000	0.951384	0.328197	0.065335	5.54512	0.750403	high		
162	Rock slope deformation	12	1	160200	6.53E+08	2324	53.200	6464.69	434.39	5256.39	0.000000	0.852211	0.978698	0.246020	0.029495	3.21084	0.343124	medium		
164	Rock slope deformation	36	1	316256	1.71E+09	2298	28.300	2015.10	10212.80	19326.05	0.000000	0.891591	0.499166	0.118130	0.077426	3.3695	0.370805	medium		
165	Rock slope deformation	12	1	58479	1.56E+08	2169	53.200	2251.50	10393.74	19383.65	0.000000	0.878873	0.940292	0.246020	0.007058	3.37999	0.372636	medium		
168	Rock slope deformation	12	1	297309	1.57E+09	2096	31.900	4122.32	1571.53	10793.41	0.000000	0.778226	0.92932	0.136620	0.070927	3.46516	0.387496	medium		
177	Rock slope deformation	12	1	223882	1.05E+09	3378	53.200	10754.35	8153.75	39532.63	0.000000	0.421434	0.600141	0.246020	0.047335	2.1578	0.159391	low		
178	Rock slope deformation	12	1	144466	5.64E+08	3567	53.200	10433.54	8536.26	39750.37	0.000000	0.438684	0.581383	0.246020	0.025471	2.16895	0.161337	low		
198	Rock slope deformation	12	4	1009317	8.89E+09	2871	170.300	6535.61	636.43	89612.22	0.600000	0.648395	0.968789	0.847458	0.401833	5.36327	0.718674	high		
199	Rock slope deformation	12	2	1153585	1.07E+10	2749	200.000	6085.21	207.50	90497.06	0.200000	0.672626	0.989824	1.000000	0.485712	4.89341	0.636966	high		

Attribute Number	Movement Type	Br	Likeli-hood	Area [m ²]	Volume [m ³]	Elevation [m a.s.l.]	Velocity cm/s	Distance to Rivers [m]	Distance to Faults [m]	Distance to Reservoir [m]	Norm. Likelihood	Norm. River (invert)	Norm. Fault (invert)	Norm. Velocity	Norm. Volume	Hazard	Normalised Hazard	30-30-40 Classification
25	Rockslide	24	4	194819	8.62E+08	1135	31,900	1248.92	0.00	13685.74	0.600000	0.932810	1.000000	0.136620	0.038933	5.21292	0.692442	high
43	Rockslide	12	4	192188	8.45E+08	2279	63,800	4383.37	2291.76	4339.31	0.600000	0.764182	0.867612	0.300462	0.038189	4.757	0.612894	high
69	Rockslide	12	3	854811	7.03E+09	2640	56,500	3746.32	3216.87	5864.13	0.400000	0.798454	0.842245	0.273241	0.317434	4.62828	0.590436	medium
87	Rockslide	12	3	121578	4.41E+08	2440	26,600	161.03	3519.16	63813.11	0.400000	0.991337	0.827421	0.109399	0.019941	4.73077	0.608318	high
98	Rockslide	12	1	210829	9.64E+08	2194	31,900	7187.11	233.24	5790.34	0.400000	0.613346	0.988562	0.136620	0.043560	3.80877	0.447449	medium
134	Rockslide	12	3	143724	5.60E+08	2886	63,875	6674.35	986.86	5101.82	0.000000	0.640931	0.951605	0.300847	0.025285	3.20053	0.341325	medium
135	Rockslide	24	1	37290	8.25E+07	1971	13,300	1333.20	7526.96	15891.34	0.000000	0.928276	0.630879	0.041089	0.003728	3.46052	0.386888	medium
138	Rockslide	24	1	85896	2.70E+08	3391	34,600	10636.36	4981.08	18372.25	0.000000	0.427782	0.755729	0.150488	0.012180	2.20174	0.167058	low
144	Rockslide	24	4	309435	1.66E+09	2904	31,900	10980.34	5638.84	23194.39	0.000000	0.409276	0.723472	0.136620	0.075607	3.36299	0.368670	medium
145	Rockslide	12	5	874089	7.25E+09	2701	42,600	10160.07	4813.85	22714.68	0.800000	0.453406	0.763929	0.191577	0.327641	4.24336	0.523276	medium
153	Rockslide	12	3	197091	8.76E+08	1580	53,300	986.50	1336.63	11525.36	0.400000	0.946928	0.934452	0.246533	0.039579	4.86135	0.631101	high
154	Rockslide	12	1	27576	1.42E+09	2237	42,600	2947.16	2779.41	9578.25	0.000000	0.841448	0.863898	0.191577	0.064341	3.64396	0.418693	medium
172	Rockslide	12	3	518468	3.46E+09	3175	47,900	11209.45	5850.42	2335.24	0.400000	0.396951	0.713096	0.218798	0.156142	3.07889	0.320101	medium
176	Rockslide	48	2	281843	1.46E+09	2962	13,300	8821.94	1387.86	31879.19	0.200000	0.525395	0.931940	0.041089	0.065749	3.01496	0.308947	medium
180	Rockslide	12	4	224359	1.05E+09	2832	53,200	3727.34	1277.49	54545.18	0.600000	0.789475	0.937352	0.246020	0.047568	4.82937	0.625521	high
182	Rockslide	12	1	177238	7.53E+08	2015	63,800	0.00	183.41	55114.39	0.000000	1.000000	0.991006	0.300462	0.034043	4.32551	0.537609	medium
210	Rockslide	12	4	288866	1.51E+09	2125	95,800	153.50	1105.91	56833.67	0.600000	0.991742	0.945766	0.464818	0.068086	5.6539	0.769383	high
2	Rockslide/Rock slope deformation	12	6	984517	8.58E+09	2323	53,200	0.00	941.26	57693.91	1.000000	0.100000	0.953841	0.246020	0.387895	6.97565	1.909199	high
12	Rockslide/Rock slope deformation	12	4	1556003	1.64E+10	1849	63,900	2639.19	2143.55	2912.56	0.600000	0.858016	0.958481	0.054476	0.074265	6.45524	0.900199	high
16	Rockslide/Rock slope deformation	36	2	1278767	1.24E+10	2072	15,900	751.64	7748.44	51236.18	0.200000	0.959563	0.820017	0.054476	0.054476	5.07749	0.688912	high
72	Rockslide/Rock slope deformation	12	3	92333	2.99E+08	3691	31,900	7322.91	11585.00	39511.32	0.400000	0.606040	0.431873	0.163842	0.013495	3.22733	0.346000	medium
83	Rockslide/Rock slope deformation	12	3	205919	9.32E+08	2031	31,900	5429.31	4946.76	48488.94	0.400000	0.707912	0.757411	0.136620	0.042118	3.85989	0.456368	medium
105	Rockslide/Rock slope deformation	12	3	104592	3.56E+08	3584	37,200	12168.95	17908.26	72380.06	0.400000	0.345331	0.121781	0.163842	0.016106	2.13772	0.155888	low
127	Rockslide/Rock slope deformation	12	4	768080	6.04E+09	3842	170,000	6782.12	712.95	91229.04	0.600000	0.635133	0.965037	0.845917	0.272723	5.18908	0.688282	high
128	Rockslide/Rock slope deformation	12	4	375828	2.19E+09	2967	85,100	7623.21	1750.43	91077.43	0.600000	0.589884	0.941459	0.409861	0.009910	4.39258	0.549312	medium
163	Rockslide/Rock slope deformation	36	1	70508	2.04E+08	2400	42,600	6007.60	102.87	4707.21	0.000000	0.676801	0.994956	0.191577	0.009204	3.22614	0.345793	medium
193	Rockslide/Rock slope deformation	12	1	95784	3.15E+08	2879	63,800	4227.50	850.12	83410.10	0.000000	0.772568	0.958310	0.300462	0.014216	3.59069	0.409399	medium
103	Rockslide/Talus Cone	12	3	293866	1.54E+09	3747	31,900	9580.36	14618.56	69751.71	0.400000	0.484593	0.283107	0.136620	0.069764	2.74327	0.261543	low
152	Rockslide/Talus Cone	12	5	874089	2.64E+02	2701	42.6	10160.07	4813.85	22714.68	0.800000	0.453406	0.763929	0.191577	0.000000	3.91572	0.466110	medium
179	Rockslide/Talus Cone	36	4	1124946	1.04E+10	3335	15,900	11785.49	5335.58	43865.15	0.600000	0.365961	0.738344	0.054443	0.046891	3.55936	0.403932	medium
209	Rockslide/Talus Cone	24	1	307939	1.65E+09	3475	10,600	9699.24	4580.88	17403.26	0.000000	0.478198	0.775354	0.027221	0.074552	2.31172	0.186247	low
45	Unknown	12	3	137133	5.24E+08	3541	37,200	6823.92	7723.83	11710.96	0.400000	0.632885	0.621224	0.163842	0.023656	3.53103	0.398990	medium
50	Unknown	12	3	508486	3.36E+09	3443	58,500	4146.71	8345.67	13757.97	0.400000	0.776914	0.590729	0.273241	0.151894	4.2865	0.532866	medium
59	Unknown	12	1	1274775	1.24E+10	1741	42,600	106.00	477.84	35014.60	0.000000	0.994297	0.976567	0.191577	0.559881	4.71072	0.604819	high
61	Unknown	12	3	700727	5.30E+09	3505	69,200	12619.13	255.76	22754.43	0.400000	0.321112	0.987458	0.139157	0.239422	3.31841	0.361893	medium
70	Unknown	12	1	136008	5.17E+08	3521	31,900	10308.30	9889.22	30680.95	0.000000	0.444531	0.515034	0.136620	0.023381	2.01133	0.133835	low
93	Unknown	12	3	387359	2.28E+09	3685	79,800	9283.45	20391.56	67444.26	0.400000	0.505666	0.000000	0.382640	0.103244	2.78758	0.269274	low
124	Unknown	48	3	48708	1.21E+08	3616	7,900	10016.15	8953.30	98480.78	0.400000	0.461148	0.560931	0.013354	0.005445	2.76157	0.265016	low
166	Unknown	12	2	131878	4.95E+08	2177	53,200	7034.77	1860.00	9864.58	0.200000	0.621541	0.908786	0.246020	0.022380	3.44181	0.383422	medium
170	Unknown	36	1	106729	3.67E+08	3544	5,300	9677.83	2562.14	9646.67	0.000000	0.879349	0.874353	0.000000	0.016675	2.32898	0.189257	low
174	Unknown	36	2	94142	3.07E+08	2292	43,100	2097.81	3114.05	42158.06	0.200000	0.887142	0.847287	0.091423	0.013872	4.01401	0.488328	medium
197	Unknown	12	1	88689	2.82E+08	3653	42,600	12539.56	5431.26	98416.88	0.000000	0.325393	0.733652	0.191577	0.012746	1.91415	0.116880	low
208	Unknown	12	4	75337	2.24E+08	3982	21,300	12643.04	4928.86	99148.98	0.600000	0.319826	0.758289	0.082178	0.010111	3.01006	0.308091	medium

Attribute Number	Movement Type	Bit	Likelihood	Area [m ²]	Volume [m ³]	Elevation [m a.s.l.]	Velocity cm/s	Distance to Rivers [m]	Distance to Faults [m]	Distance to Reservoir [m]	Norm. Likelihood	Norm. River (invert)	Norm. Fault (invert)	Norm. Velocity	Norm. Volume	Hazard	Normalised Hazard	30-30-40 Classification
15	Soil Creep	24	4	840601	6.88E+09	1409	47.900	884.18	2735.46	0.00	0.600000	0.962432	0.886563	0.218798	0.309873	5.76189	0.788226	high
20	Soil Creep	12	1	265172	1.33E+09	2634	42.600	4038.08	2261.32	68317.25	0.000000	0.782758	0.889105	0.191577	0.060300	3.54956	0.402222	medium
22	Soil Creep	12	3	160350	6.54E+08	2035	53.200	4395.26	2796.98	14956.35	0.400000	0.763542	0.882836	0.246020	0.029534	4.25855	0.525926	medium
23	Soil Creep	12	3	162918	6.69E+08	1935	58.500	5008.33	3443.83	15120.67	0.400000	0.730650	0.831115	0.273241	0.030207	4.15645	0.508112	medium
24	Soil Creep	12	3	150423	5.97E+08	2072	69.200	4465.56	2993.97	14633.62	0.400000	0.705976	0.853176	0.328197	0.026974	4.3146	0.535706	medium
28	Soil Creep	12	3	188888	8.25E+08	1638	69.200	2053.17	2218.82	6666.33	0.400000	0.889543	0.889189	0.328197	0.037290	4.76259	0.613870	high
29	Soil Creep	12	3	130961	4.90E+08	1783	69.200	2599.84	2718.86	6515.19	0.400000	0.860133	0.866667	0.328197	0.022159	4.61958	0.588818	medium
30	Soil Creep	12	3	398697	2.38E+09	2574	47.900	7192.39	7147.13	12270.04	0.400000	0.613062	0.649506	0.218798	0.107558	3.72261	0.432415	medium
32	Soil Creep	12	3	217704	1.01E+09	2532	47.900	5394.72	5371.93	7165.95	0.400000	0.709773	0.736561	0.218798	0.045579	3.97584	0.476598	medium
33	Soil Creep	12	3	97529	3.23E+08	2033	31.900	3607.68	3052.88	3635.17	0.400000	0.805913	0.850287	0.136620	0.014585	4.23382	0.521610	medium
36	Soil Creep	12	3	186639	8.10E+08	1564	26.600	17163.28	1875.54	15514.06	0.400000	0.766645	0.908024	0.109399	0.036606	2.12057	0.152895	low
38	Soil Creep	12	3	64325	1.79E+08	2100	31.900	18587.95	14102.24	25693.50	0.400000	0.000000	0.308428	0.136620	0.008080	1.26121	0.002955	low
39	Soil Creep	12	1	215194	9.92E+08	2864	53.200	16808.96	7719.02	15734.01	0.000000	0.095707	0.621460	0.246020	0.044835	1.24427	0.000000	low
40	Soil Creep	24	3	110544	3.86E+08	2294	34.500	16292.62	10225.54	16171.96	0.400000	0.123485	0.488540	0.149874	0.017422	1.88381	0.106352	low
41	Soil Creep	24	3	176219	7.47E+08	2204	42.600	16637.93	10020.98	16519.17	0.400000	0.104908	0.508572	0.191577	0.033766	1.8824	0.111340	low
44	Soil Creep	12	3	196392	8.72E+08	1273	42.600	331.76	1796.46	0.00	0.400000	0.982152	0.911902	0.191577	0.039380	4.92869	0.642851	high
49	Soil Creep	12	1	55404	1.45E+08	1613	31.900	742.64	2841.42	645.37	0.000000	0.960047	0.880657	0.136620	0.006538	3.89049	0.481708	medium
54	Soil Creep	12	3	261422	1.31E+09	2004	53.200	5450.56	94.34	10826.59	0.400000	0.706769	0.995373	0.246020	0.059093	4.27989	0.529648	medium
67	Soil Creep	12	1	142978	5.55E+08	1974	26.600	972.57	592.36	39226.15	0.000000	0.947678	0.970951	0.109399	0.025099	3.94848	0.471826	medium
73	Soil Creep	12	1	81212	2.49E+08	2208	26.600	8360.08	3201.62	36214.80	0.000000	0.550242	0.842993	0.109399	0.011248	2.61437	0.239052	low
74	Soil Creep	12	3	87629	2.77E+08	2919	37.200	10857.15	4538.22	32261.14	0.400000	0.415904	0.777446	0.163842	0.012530	3.00153	0.306603	medium
75	Soil Creep	12	3	175883	7.45E+08	3174	31.900	11050.11	4480.59	31384.94	0.400000	0.405523	0.780272	0.136620	0.033675	2.96714	0.300602	medium
76	Soil Creep	12	3	52718	1.35E+08	2393	26.600	10752.88	4823.59	34233.70	0.400000	0.421514	0.763452	0.109399	0.006092	2.96438	0.296476	low
77	Soil Creep	12	1	38064	8.49E+07	3772	31.900	10034.80	9517.92	39671.60	0.000000	0.460145	0.553242	0.136620	0.003838	2.05144	0.141304	low
78	Soil Creep	12	1	63437	1.75E+08	1854	15.900	2084.27	1930.16	45247.63	0.000000	0.887870	0.905345	0.054443	0.007922	3.63132	0.416488	medium
79	Soil Creep	12	1	57759	1.53E+08	1967	10.600	7170.96	4238.81	40471.73	0.000000	0.614214	0.792129	0.027221	0.006935	2.48572	0.324872	low
82	Soil Creep	12	3	373122	2.17E+09	2289	63.800	1154.88	1087.05	549691.79	0.400000	0.937869	0.946691	0.300462	0.097901	5.98866	0.648080	high
84	Soil Creep	12	3	91330	2.94E+08	2101	42.600	4681.35	4253.97	49853.58	0.400000	0.748151	0.791386	0.191577	0.013287	4.0407	0.487916	medium
88	Soil Creep	12	3	482064	3.12E+09	2068	58.500	1876.92	7373.15	55512.90	0.400000	0.899025	0.638421	0.273241	0.140817	4.54955	0.576700	medium
89	Soil Creep	12	3	106699	3.67E+08	2266	53.200	4951.10	5898.75	58679.39	0.400000	0.736359	0.710726	0.246020	0.016659	3.97423	0.476318	medium
92	Soil Creep	12	3	50450	1.27E+08	2385	31.900	5298.33	5410.92	58980.39	0.400000	0.714959	0.734649	0.136620	0.005724	3.82187	0.449734	medium
94	Soil Creep	12	3	67065	1.90E+08	2363	15.900	731.88	11614.72	74806.71	0.400000	0.960626	0.430415	0.054443	0.008573	4.17531	0.511402	medium
96	Soil Creep	12	3	163052	6.69E+08	2294	31.900	1007.97	5251.03	71391.38	0.400000	0.945773	0.742490	0.136620	0.030243	4.54667	0.576197	medium
97	Soil Creep	12	3	102751	3.48E+08	2178	26.600	359.83	0.00	65894.24	0.400000	0.980636	1.000000	0.109399	0.015706	4.86701	0.632089	high
99	Soil Creep	12	3	81258	2.48E+08	2750	26.600	2014.10	8065.28	73822.66	0.400000	0.891645	0.604480	0.109399	0.011257	4.20007	0.515722	medium
101	Soil Creep	12	3	186639	8.12E+08	3731	85.100	1995.34	784.60	69912.65	0.400000	0.892654	0.961523	0.409861	0.036868	4.88603	0.635408	high
102	Soil Creep	24	1	484192	3.14E+09	1958	23.900	1518.66	3092.04	68742.67	0.000000	0.918299	0.848367	0.095532	0.141700	3.84049	0.452984	medium
104	Soil Creep	12	1	222680	1.04E+09	2984	42.600	10701.39	9623.22	75557.39	0.000000	0.424284	0.528078	0.191577	0.047064	2.03957	0.138762	low
117	Soil Creep	12	3	159659	6.50E+08	2823	26.600	589.94	984.46	73657.47	0.400000	0.966322	0.762575	0.109399	0.029354	4.60611	0.586568	medium
131	Soil Creep	24	3	235644	1.13E+09	1915	23.950	8897.41	9664.66	4027.49	0.400000	0.521335	0.526046	0.095788	0.051060	3.0369	0.312774	medium
136	Soil Creep	24	1	124635	4.57E+08	2787	18.600	4368.66	15601.28	23729.75	0.000000	0.764973	0.234915	0.068310	0.020656	2.6188	0.239826	low
148	Soil Creep	36	4	533280	3.60E+09	3540	12.400	7247.00	4831.24	50748.26	0.600000	0.610124	0.763076	0.036466	0.162510	3.99242	0.479492	medium
158	Soil Creep	12	1	246227	1.20E+09	1888	85.000	5100.97	1661.12	2987.74	0.000000	0.725576	0.918539	0.409348	0.022073	3.55589	0.403851	medium
160	Soil Creep	48	1	279568	1.44E+09	1527	15.900	1789.47	3344.01	551.79	0.000000	0.903730	0.836010	0.054443	0.064997	3.66664	0.422650	medium
161	Soil Creep	12	1	59639	1.61E+08	2187	42.600	9849.06	9517.33	9517.33	0.000000	0.933317	0.517003	0.191577	0.007258	3.51579	0.396330	medium
173	Soil Creep	24	1	1390601	4.88E+08	2358	18.600	5574.71	371.08	16809.30	0.600000	0.705909	0.981802	0.068310	0.022073	3.17246	0.336426	medium
181	Soil Creep	12	4	119400	4.30E+08	3275	37.200	7571.66	5025.79	50853.65	0.600000	0.592658	0.753536	0.163842	0.019436	3.91479	0.465946	medium
183	Soil Creep	12	4	108693	3.76E+08	1636	53.200	230.21	1382.04	61652.40	0.600000	0.987615	0.932225	0.246020	0.017010	5.3581	0.717773	high
201	Soil Creep	12	4	283631	1.32E+09	2012	31.900	427.39	1117.34	8901.38	0.600000	0.977007	0.946206	0.136620	0.059797	5.27265	0.702863	high
202	Soil Creep	24	2	304077	1.62E+09	2024	26.600	346.41	1020.65	89011.98	0.200000	0.981364	0.949948	0.109399	0.073229	4.47667	0.563982	medium
203	Soil Creep	48	1	447951	2.81E+09	1915	21.300	321.97	1301.62	87918.17	0.000000	0.982679	0.936169	0.082178	0.126890	4.09327	0.497088	medium

Attribute Number	Movement Type	Bt	Likelihood	Area [m2]	Volume [m3]	Elevation [m a.s.l.]	Velocity cm/a	Distance to Rivers [m]	Distance to Faults [m]	Distance to Reservoir [m]	Norm. Likelihood	Norm. River (invert)	Norm. Fault (invert)	Norm. Velocity	Norm. Volume	Hazard	Normalised Hazard	30-30-40 Classification
14	Soil Creep/Slide	36	2	422996	2.59E+09	1335	24.800	861.74	976.88	0.00	0.200000	0.953640	0.952094	0.100154	0.116977	4.54712	0.576275	medium
17	Soil Creep/Slide	12	6	793724	6.32E+09	1840	58.500	523.56	1987.74	69452.02	1.000000	0.971833	0.902521	0.273241	0.285734	6.66273	0.945402	high
18	Soil Creep/Slide	48	4	173166	7.29E+08	1834	85.100	689.16	1463.88	76095.53	0.600000	0.962925	0.928212	0.409861	0.032936	5.49272	0.741281	high
19	Soil Creep/Slide	12	4	498122	3.26E+09	1861	53.200	484.43	1050.58	76992.32	0.600000	0.973938	0.948480	0.246020	0.147520	5.61135	0.761960	high
26	Soil Creep/Slide	12	3	367813	2.12E+09	2236	47.900	10441.55	9894.54	15224.01	0.400000	0.438283	0.514773	0.218798	0.095930	3.04022	0.313354	medium
27	Soil Creep/Slide	12	1	182006	7.82E+08	2451	37.300	10152.20	9417.32	15647.35	0.000000	0.453829	0.538176	0.164355	0.035350	2.13472	0.155364	low
37	Soil Creep/Slide	12	3	78220	2.36E+08	3601	31.900	3792.02	14730.15	14730.15	0.400000	0.795996	0.340784	0.136620	0.010665	3.68672	0.426154	medium
51	Soil Creep/Slide	12	2	248989	1.22E+09	1856	58.500	441.93	748.24	78262.78	0.200000	0.976225	0.963307	0.273241	0.055108	4.67544	0.598653	medium
55	Soil Creep/Slide	12	1	481753	3.11E+09	2135	85.000	2044.59	5554.16	15046.39	0.000000	0.890004	0.727625	0.409348	0.140688	4.08836	0.496232	medium
58	Soil Creep/Slide	12	1	420198	2.56E+09	1898	37.200	12248.05	2719.75	15049.44	0.000000	0.341076	0.968624	0.163842	0.115684	2.28546	0.181664	low
63	Soil Creep/Slide	12	1	950708	8.17E+09	2012	31.900	1133.01	1685.74	40118.95	0.000000	0.939046	0.917331	0.136620	0.369130	4.24022	0.522727	medium
80	Soil Creep/Slide	12	3	173327	7.30E+08	2907	47.900	6492.17	0.00	54440.99	0.400000	0.650733	1.000000	0.218798	0.032982	4.00398	0.481508	medium
116	Soil Creep/Slide	12	1	160057	6.52E+08	3300	31.900	6158.82	326.18	76011.99	0.000000	0.668666	0.984004	0.136620	0.029458	3.15608	0.333569	medium
125	Soil Creep/Slide	12	4	71407	2.07E+08	3528	42.600	1098.65	438.80	91371.60	0.600000	0.940895	0.978481	0.191577	0.009371	5.20211	0.690557	high
126	Soil Creep/Slide	12	4	213761	9.83E+08	3546	127.700	1364.25	185.96	91723.22	0.600000	0.926606	0.990880	0.628659	0.044412	5.64377	0.767616	high
129	Soil Creep/Slide	12	2	109771	3.82E+08	3538	74.500	2011.65	0.00	92509.73	0.200000	0.891777	1.000000	0.355419	0.017250	4.448	0.558980	medium
130	Soil Creep/Slide	12	4	360173	1.98E+09	2351	21.300	4291.92	380.36	89757.81	0.600000	0.789102	0.981347	0.082178	0.089468	4.6603	0.596022	medium
137	Soil Creep/Slide	12	3	170573	7.14E+08	2289	21.300	5204.64	10391.92	29534.40	0.400000	0.719999	0.490381	0.082178	0.0323241	3.5648	0.404881	medium
146	Soil Creep/Slide	12	1	227789	1.08E+09	1584	42.600	1746.42	813.34	23706.82	0.000000	0.906045	0.960114	0.191577	0.048604	3.91843	0.466582	medium
149	Soil Creep/Slide	12	1	200343	8.97E+08	2434	58.500	1920.41	9961.26	59664.42	0.000000	0.896685	0.511501	0.273241	0.040509	3.51531	0.396246	medium
5	Soil Slide	12	1	134487	5.09E+08	2868	26.600	6603.04	135.60	72819.83	0.000000	0.644768	0.993350	0.109399	0.023011	3.08307	0.320831	medium
86	Soil Slide	12	1	104295	3.55E+08	2398	31.900	8089.45	2330.11	53966.14	0.000000	0.564802	0.885732	0.136620	0.016042	2.7328	0.259716	low
167	Soil Slide	48	1	94735	3.10E+08	2017	19.900	6829.79	1718.78	9353.32	0.000000	0.632569	0.915711	0.074987	0.013996	2.9024	0.289307	low
192	Soil Slide	48	1	80895	2.48E+08	3307	9.300	7166.34	491.69	81889.68	0.000000	0.614463	0.975888	0.020544	0.011186	2.85101	0.280341	low