



# **Assessing the Effectiveness of Structural Mitigation Measures against Debris Flows in Swiss Alpine Catchments using Field Data and Simulations**

GEO 511 Master's Thesis

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## Abstract

Natural hazards occur in Switzerland on a regular basis and are part of life in Switzerland, just as the mountains are. Among the natural hazards originating from mountainous areas, debris flows are among the most destructive. The events in summer 2024 once again showed their devastating potential. Several debris flows caused fatalities and severe damage to infrastructure and settlements. These events raised questions about whether the hazards had been underestimated, whether climate change is intensifying debris flows, and ultimately whether Switzerland is adequately prepared for natural hazards in a future climate.

In this thesis, debris flow scenarios are developed for five catchments along the northern flank of the Alps. For each catchment, the scenarios are calculated under current climate conditions and under conditions influenced by climate change. The results are then simulated using RAMMS – Rapid Mass Movement Simulation and presented in hazard maps. The possible extent and magnitude of the simulated debris flows are investigated and the structural mitigation measures in each catchment are evaluated to determine whether they are able to withstand these scenarios.

The results suggest that debris flows may become larger with continued climate change. In three out of five catchments, the current mitigation measures are overloaded by the proposed scenarios, especially under future climate conditions. However, the scenarios simplify the complex processes of debris flows and their interactions with the environment, leading to considerable uncertainty. Additionally, the scenarios with climate change are based on static scaling of projected precipitation changes and do not include dynamic climate models. Despite these limitations, the applied methods and the subsequent results provide a first general assessment and can serve as a basis for further, more detailed investigations.

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# 1 Introduction

The worldwide effect climate change has on temperature and precipitation patterns affects the frequency and geographic distribution of natural hazards, as well as the consequences of such Events. Changes in extreme precipitation, longer dry periods followed by intense rainfall, rising temperatures and shifts in snow and glacier dynamics affect both hydrological and gravitational processes. Several studies and international reports on climate change highlight that these climatic shift not only affect the probability of hazardous events but also the consequences of such events (IPCC, 2012; Jacquemart et al., 2024; MeteoSwiss & ETH Zürich, 2025; NCCS, 2018). Exposure and Vulnerability to natural hazards intersect increasingly with the dynamic environmental system.

Mountain regions are particularly sensitive to these changes (Kotlarski et al., 2023). Steep topography, complex geology and high relief energy create favourable conditions for a wide range climate conditions and therefore also natural hazards. Globally, mountainous areas are affected by landslides, rockfall, avalanches, floods and debris flows, with their relative frequency depending on climatic and geomorphological settings. While some hazards occur locally and episodically, others affect entire valleys or regions. The distribution of hazard types is therefore spatially heterogeneous.

In mountainous terrain debris flows are one of the most destructive processes while also occurring regularly. They occur on steep slopes and are controlled by sediment availability and water input. They mostly follow the existing stream bed and form a deposition fan in the plain (Calligaris & Zini, 2012). Due to being controlled for one by water input, changes in precipitation patterns and intensities caused by climate change affect the frequency of debris flows as a study by Turkington et al. (2016) shows. Sediment availability being the other controlling factor is affected by climate change due to rising temperatures. On one hand, debris provided from freeze-thaw cycles becomes less as temperatures do not reach the freezing point as often anymore at lower elevations (Hirschberg et al., 2021). On the other hand, higher temperatures lead to glacier melt and permafrost degradation, decreasing slope stability and increasing mass movement activity, which provide sediment for debris flows (IPCC, 2012).

As a mountainous country Switzerland is prone to a wide array of natural hazards, including debris flows. Natural hazards are part of everyday reality and have long shaped settlement patterns, infrastructure planning and risk management in the country. Debris flows, rockfall, avalanches and landslides are typical in alpine terrain, while floods regularly affect both alpine catchments and the Swiss Plateau. Although many processes originate in steep headwaters, their impacts often extend into economically important valley bottoms, where infrastructure and settlements are concentrated (Bundesamt für Umwelt (BAFU), n.d.). Among all natural hazards in Switzerland, water-related processes have the greatest overall impact with debris flows counting towards the most destructive processes in steep mountain catchments (WSL, 2025).

The government and the population are aware of the dangers which is why there are many mitigation measures already in place including protecting structures, laws on stream and forest management and zoning laws based on hazards maps. Despite the numerous measures to protect population and infrastructure, natural hazards are still causing high amounts in damage per year (BAFU, 2024) as well as fatalities, as numerous events in the past century and most recently during the summer of 2024 demonstrated. A first Analysis of the events during the summer 2024 show a rather large difference between the extent of the debris flows that occurred compared to what was expected based on the estimates used for the hazard maps for example in Lostalio GR (Titz & Weber, 2026). With continuing climate change, events comparable to those of 2024 are likely to become more frequent. Altered

precipitation patterns triggering conditions might change and sediment availability increases with glacier retreat and permafrost degradation causing reduced slope stability at high elevation (Hirschberg et al., 2021; Jacquemart et al., 2024; Stoffel et al., 2014). Consequently, hazard assessments based on static environmental conditions increasingly fail to capture the dynamic nature of future debris-flow activity, highlighting a growing mismatch between traditional hazard mapping approaches and evolving process regimes (Gallina et al., 2016).

The extreme and widespread debris-flow events of 2024 have highlighted limitations in existing hazard maps and underscored the need for their periodic reassessment, including the incorporation of climate change effects. In response, this thesis applies a deliberately simple and transferable approach to estimate debris-flow magnitudes in five non-instrumented mountain torrents and limited event documentation, representing the typical conditions of the majority of Swiss torrent systems. The approach is extended to include future scenarios that are affected by climate change in order to assess potential changes in debris flow dimensions. The proposed methodology and results are intended to support hazard management authorities and practitioners by providing an initial estimate to evaluate whether more detailed, site-specific investigations are required. Such preliminary assessments can help guide decisions on the necessity and prioritisation of further studies and projects concerning mitigation measures within a given catchment.

## 1.1 Context and Motivation

In 2024, especially between May and August, extreme weather events triggered several debris flows, floods and landslides throughout alpine Switzerland causing nearly 905 Mio CHF in damages and 16 fatalities (Liechti & Badoux, 2025). In June numerous debris flows occurred in the canton of Valais, the Misoix, and the Maggia Valley, where entire settlements, transport corridors, and critical infrastructure were severely affected. In Lostallo (GR), a series of debris flows mobilised exceptionally large sediment volumes, burying parts of the village and destroying part of the A13 express road, leading to closure and reduced capacity of the road for several weeks. Later in August a convective storm initiated a debris flow that overwhelmed existing retention structures and caused extensive damage to the village of Brienz and its infrastructure (MeteoSchweiz, 2024).

The flood and debris flow events in summer 2024 were marked by recurring periods of rainfall in spring accompanied by snow melt followed by numerous independent intense convective storms, which occurred widely scattered over Switzerland (MeteoSchweiz, 2024). In contrast to classic flood events caused by large scale continuous rainfall, the events in June and August of 2024 affected only very small areas or narrow trajectories at a time. In addition to the precipitation events being very localized they also were short (minutes to hours) and marked by very high intensities. The intense and localized precipitation trigger flash floods and debris flows, which overwhelmed several protective structures. In most areas the observed process intensities were higher than expected, resulting in considerable damage (Liechti & Badoux, 2025).

It was precisely within this context of unexpectedly severe impacts that the idea for this thesis emerged. The events of 2024 raised fundamental questions: Were these processes truly exceptional in a statistical sense, or did they merely expose an underestimation of existing hazards? Did existing design scenarios and hazard assessments rely on assumptions that underestimated the true magnitude of potential events, or do the observations reflect an emerging signal of climate driven intensification of short-duration extremes? This discourse provided the central motivation for this work and guided the formulation of its research questions.



## 1.2 Aim of this Thesis

Overall, climate change modifies both atmospheric forcing and geomorphic preconditioning in torrent systems. Intensified short duration rainfall debris-flow triggering potential, while glacier retreat and permafrost degradation increase sediment supply. Observations from the past decades, including the major flood events of 2005 and 2024, indicate that extreme events increasingly challenge existing risk assumptions. Even though trends in event frequency are uncertain, the magnitude of extremes and the dynamic climate underscore the need to reassess hazard frameworks under changing climate conditions.

Based on the most recent flood events, current hazard maps for torrents capable of producing debris flows might underestimate flow volumes, especially under a changing climate. This thesis intends to get a better understanding of the magnitude and spatial extent of debris flows in small mountain catchments under climate change. To achieve this, traditional hazard assessment approaches based on static climate conditions are applied and , and then extended to incorporate plausible future climate scenarios. The following research questions guide this work.

- 1) What are the 30, 100 and 300-year debris flow scenarios in the chosen catchments and how might these scenarios change under the influence of climate change?
- 2) Do the hazard maps in the chosen catchments assume similar dimensions for the different debris flow scenarios?
- 3) Are the protection measures (existing or planned) capable of sufficiently mitigating current and future scenarios?
- 4) What are the consequences of an event exceeding the protection measure's design scenario?

In this thesis the aim is to use a simple method to estimate debris flow volumes for a chosen catchment to evaluate existing hazard maps and mitigation measures may require reassessment. The focus lies on first order volume and spatial extent estimations rather than on detailed process modelling. There are many complex factors contributing to the formation of discharge and debris flows in a catchment, which will not all be considered in this thesis. Debris flow discharge scenarios are derived from precipitation data using established hydrological estimation methods and debris flow volume will be estimated using typical sediment-water mixtures for alpine debris flows combined with discharge to volume relations. Complex hydrological and geomorphological interactions and precise sediment budget and composition analysis are not considered, as this is highly specific to each catchment and would not be feasible to undertake for all five catchments. The results therefore provide indicative estimates intended to support preliminary hazard evaluations rather than a detailed analysis.

### 1.3 Research Area

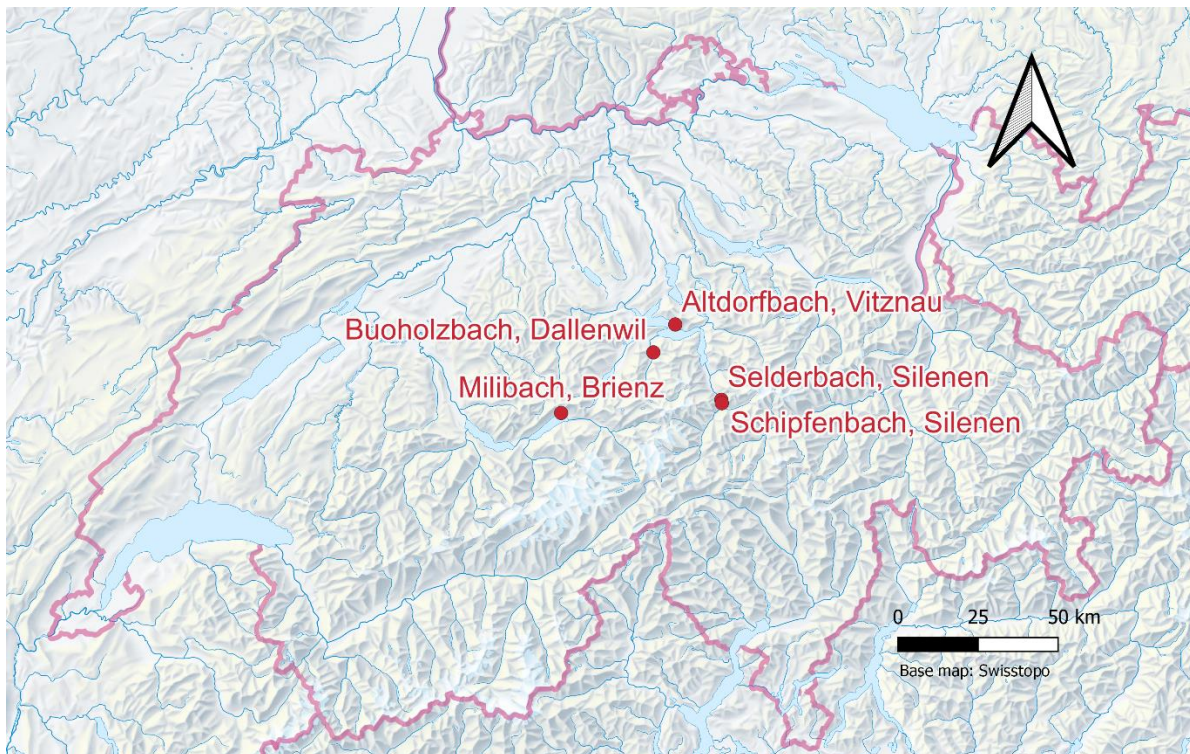
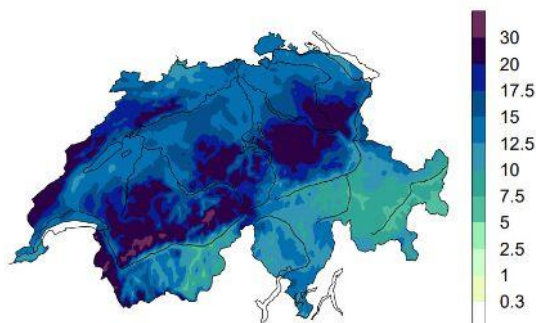


Figure 1 Map of the location of the five catchments.

The five investigated catchments, Milibach, Altdorfbach, Selderbach, Schipfenbach and Buoholzbach are located along the northern flank of the Swiss Alps (Alpenordhang) within the Prealpine (Voralpen) region of Central Switzerland (Figure 1). Geologically the region belongs to the Helvetic and Prealpine zone, which is structurally complex characterised by folding, thrusting and nappe structures. The zone is dominated by flysch, marl and molasse formations and is highly susceptible to erosion and weathering because of its complex structure and development lead to fractured bedrock. Combined with widespread quaternary deposits, sediment availability is generally high (Gisler, 2018; Hantke, 2006; Hantke & Brückner, 2011; Strasky et al., 2022).

a) Westerly blocking situation



b) North westerly blocking situation

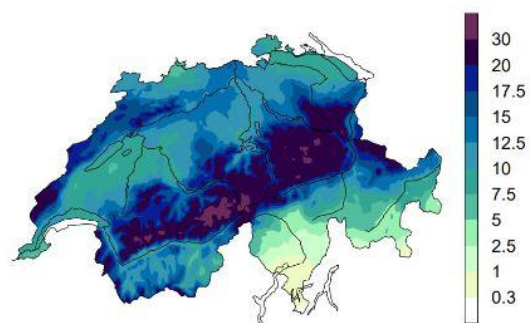


Figure 2 Distribution of 84th quantile daily precipitation totals [mm] in Switzerland for active a) westerly blocking situations and b) north-westerly blocking situations (MeteoSchweiz, 2026c).



The region of the Alpine Northflank belongs to the most precipitation rich areas of Switzerland due to north alpine orographic lifting. Moist air arriving predominantly from the west to northwest are forced to ascend at the alpine ridge, leading to increased precipitation under orographic blocking situations (Staulagen) as showcased in Figure 2. The Northalpine Flank therefore is predisposed to high precipitation totals and intense precipitation events (MeteoSchweiz, 2026c). During the summer months convective storms regularly develop along the Northalpine Flank and become either trapped within or move along it. Thunderstorms developing along the Northalpine Flank can reach high intensities and are among the most violent in Switzerland (MeteoSchweiz, 2026a). The spatial frequency distribution of convective storms further show a distinct frequency maximum along the northern pre-Alps (MeteoSwiss & ETH Zürich, 2025).

### 1.3.1 Milibach (Brienzen, BE)

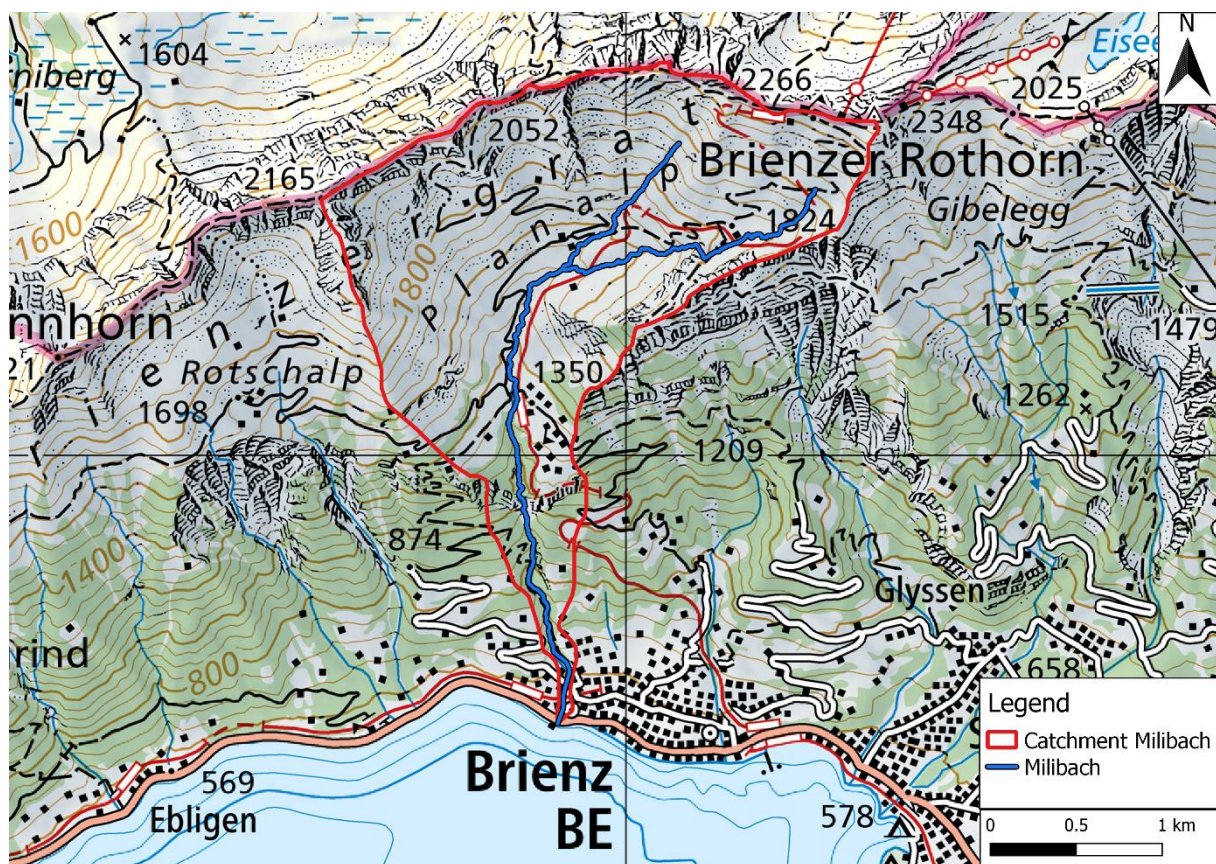


Figure 3 Map of the Milibach Catchment in Brienzen, BE (Basemap and catchment outline by Swisstopo (2026)).

The Milibach catchment (Figure 3) lies in the southeastern corner of the canton of Bern. It starts just below the Brienzer Rothorn and descends 1682 m down over a length of 5300 m into the Brienzersee. The Milibach drains an area of 4.8 km<sup>2</sup>. The upper part of the catchment above Planalp has a bowl-shaped morphology with numerous short side gullies and tributaries that feed into the main channel. The main stream and the contributory side gullies are generally steep and mostly flow on bedrock or over areas with thin soil cover. Below Planalp the Milibach falls over the Milibachflue and flows on in a steep V-shaped valley until it reaches its fan where the village of Brienzen lies. Just above the village the Milibach is controlled by a sediment retention dam and then channel through the village until it reaches the lake.

The Milibach catchment lies within the Helvetic nappe system, mainly including formations of the Drusberg nappe. The bedrock consists predominantly of Helvetic silicious limestone (Kieselkalk), and marly limestone. The area contains several lithological boundaries and highly fractured rock masses. The marl rich formations are mechanically weak and prone to weathering. Additionally the catchment contains extensive areas with quaternary deposits, talus slopes, landslide masse and more recent glacial deposits (Strasky et al., 2022). These unconsolidated materials provide abundant sediment supply.

The Milibach catchment has a south to southwest exposition and is directly exposed to moist air masses during westerly and north-westerly flows. It also lies in the zone with high precipitation during orographic blocking situations of the same flows. Thunderstorms in Switzerland often move from southwest to northeast, leading to potential capture of storm cells within the Milibach catchment. Because of the steep relief of the catchment the Milibach is highly sensitive to intense rainfall, even for short durations, it is capable of sudden flash floods. In combination with the abundant sediment supply it is possible for debris flows to occur.

This characteristic of the Milibach poses a threat to the settlement of Brienz, located on the alluvial fan of the torrent. Therefore the population tried to control the Milibach early on. In 1902 the stream was channelled through the village and in 2017 a retention dam was constructed above the village. Above the retention dam the Milibach remains mostly natural. These measures were necessary as the Milibach is an active torrential system historical records show. However, the Milibach has been relatively inactive over the past centuries compared to its neighbours with only five recorded debris flow events in the last 200 years. Debris flows were recorded in 1824, 1915, 1922, 2022 and 2024, with the magnitude of the first three relatively unknown and the event in 2022 being rather small only filling one third of the retention basin (Bundesamt für Umwelt BAFU, 2026; Gemeinde Brienz, 2026).

On the 24. July 2024 during a thunderstorm the Milibach showed its potential, delivering approximately 65'000 m<sup>3</sup> of material to the fan. The retention dam designed for a 100-year event of 12'000 m<sup>3</sup> of sediment was able to retain 18'000 m<sup>3</sup> before it was overflowed after 20 minutes. The remaining 45'000 m<sup>3</sup> of sediment flowed uncontrolled through the village causing at least 30 Mio CHF of damages (WSL, 2025). The event surpassed all estimates of earlier hazard assessments and sparked the conversation on how to deal with the dangers posed by the Milibach and weather this event was the effect of ongoing climate change.



### 1.3.2 Altdorfbach (Vitznau, LU)

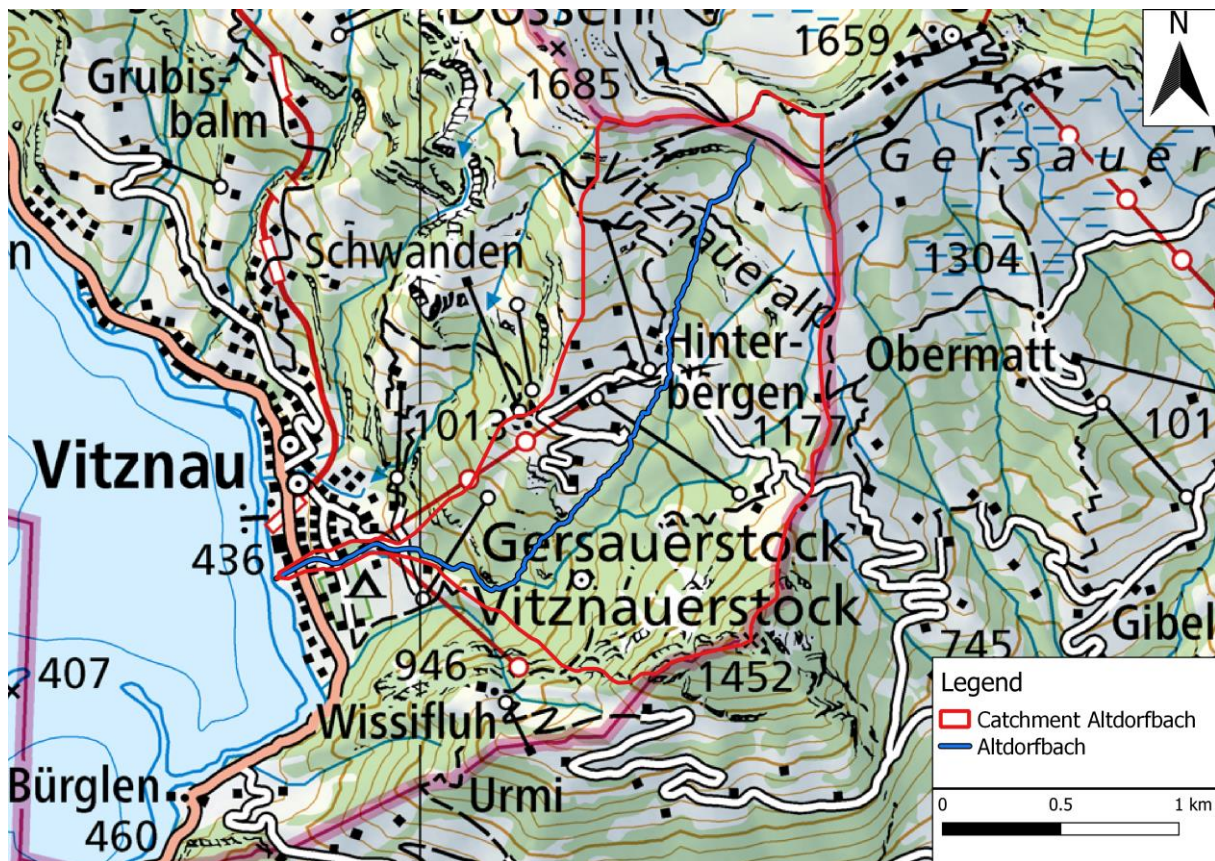


Figure 4 Map of the Altdorfbach Catchment in Vitznau, LU (Basemap and catchment outline by Swisstopo (2026)).

The Altdorfbach catchment (Figure 4) lies in the canton of Lucerne above the village of Vitznau. The torrent originates on the steep slopes of the Vitznaueralp and descends 1100 m over a length of roughly 1500 m before reaching Lake Lucerne (Vierwaldstättersee). The Altdorfbach catchment spans from Rigi Dossen and the Vitznauerstock and drains an area of about 2.7 km<sup>2</sup> (Swisstopo, 2026). The upper part of the catchment is characterised by steep headwater slopes with several tributaries that converge into the main channel above village of Vitznau. The upper northern part of the catchment consists of mainly pastures and grass fields with small areas of forest. The slopes below Vitznauerstock are covered in forest which continuous all the way down to the village. In the middle reach the many arms of the Altdorfbach flow through a confined valleys with high channel gradients before the arms merge into one stream and it reaches its alluvial fan. In the lower section the Altdorfbach is channelised and guided through the village of Vitznau before discharging into Lake Lucerne.

The Altdorfbach catchment lies within the Subalpine Molasse zone of the Northalpine Flank. The bedrock consists predominantly of Nagelfluh conglomerates of the Rigi-Formation in the north and Limestones of the Helvetic nappe in the south. The area is structurally complex due to folding and tectonic deformation at the Alpine front. Extensive quaternary deposits, talus slopes and extensive landslide areas occur throughout the basin. These unconsolidated materials provide abundant sediment supply to the channel (Hantke, 2006).



The Altdorfbach catchment has a predominantly west facing exposition towards Lake Lucerne. It lies within the zone of high precipitation during westerly and north-westerly blocking situations, where moist air masses are forced to ascend over the Rigi, leading to pronounced orographic precipitation. Thunderstorms in central Switzerland often move from southwest to northeast, allowing convective cells to intensify along the northern Alpine slopes. Due to its steepness the Altdorfbach reacts rapidly to intense rainfall events (MeteoSchweiz, 2026c).

The Altdorfbach is not a particularly active torrent in regards of debris flows but still is capable of producing them. There are oral accounts of a devastating debris flow without detailed information on what and when it happened. But in more recent time during the flood in 2005 the Altdorfbach produced several debris flows which reached the lake (WSL, 2025). Following this event a sediment retention dam was built above the village in 2007 (Schubiger Bauingenieure AG & Kanton Luzern Verkehr und Infrastruktur, 2006).

In 2024 the Gassrübi landslide, through which the Altdorfbach flows, was remobilised by persistent and repeating precipitation. On the 1. June 300'000 m<sup>3</sup> earth slid in the Gassrübi which continued to move throughout June and July. Continuing intense rainfall triggered several smaller debris flows on the landslide that did not reach the fan. The looming threat of a very large debris flow originating in the Gassrübi lead to constant surveillance of the landslide and the Altdorfbach until early August when the conditions eased up (WSL, 2025). After the remobilisation of the Gassrübi the canton of Lucerne initiated a project to build a larger retention dam to protect Vitznau.

### 1.3.3 Selderbach (Silenen, UR)

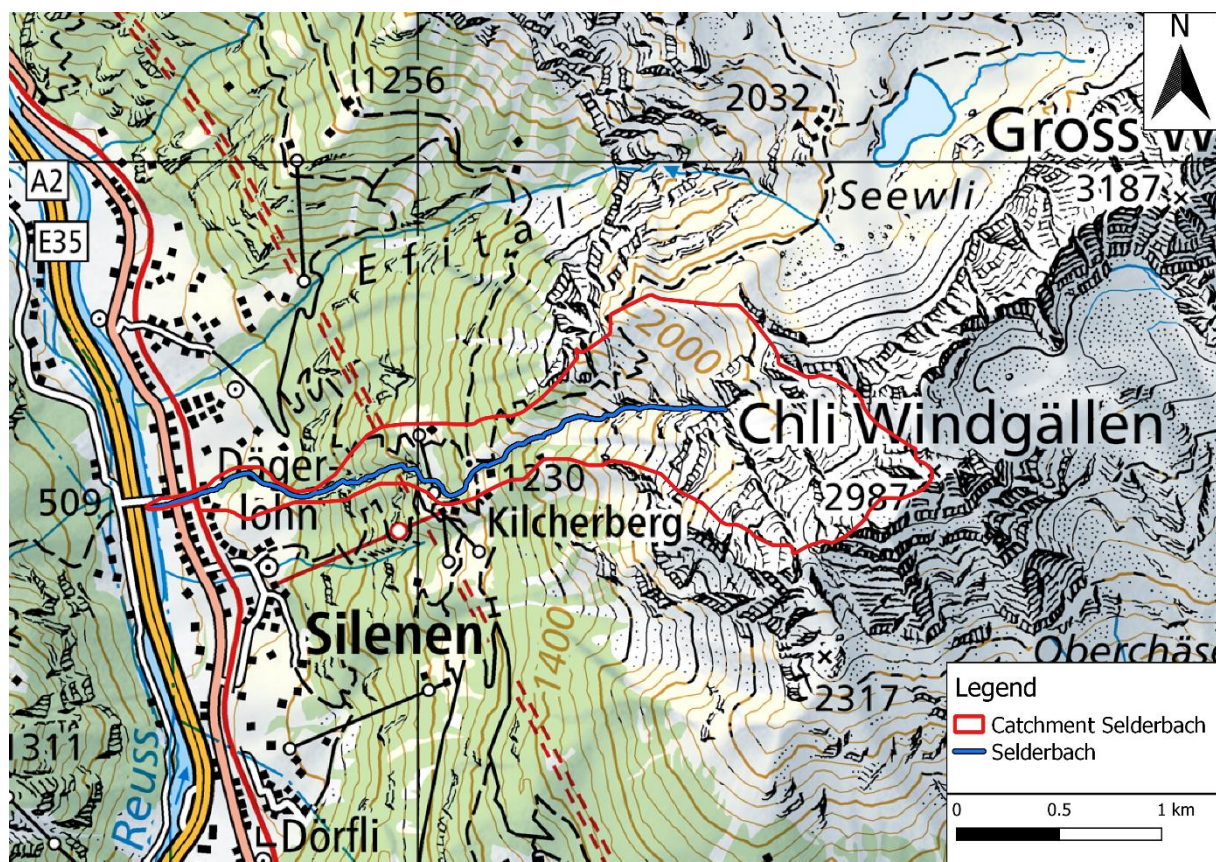


Figure 5 Map of the Selderbach Catchment in Silenen, UR (Basemap and catchment outline by Swisstopo (2026))



The Selderbach catchment (Figure 5) lies in the canton of Uri in the municipality of Silenen. The torrent originates on the northwest flank of Chli Windgällen at nearly 3000 m.a.s.l. The catchment is the highest studied here with nearly half of its area above 2000 m.a.s.l. draining a total area of 1.8 km<sup>2</sup>. The Selderbach itself starts at around 2000 m.a.s.l. and descends 1500 m over a length of about 3250 m before it flows into the Reuss. With the tree line at around 1800 m.a.s.l. Large parts of the catchment are treeless with either exposed bedrock or grassy areas on very shallow soil layers. Due to the catchment reaching into the north flank of Chli Windgällen between 2000 and 3000 m.a.s.l. permafrost is expected to be present (Figure 6). The lower part of the catchment then becomes increasingly narrow. The Selderbach flows mostly on deeply incised bedrock in a steep forested valley before it reaches its fan from where it flows mellowly between the quite dispersed settlements belonging to Silenen (Swisstopo, 2026).

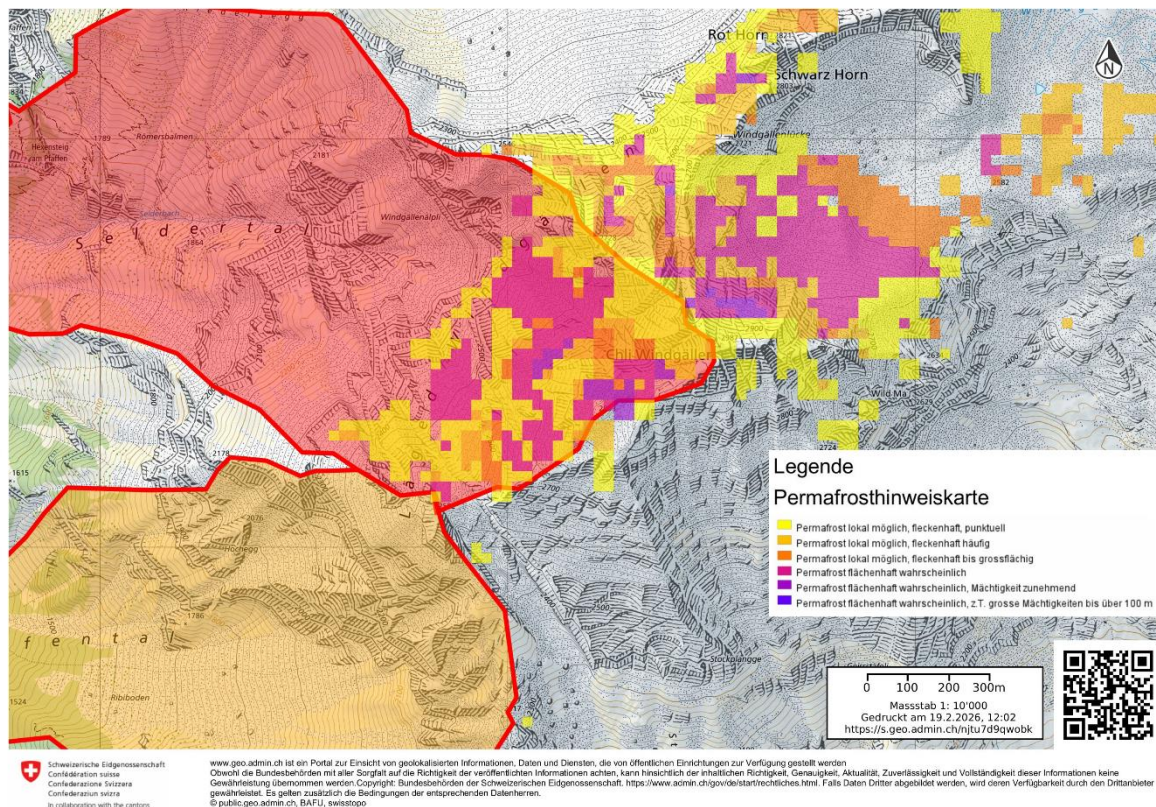


Figure 6 Extent of Permafrost at Chli Windgällen with the Selderbach catchment in red and the Schipfenbach catchment in orange (Swisstopo, 2026).

The Selderbach catchment lies in the tectonically complex transition zone between the Helvetic nappes and the crystalline Aar Massif. The southern, higher part of the catchment is dominated by crystalline rocks, mainly gneiss and amphibolites. In the northern sections, Helvetic sedimentary formations with limestones and marls occur. Even though the crystalline bedrock is mechanically strong it's strongly fractured due to Alpine tectonics. Several structural discontinuities, fault zones and lithological boundaries are present within the catchment. Extensive talus accumulations, quaternary deposits and subsidence areas are present in the catchment, providing an abundant sediment supply to the torrent.



The Selderbach catchment has a mostly west facing exposition and lies in the narrow north-south Urner Reuss valley. It too lies in the high precipitation zone during westerly and north-westerly blocking situations, however slightly protected by the western flank of the of the Urner Reuss valley (MeteoSchweiz, 2026c). The Selderbach is known to react quickly from short and intense precipitation for example produced by convective storms and is an active torrent producing many debris flows.

In his letter to the Swiss federal council in 1864 on Swiss torrents Carl Culman mentions the devastating debris flow event of 1859 causing an estimated 30'000 CHF in damages at the time. At least another ten medium to large debris flows affecting the valley floor were recorded since then (Bundesamt für Umwelt BAFU, 2026). In 1995 a retention basin was constructed at the top of the deposition fan designed to withhold a volume 18'000 m<sup>3</sup> (BAFU, 2008a). During the flood in 2005 the Selderbach delivered another large debris flow with approximately 27'000 m<sup>3</sup> of sediment overloading the retention dam, causing damages to the dam and the stream bed, to the SBB railway tracks and roads (WSL, 2025). The sediment reached into the Reuss, pushing the Reuss out of its channel and flowing over the A2 highway. In 2023 a thunderstorm triggered another debris flow filling the retention basin without overtopping it (Bundesamt für Umwelt BAFU, 2026).

#### 1.3.4 Schipfenbach (Silenen, UR)

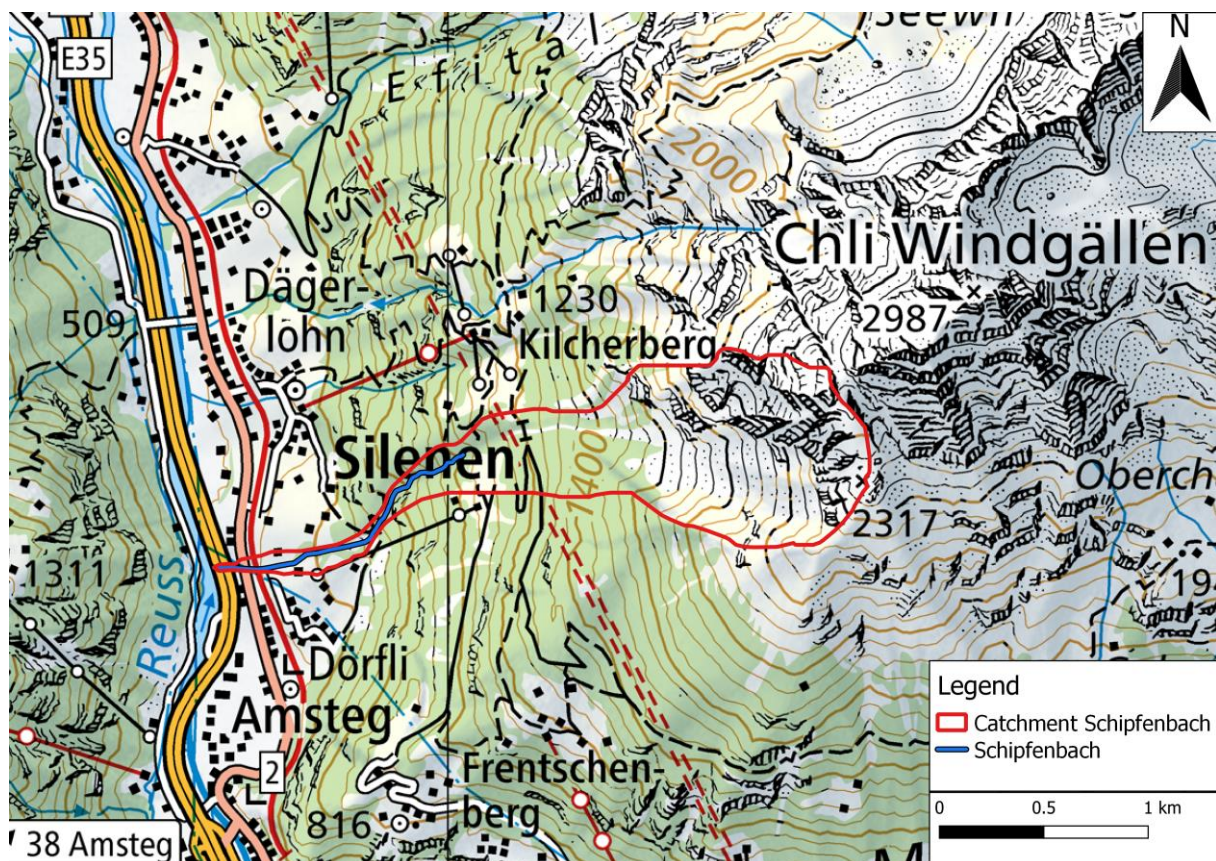


Figure 7 Map of the Schipfenbach Catchment in Silenen, UR (Basemap and catchment outline by Swisstopo (2026))



The Schipfenbach catchment (Figure 7) lies in the canton of Uri within the municipality of Silenen, a short distance south of the Selderbach. The torrent drains the steep western slopes of the mountain Chli Windgällen and flows into the river Reuss. The catchment is the smallest but steepest of the five studied catchments, draining an area of 1.4 km<sup>2</sup>. The Schipfenbach descends 1200 m over a distance of 2560 m with the highest point of the catchment reaching 2500 m.a.s.l and the lowest at 500 m.s.a.l (Swisstopo, 2026).

The upper catchment is characterised by steep talus slopes with limited soil cover and some scattered alpine grasslands. Forest cover becomes more continuous below 1600 m.a.s.l. The torrent flows in a narrow, deeply incised channel. Several short and very steep side gullies contribute directly to the main channel. In the valley floor, the Schipfenbach forms a relatively large alluvial fan before entering the Reuss.

Geologically, the Schipfenbach catchment lies within the tectonically complex zone between the crystalline Aar Massif and Helvetic sedimentary units. The bedrock is highly fractured and numerous fault zones, shear zones and lithological boundaries traverse the area (Hantke & Brückner, 2011). The catchment also contains extensive areas of talus accumulations and quaternary deposits. Between 1933 and 1937 several rockfalls deposited approximately 1 Mio m<sup>3</sup> of debris in the upper catchment (Bundesamt für Umwelt BAFU, 2026; Rickenmann et al., 2001). The channel of the Schipfenbach is deeply incised into these unconsolidated materials, which provide a substantial and continuously renewed sediment supply to the system.

The catchment has a predominantly west exposition within the north-south running Urner Reuss valley. It lies within a region of high precipitation during westerly and north-westerly blocking situations along the Northalpine Flank. Short duration, high-intensity convective storms frequently affect the region during summer (MeteoSchweiz, 2026c). Due to the steep relief and small catchment size with limited storage capacity the Schipfenbach reacts rapidly to intense rainfall. Combined with the abundant loose material the Schipfenbach is a very active torrent producing regular debris flows, sometime more than one per year. In 1977 and 1987 the torrent produced two particularly large debris flow. The event in 1977 delivered approximately 50'000 m<sup>3</sup> (Rickenmann et al., 2001) with some estimates of up to 90'000 m<sup>3</sup> (MeteoSchweiz, 2026b) material to the fan. In 1987 the Schipfenbach delivered another 50'000 m<sup>3</sup> to the fan. There were at least three more events that deposited 10'000 m<sup>3</sup> or more on the fan since 1930 (Rickenmann et al., 2001), with the most recent in 2022 (Bundesamt für Umwelt BAFU, 2026). In 1989 a retention basin was built to stop debris flows from reaching and damaging vital infrastructure like the A2 north-south highway or the train tracks of the Gotthard line (Swartz et al., 2004). Because of its regular activity a monitoring station to research the debris flow activity was established in 1997 (Spreefico & Weingartner, 2005).

### 1.3.5 Buholzbach (Dallenwil, NW)

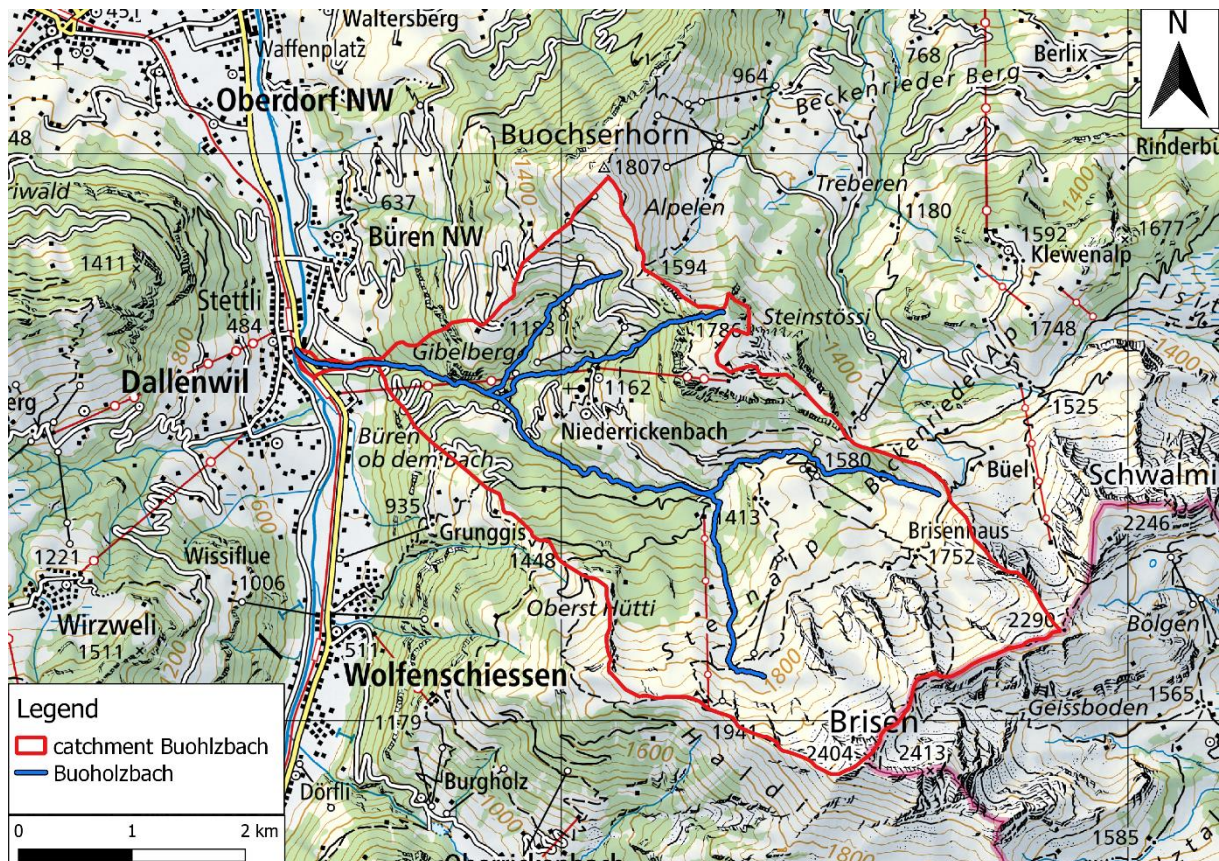


Figure 8 Map of the Buholzbach Catchment between Oberdorf and Wolfenschiessen, NW (Basemap and catchment outline by Swisstopo (2026)).

The Buholzbach catchment (Figure 8) lies in the canton of Nidwalden between the municipalities of Wolfenschiessen, Oberdorf with some of the Catchment reaching into Beckenried. The torrent drains the area between Buochserhorn and Brisen which is the highest point at 2400 m.a.s.l., towards the Engelberger Aa near Dallenwil. The Buholzbach descends 1200 m over a distance of 6600 m making it the flattest catchment and with a total area of 14 km<sup>2</sup> also the largest (Swisstopo, 2026).

The upper catchment consists of steep alpine meadows and forested slopes dissected by numerous short side gullies and some talus slopes below the Brisen. At Alpboden the Buholzbach absorbs the tributary Chäserenstadgraben, which drains the area below the Haldigrat. After that the Buholzbach flows through a narrow, deeply incised V-shaped valley with bedrock controlled sections alternating with alluvial deposits and in the Chollertobel it absorbs two more major tributaries, the Bleikigraben and Huetlerentobel. On the valley bottom the torrent flows over it large debris fan before flowing into the Engelberger Aa.

Geologically the catchment is situated within the Helvetic units of the northern Alps. The bedrock consists of mainly of limestones and Marl of the Drusberg nappes. The northern part of the catchment contains limestone of the Penninic remnants. The lithologies are very heterogeneous with large fractures and faults. Vast extents of quaternary sediments are present, including moraine walls from the quaternary and Holocene, as well as large talus slopes, subsidence areas and many landslides (Hantke, 2006). These unconsolidated sediments provide an abundant sediment supply to the torrent system.

The Buoholzbach catchment has a predominantly northwest exposition, facing out of the Engelberg valley towards Stans. With the Brisen and its surrounding peaks and ridges are the highest point of the area towards the north and form the first line of the Alpine Northflank. The catchment is therefore exposed to moist air masses during westerly and north-westerly flows and often experiences high precipitation caused by orographic lifting (MeteoSchweiz, 2026c). During the summer months the catchment often lies on the path of convective storms causing sudden high discharge in the torrent.

The Buoholzbach does not produce very regular debris flows. There were large events in the years 1762, 1806, 1831 and 1846 (Culman, 1864), however without information whether they were debris flows or floods. In 1910 deposits from a debris flow in the Buoholzbach pushed the Engelberger Aa out of its bed, causing large damages further downstream (Härry, 1910). In 1984 the Buoholzbach produced two debris flows depositing 10'000 m<sup>3</sup> and another 15'000 m<sup>3</sup> (WSL, 2025). After these events a retention basin was built on the fan with a design volume of 20'000 m<sup>3</sup>. In August 2005 a debris flow with a volume of 70'000 m<sup>3</sup> overloaded the retention basin considerably (BAFU, 2008a), initiating a long planning phase for a larger structure for which construction started in 2024.

## 2 State of the Art

### 2.1 Climate Change and its impact on natural hazards

Climate change has become clearly measurable in Switzerland and other mountain regions of the world over the past decades. Switzerland has already warmed by approximately 2°C relative to the pre-industrial period, exceeding global mean and reflecting a pronounced elevation dependent warming (MeteoSwiss & ETH Zürich, 2025). Similar high-elevation amplification effects have been documented across mountain regions worldwide (Pepin et al., 2015). The rising temperatures affect both atmospheric processes and the cryosphere, altering fundamental boundary conditions for the generation of floods and debris flows (Adler et al., 2022; Hock et al., 2019).

A key driver of both floods and debris flows is the intensification of extreme precipitation. Warmer air masses can hold approximately 7% more moisture per degree of warming, increasing the potential for heavy rainfall (O'Gorman, 2015). Observations from Switzerland indicate that the mean precipitation has not increased substantially since 1901, but annual maximum precipitation have increased by 5-20% at more than 90% of stations, with an increase in frequency by 10-50% (Scherrer et al., 2016). Climate projections consistently indicate further intensification and an increase of frequency of short-duration extreme precipitation, especially convective precipitation (MeteoSwiss & ETH Zürich, 2025; Westra et al., 2014). Under continuing warming, events historically associated with long return periods are expected to occur more frequently. This leads to the failure of static assumptions in traditional hazard assessment (Gallina et al., 2016). High-resolution simulations suggest that short duration summer convective storms in mountainous terrain may intensify disproportionately, directly affecting flash-flood and debris-flow triggering potential (Peleg et al., 2025).

Evidence from Switzerland and Europe indicates that climate change influences flood regimes. While a even increase in flood frequency cannot be identified across Europe, significant regional and temporal shifts have been documented (Blöschl et al., 2017). In Switzerland, alpine rivers show increasing annual peak discharges, partially attributed to higher a 0°C line elevation, as well as changing snowmelt dynamics (D. L. Vischer, 2003). Recent past events further demonstrate the



consequences of extreme precipitation. The flood of August 2005 exceeded design expectations in several locations, with discharge and sediment volumes surpassing previous assumptions and pushing protective measures to their limits (BAFU, 2007, 2008a). Similar patterns were observed during the subsequent major events in the last 20 years, especially those in 2024 (Hilker et al., 2008; Liechti et al., 2022; Liechti & Badoux, 2025). These events raised questions about the suitability of the current practices for hazard assessment.

Additionally to hydrological triggers debris flows depend critically on sediment availability. Rising temperatures accelerate glacier retreat and permafrost degradation, which leads to slope instability and therefore increased sediment supply in high alpine catchments (Hock et al., 2019). Glacier retreat promotes rockfall, slope failure and enhance mass movement activity, which recharge sediment store in torrent systems at a accelerated rate (Stoffel & Huggel, 2012). Climate change therefore affects debris flow on two levels. On the one hand, more frequent and intense precipitation lead to potentially more debris flow triggering conditions and on the other hand an increased sediment availability and faster recharge of sediment store support the creation of more frequent major debris flows (Turkington et al., 2016). However, this trend is difficult to prove through statistical analysis due to strong interannual variability and limited event documentation of debris flows (Jacquemart et al., 2024).

## 2.2 Natural Hazards in Switzerland

Switzerland is a mountainous country whose geomorphological structure inherently predisposes it to natural hazards. Steep catchments, short response times, high sediment availability, and densely settled valley floors create conditions in which rock falls, floods, debris flows, and landslides are not exceptional but recurring phenomena. Since 1972, the start of consistent documentation of damages caused by natural hazard by WSL, water-related processes are the most frequent and have consistently produced the largest impacts and damages (Figure 9) throughout Switzerland (WSL, 2025). This observation is not just a feature of recent decades but is embedded in Switzerland's long-term environmental history, as evidenced by the repeated occurrence of severe flood disasters documented over several centuries.

Historical records document several major flood events in nearly every decade with flood protection structures found from roman times (D. L. Vischer, 2003). The floods in late August 1566, September 1570, September 1640, late August 1834, September 1839 and September 1868 reached a magnitude comparable to that of the 1987 and 2005 flood event (BAFU, 2007; Bundesamt für Wasserwirtschaft & Bundesamt für Umwelt Wald und Landschaft, 1991). In the fourteenth and fifteenth centuries, the floods of 1342 and 1480 were of a similar order of magnitude to the 1987 event, with potentially the 1342 flood significantly exceeding it (Bundesamt für Wasserwirtschaft & Bundesamt für Umwelt Wald und Landschaft, 1991). On a more local scale, many more severe flood events are recorded, a particularly tragic example is the debris flow event in the Buochser Ribi of 1764, which caused eleven fatalities.

Until the middle to late nineteenth century the perception of these events, differed distinctly from modern scientific interpretations. Spiritual explanatory models were influential where floods and severe storms were often interpreted as acts of divine intervention or as manifestations of a "higher power". One widespread interpretation regarded floods as an "Act of God," implying a force that strikes indiscriminately or even punishes blindly (Vischer, 2003). Such interpretations framed natural hazards not primarily as physical processes, but as morally or spiritually meaningful events beyond human control.



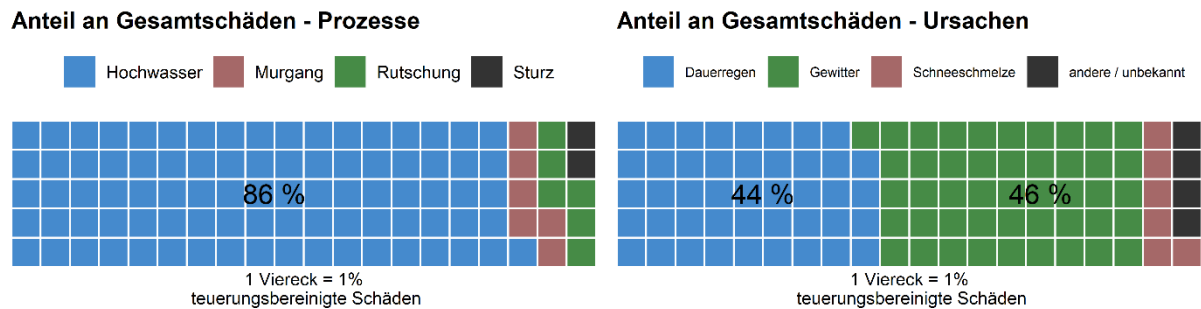


Figure 9 Extract from the severe weather damages data bank illustrating the overwhelming proportion of damages caused by water-based processes (WSL, 2025).

The nineteenth century was marked by numerous catastrophic flood events that caused extensive damage and significant loss of life across Switzerland. In 1834, severe floods affected the cantons of Valais, Graubünden, Ticino, Uri, and Glarus. Just a few years later in 1837, the Emmental region experienced what was described as a “century flood”. In 1852, the Aare river reached the highest water level ever recorded at that time. Additional major flood events occurred in 1868, 1876, 1881, and 1886. After the devastating flood in 1868, public discourse increasingly reflected the perception that floods had become more frequent (D. L. Vischer, 2003) and this growing awareness represented a decisive turning point in Swiss hazard management. It triggered the first national strategies to address flood-related risks and led to the enactment of the Federal Act on Forest Police (Bundesgesetz über die Forstpolizei) in 1876 and the Federal Act on Water Engineering Police (Bundesgesetz über die Wasserbaupolizei) in 1877. These laws marked the beginning of serious federal efforts to control and stabilise torrents and to improve flood protection (BAFU, 2008b). As a consequence, substantial investments were made in structural protection measures, and large-scale river corrections were initiated. Torrents and valley rivers were channelised, slopes were stabilised, and extensive protective infrastructure was constructed. This era of hazard defence through engineering measures fundamentally shaped Switzerland’s approach to natural hazards well into the twentieth century (Brönnimann et al., 2018; D. L. Vischer, 2003).

During the twentieth century, Switzerland experienced a comparatively long period without catastrophic floods (Figure 10), which contributed to a gradual decline in public risk awareness. This relative “flood pause” combined with rapid population growth and economic development, led to an expansion of settlements and agricultural land into areas that had previously been avoided due to flood risk. The flood of 1910 already raised critical questions regarding how increasing population density and intensified land use could be resolved with effective flood protection (Härry, 1910). However, it was not until the flood of 1987 that flood risk once again returned painfully to the public and political spotlight.

After the 1987 flood it became increasingly evident that absolute protection against natural hazards is impossible and the realisation that structural measures alone are insufficient to ensure comprehensive flood protection matured. Preventive strategies therefore shifted from purely protection toward land use practices and spatial planning measures that allow rivers the space required during periods of high flow. This paradigm shift required the systematic development of hazard maps and the formulation of explicit protection objectives. The guiding questions: “What can happen and what may be allowed to happen in specific areas?” were central. Strategies also needed to account for overload scenarios, including emergency planning aimed at limiting residual risk. These principles were codified in the revised Federal Water Engineering Act (Bundesgesetzen über den Wasserbau WBG) and the Federal Forest Act (Bundesgesetzen über den Wald WaG) in 1991 (BAFU, 2008b).

Although still relatively young, the twenty-first century has already been marked by a remarkable number of major flood events in Switzerland. Significant nationwide or regional floods occurred in 2000 (Hegg et al., 2001), 2002 (Hegg et al., 2003), 2005 (BAFU, 2008b), 2007 (Hilker et al., 2008), 2021 (Liechti et al., 2022), and most recently in 2024 (Liechti & Badoux, 2025). Among these, the floods of 2005 and 2024 stand out as particularly notable due to their spatial extent, process diversity, and socio-economic impact.

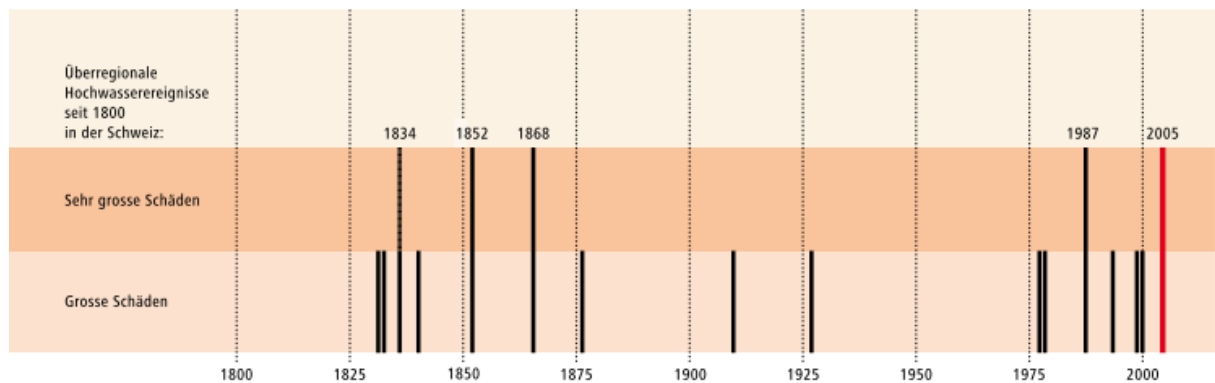


Figure 10 Timeline of large scale flood events in Switzerland since 1800, showcasing the "flood pause" in the twentieth century (BAFU, 2008b).

The flood of 2005 marked another a decisive moment in modern Swiss hazard management. It demonstrated that overload situations are not theoretical scenarios but realities. The event made clear that flood protection principles must go beyond traditional design standards and incorporate robust, overload-capable mitigation concepts. Systems must be designed to fail safely under extreme conditions. Further, the need for action extends beyond prevention to the management of severe events. Optimal preparedness and effectively coordinated emergency response can significantly reduce the impacts and damages. As a result, governing bodies and emergency forces must incorporate natural hazard scenarios into their training. For this to be effective it requires also stronger integration of the affected population and awareness on risks associated with floods as well on behaviour during and event (BAFU, 2008b).

Nearly two decades later the summer of 2024 once again underscored the dynamic and evolving character of water-related hazards. Between May and August extreme weather events triggered several debris flows, floods and landslides along the northern Alps throughout Switzerland accounting for nearly 905 Mio CHF in damages (Liechti & Badoux, 2025). Extreme rainfall in June triggered numerous debris flows in the canton of Valais, the Misoix, and the Maggia Valley, where entire settlements, transport corridors, and critical infrastructure were severely affected. In Lostalio (GR), a series of debris flows mobilised exceptionally large sediment volumes, burying parts of the village and destroying part of the A13 motorway, leading to closure and reduced capacity of the road for several weeks. Later in August a convective storm initiated a debris flow that overwhelmed existing retention structures and caused extensive damage to the village and its infrastructure (MeteoSchweiz, 2024). Even though the events in 2024 did not cause as damages comparable to 2005 or 1987 (Figure 11) it was remarkable for its several small scale but severe independent events and high amounts of major debris flows.

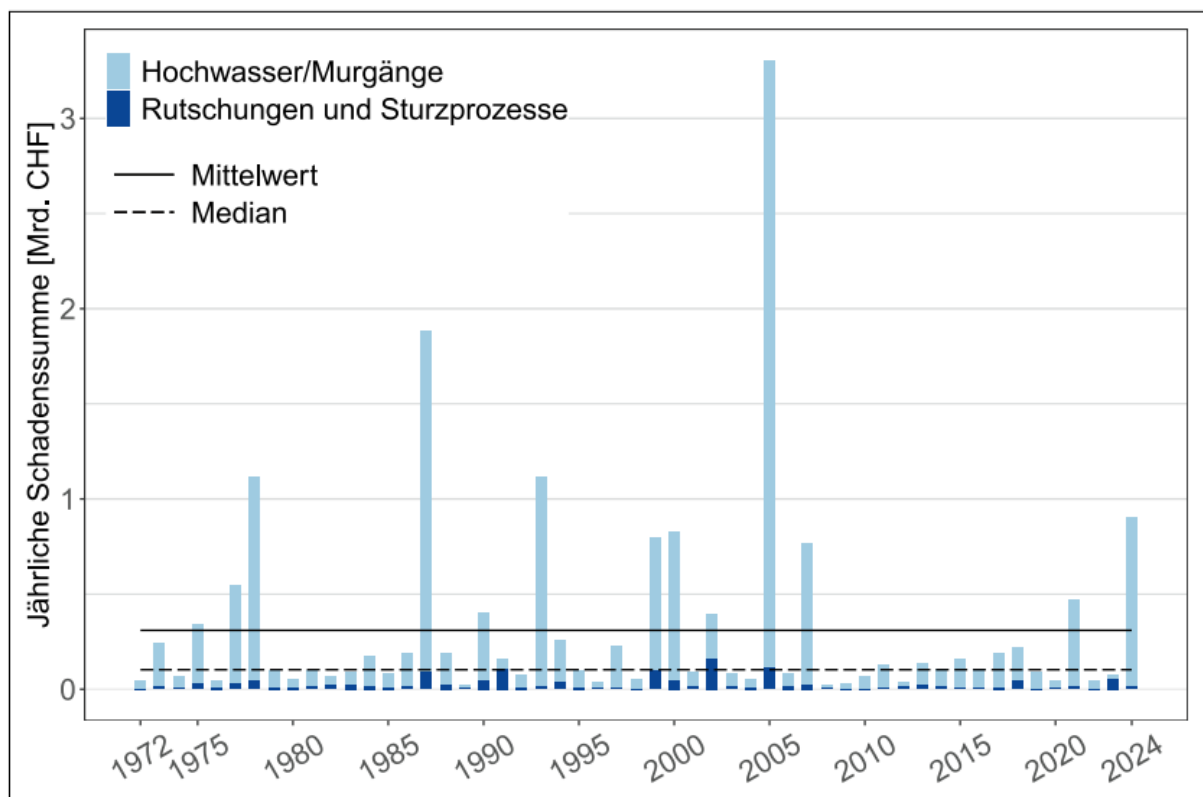


Figure 11 Yearly damage sums for the different natural hazard processes from 1972 to 2024 (Liechti & Badoux, 2025).

## 2.3 Natural Hazard Mitigation in Switzerland

Natural hazard mitigation in Switzerland evolved in response to repeated catastrophic events. With the Culman report hazard mitigation was brought to a national level. The flood of 1868 marked a decisive turning point in federal water management policy and led to the systematic investigation and stabilization of mountain catchments (Brönnimann et al., 2018). Early engineering approaches focused primarily on channelization, sediment retention with check dams, and structural stabilization of torrents (D. L. Vischer, 2003). Over time scientific documentation and systematic recording of weather related damages as done by WSL improved, including nationwide compilations of natural hazard events in data banks like StorMe. Further, historical events were reconstructed and analysed (Ruf & Zesiger, 2021).

However debris flows as a distinct process were only more intensively investigated after the severe flood and debris flow events of 1987. These events revealed clear knowledge gaps and demonstrated that purely structural approaches were insufficient for managing complex alpine hazard systems (Bundesamt für Wasserwirtschaft & Bundesamt für Umwelt Wald und Landschaft, 1991). A fundamental paradigm shift occurred in the late twentieth century. Switzerland gradually moved from a hazard control philosophy towards an integral risk management (IRM) approach. Rather than attempting to eliminate hazards entirely, IRM recognizes that natural processes cannot be fully prevented and that residual risk will always remain. The focus therefore shifted towards reducing vulnerability and exposure, increasing system robustness, and integrating multiple layers of intervention. Structural measures remained important but became embedded within a broader framework that includes spatial planning, ecological measures such as reforestation, emergency planning, and early warning systems (BAFU, 2016).

The IRM is characterized by a cyclical learning process. Major events trigger systematic post event analyses, which generate new insights into process behaviour, structural performance and organizational preparedness. These lessons are subsequently incorporated into updated guidelines, revised hazard maps and adapted protection concepts. The flood events of 1999 and especially 2005 reinforced this adaptive approach and strengthened the emphasis on early warning systems and risk communication (BAFU, 2008a). Climate related extremes in recent decades have further highlighted the importance of continuously reassessing hazard assumptions under changing boundary conditions (Gallina et al., 2016).

Within the IRM structural protection measures remain a central component but are no longer viewed as standalone solutions. Retention basins, check dams, channel training works, and diversion structures are designed to reduce peak discharge and trap sediment before debris flows reach settlements (Piton et al., 2017). Their dimensioning is typically linked to defined return periods and probabilistic design scenarios (Bundesamt für Wasser und Geologie, 2001). However, the IRM explicitly acknowledges the possibility of overload. Protection structures are therefore increasingly designed to behave robustly under exceedance conditions, preventing catastrophic failure even if design thresholds are surpassed. This overload concept reflects the understanding that extreme events beyond statistical expectations may occur (BAFU, 2016).



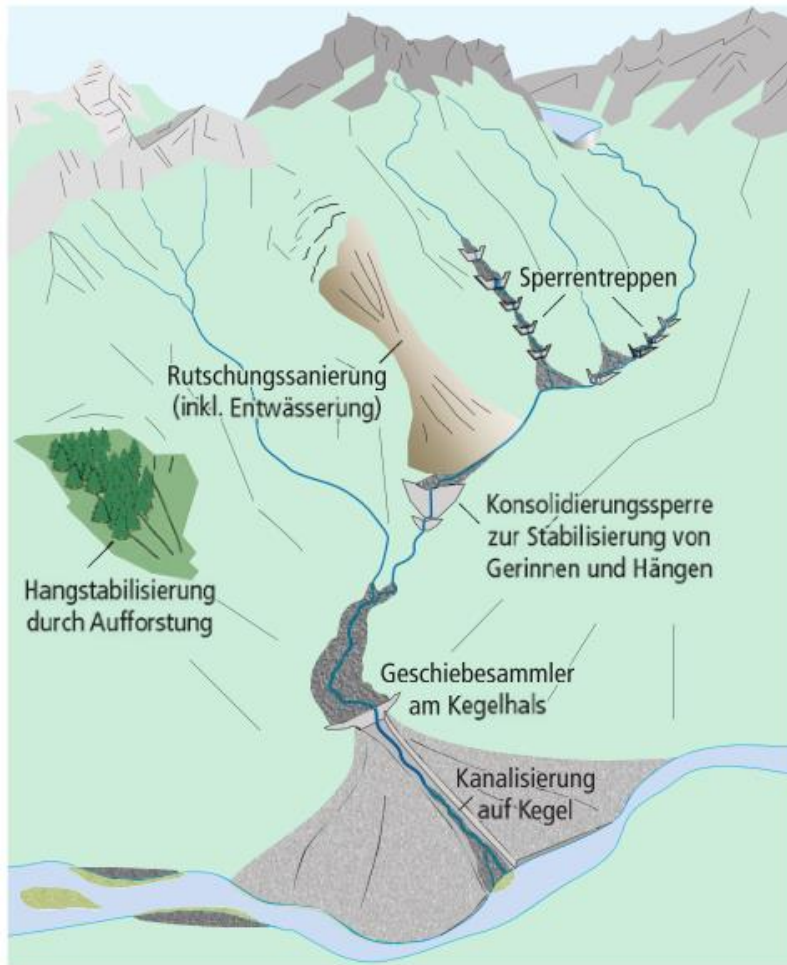


Figure 12 The many mitigation measures used in torrent systems to control sediment transport and erosion processes (Brönnimann et al., 2018; Piton et al., 2017).

Parallel to structural mitigation like in Figure 12, hazard maps have become a key instrument of risk communication and spatial governance. Switzerland maintains hazard maps for all populated areas, translating probabilistic scenarios into spatially explicit planning zones (Bundesamt für Umwelt (BAFU), 2025). The development of harmonized hazard mapping guidelines marked another milestone in Swiss risk governance (BAFU, 2016). Building upon earlier avalanche guidelines, standardized hazard classification schemes were introduced for floods and mass movements, ensuring consistency across cantons (Bundesamt für Raumentwicklung et al., 2000).

Hazard maps are legally binding instruments that guide land use planning and building regulations (Bundesamt für Raumentwicklung et al., 2000). They serve not only as technical documents but also as communication tools that make hazard information accessible to authorities, planners, and the public. After major events, such as the flood of 2005, many hazard maps were revised to incorporate updated modelling approaches, improved terrain data, and new insights from event documentation (BAFU, 2008a). This iterative updating process reflects the adaptive character of IRM.

Recent climate assessments indicate increasing temperatures and intensified heavy precipitation in Switzerland with projections suggesting further amplification of short duration extreme rainfall (MeteoSwiss & ETH Zürich, 2025). In mountain regions, additional geomorphic changes such as glacier retreat and permafrost degradation influence sediment availability and slope stability (Adler et al., 2022; Hock et al., 2019). Although long term trends in debris flow frequency are difficult to quantify, analyses indicate that climate change may alter both triggering mechanisms and preconditioning factors (Huggel et al., 2012).

These developments pose new challenges for the IRM practised in Switzerland, particularly regarding the assumption of stationarity in return period estimation and the adequacy of existing protection capacities. Evaluating whether existing hazard maps and protection measures remain adequate under changing climatic conditions becomes a necessary step in maintaining long term safety in alpine settlement areas and possibly poses the next step in the Swiss approach to natural hazard management.

## 3 Methods and Data

### 3.1 Scenarios

Extreme events are rare by definition and lie in the upper tail of the probability distribution. Classical descriptive statistics are therefore insufficient for estimating the magnitude of events associated with long return periods like 100- or 300-year events. The extreme value theory (EVT) provides a mathematical framework for modelling the statistical behaviour of distribution tails and allows extrapolation beyond the observed record (Coles, 2001; Katz et al., 2002). By fitting appropriate distributions such as the Generalized Extreme Value (GEV) distribution or applying Peak-Over-Threshold (POT) approaches, precipitation intensities can be associated with defined annual exceedance probabilities.

Return levels derived from extreme value statistics are widely used in hydrology and hazard assessment to define design events and scenario magnitudes. For Switzerland return levels of daily and hourly precipitation extremes are routinely derived from long term observations using extreme value approaches, as documented in the Climate CH2025 assessment (MeteoSwiss & ETH Zürich, 2025) and regularly published for selected MeteoSwiss stations (MeteoSchweiz, 2023). The application of extreme value statistics is a valuable tool to derive statistically robust scenarios.

Precipitation scenarios as a basis for debris flow scenarios are useful because in small Alpine torrent catchments, continuous discharge or sediment transport measurements are rarely available. Enough observations over sufficiently long time periods to produce statistically robust are even rarer (Rickenmann, 2016a). However, intense rainfall represents a dominant triggering mechanism for debris flows. Numerous studies have demonstrated a strong relationship between intense rainfall and the initiation of shallow landslides and debris flows (Borga et al., 2014; Guzzetti et al., 2008; Marra et al., 2016; Stoffel et al., 2005).

For the European Alps in particular, heavy precipitation events are recognised as key drivers of mass movement processes (Pelfini & Santilli, 2008; Stoffel et al., 2014). Precipitation records therefore represent the most reliable and spatially consistent long term dataset for reconstructing triggering conditions and defining scenarios. Precipitation measurements by MeteoSwiss extend back to the late nineteenth century at many stations providing a long term record with continuous and homogeneous measurements. Using precipitation based return levels derived from extreme value statistics as a proxy for debris flow activity, sound and reproducible debris flow scenarios can be attained under both present day and future climatic conditions (Turkington et al., 2016).

### 3.1.1 Precipitation extreme value statistics

Daily precipitation data was obtained from MeteoSwiss weather stations for the time period from the earliest year recorded to 2024. For each investigated catchment, the two to three closest stations, where possible in the same valley as the catchment, were chosen. When possible characteristics like exposition, elevation and topography between station and catchment, meaning consideration for topography influencing local weather patterns, were considered. Selection criteria further included the availability of continuous 24-hour precipitation sums and a minimum record length of 30–40 years, with preference given to longer time series to increase statistical robustness for rare return period estimation. The chosen weather stations (Table 1) have recorded precipitation since the late nineteenth century or very early twentieth century providing records of over 100 years, with only three stations, Gersau, Bristen and Stans, beginning operation after 1975 and therefore providing shorter records of less than 50 years (MeteoSchweiz, 2025).

Cumulative 24-hour precipitation totals were used for the extreme value analysis. Although sub daily precipitation data would be more relevant for the application as triggering conditions for debris flows, long and homogeneous sub daily records are only available for a comparatively short period in Switzerland of mostly less than 40 years. In contrast, daily precipitation series extend back to the late nineteenth century at many stations, providing substantially longer and statistically more robust datasets for the estimation of rare return periods. The use of 24-hour sums therefore represents a compromise between process relevance and data availability, ensuring consistency across stations and sufficient record length for reliable extreme value analysis.

To derive precipitation scenarios for 30-, 100- and 300-year return periods, two established extreme value approaches were applied and compared. The block maxima method using the Generalized Extreme Value (GEV) distribution and the Peak-Over-Threshold (POT) method using the Generalized Pareto Distribution (GPD). Both approaches were implemented in R programming environment and evaluated using standard diagnostic procedures.

For the GEV approach, the annual maximum 24-hour precipitation amount was extracted for each year of record and a GEV distribution was fitted to the series of annual maxima. Model performance was assessed using histograms of annual maxima with fitted distribution curves, quantile–quantile (QQ) plots and return level plots. Return levels were calculated for 10-, 30-, 100-, 300- and 1000-year return periods with a 95% confidence interval.

*Table 1 List of the MeteoSwiss stations from which data was used for the scenario calculations for each catchment, including key characteristic relevant to the application (MeteoSchweiz, 2025).*

| catchment    | station name<br>(abbreviation) | operation<br>mode<br>(present) | daily<br>precipitation<br>data since | distance<br>from<br>catchment<br>[km] | elevation<br>[m.a.s.l.] | exposition   |
|--------------|--------------------------------|--------------------------------|--------------------------------------|---------------------------------------|-------------------------|--------------|
| Milibach     | Brienz (BRZ)                   | automatic                      | 1901                                 | 5                                     | 567                     | valley floor |
|              | Meiringen (MER)                | automatic                      | 1889                                 | 12                                    | 589                     | valley floor |
|              | Interlaken (INT)               | automatic                      | 1894                                 | 16                                    | 578                     | valley floor |
| Altdorfbach  | Luzern (LUZ)                   | automatic                      | 1880                                 | 15                                    | 454                     | valley floor |
|              | Gersau (GES)                   | automatic                      | 1998                                 | 3                                     | 521                     | S            |
| Selderbach   | Bristen (BRT)                  | automatic                      | 1982                                 | 3                                     | 784                     | E-W valley   |
|              | Altdorf (ALT)                  | automatic                      | 1864                                 | 11                                    | 438                     | valley floor |
|              | Göschenen (GOS)                | automatic                      | 1883                                 | 13                                    | 950                     | N-S valley   |
| Schipfenbach | Bristen (BRT)                  | automatic                      | 1982                                 | 2                                     | 784                     | E-W valley   |
|              | Altdorf (ALT)                  | automatic                      | 1864                                 | 12                                    | 438                     | valley floor |
|              | Göschenen (GOS)                | automatic                      | 1883                                 | 13                                    | 950                     | N-S valley   |
| Buoholzbach  | Stans (SNS)                    | automatic                      | 1976                                 | 8                                     | 439                     | valley floor |
|              | Engelberg (ENG)                | automatic                      | 1864                                 | 12                                    | 1036                    | S-W          |

To better represent the upper tail behaviour of precipitation extremes and to increase statistical efficiency, a Peak-Over-Threshold analysis was conducted. A high threshold corresponding to the 98th percentile of daily precipitation was selected. The threshold was evaluated iteratively with long and short time series records to ensure a sufficient number of exceedances. Since extreme precipitation events may occur within storm systems over several days, temporal dependence was addressed through declustering. All exceedances occurring within two days of a previous exceedance were considered part of the same meteorological event, and only the maximum value per cluster was retained. This procedure ensures some independence of extreme events.

Exceedances above the threshold were fitted using a Generalized Pareto Distribution. Model diagnostics included mean residual life plots, parameter stability plots, QQ-plots and return level plots to evaluate the adequacy of the fitted model. Return levels were calculated for 10-, 30-, 100-, 300- and 1000-year return periods, each accompanied by 95% confidence intervals to quantify statistical uncertainty. Return level curves showing maximum cumulative 24-hour precipitation as a function of return period were then derived.

Although both methods were evaluated, the POT approach was selected as the basis for the precipitation scenarios used in the subsequent discharge calculations. The POT method provides a more efficient use of available data by incorporating multiple extreme events per year instead of restricting the analysis to a single annual maximum. This is particularly advantageous for stations with shorter records, where the block maxima method would yield a very limited number of data points, leading to even greater uncertainties with longer return periods. Furthermore, the POT approach directly models threshold exceedances and is therefore better suited to characterise the tail behaviour of precipitation distributions. For these reasons, precipitation return levels resulting from the POT analysis were used to define the 30-, 100- and 300-year precipitation scenarios applied in the discharge and debris flow scenarios.



### 3.1.2 Debris Flow scenarios

To transform precipitation return levels into discharge scenarios various approaches are available to convert rainfall into peak discharge. A method comparison by Hegg (2004) discharge calculation results using the modified rational method often represented the 100-year return value best and is therefore recommended for the use of finding design discharge. In this study the modified rational method was applied as described in the practical aid by the former Bundesamt für Wasser und Geologie (2003). The precipitation scenarios derived from extreme value analysis were used as input to calculate the discharge scenarios for each catchment.

With the modified rational method peak discharge is calculated using:

$$Q_{max} = 0.278 \cdot C \cdot i(T_c, x) \cdot A$$

where  $Q_{max}$  is the peak discharge [ $m^3/s$ ],  $C$  the peak runoff coefficient [-],  $i(T_c, x)$  the rainfall intensity [ $mm/h$ ] corresponding to the return period  $x$  with a duration equal to the concentration time  $T_c$  and  $A$  the catchment area [ $km^2$ ]. The fundamental assumption of the modified rational method is that peak discharge occurs when rainfall duration equals the concentration time of the catchment. Rainfall is assumed to occur uniformly over the entire catchment area and with constant intensity over the considered duration (block rainfall assumption).

The concentration time  $T_c$  is defined as the time required for runoff from the most distant point of the torrent to reach the outlet. In the modified formulation, the concentration time consists of the flow time  $T_{Fl}$  and the wetting time  $T_B$ :

$$T_c = T_{Fl} + T_B$$

The flow time  $T_{Fl}$  was calculated using the Kirpich equation.

$$T_{Fl} = 0.0195 \cdot L^{0.77} \cdot S^{-0.385}$$

where  $L$  is the maximum flow length [ $m$ ] measured along the main channel from the outlet to the most distant point of the torrent, and  $S$  is the mean slope along this flow path [ $m/m$ ], defined as  $\Delta H/L$ . The resulting flow time is expressed in minutes.

The wetting time  $T_B$  represents the time required for the rainfall event to wet the top most soil before discharge occurs. According to Kölla (1986) this wetting time depends primarily on soil properties, geology and land cover.  $T_B$  is determined iteratively. However, in the present study, the wetting time was assumed negligible ( $T_B = 0$ ). This assumption was made because the analysed scenarios represent short duration, high-intensity convective storm precipitation events in steep Alpine torrent catchments. Under such conditions, rainfall intensities are expected to exceed infiltration capacities, and storage volumes in shallow Alpine soils are small relative to total event rainfall. Furthermore, several investigated catchments contain significant proportions of shallow soils and exposed bedrock (Table 2), which favour rapid runoff generation. Setting  $T_B = 0$  simplifies the concentration time to  $T_c = T_{Fl}$ .

This assumption may lead to a slight overestimation of peak discharge, as initial infiltration is neglected. However, for the purpose of hazard assessment of extreme events, this represents a conservative and acceptable approximation.

Because precipitation return period values were derived from 24-hour sums, rainfall depths corresponding to the concentration time were obtained using duration dependent scaling

$$P_{T_c} = P_{24} \cdot R_t$$

where  $P_{T_c}$  is the precipitation depth for duration  $T_c$ ,  $P_{24}$  the 24-hour return level precipitation depth, and  $R_t$  a scaling factor derived from Swiss intensity–duration–frequency relationships and validated for each catchment using extreme point precipitation of different return periods from the hydrological Atlas of Switzerland (Geografisches Institut der Universität Bern & Bundesamt für Umwelt BAFU, 2015).

The relevant rainfall intensity was then calculated with:

$$i(T_c, x) = \frac{P_{T_c}}{T_c}$$

The last component required for the modified rational method is the peak runoff coefficient  $C$ .  $C$  is influenced by land cover type. Given the land cover characteristics across the investigated catchments (Table 2) is somewhat comparable and the focus on short, high intensity storm events attenuates effects of land cover types, a uniform runoff coefficient of  $C = 0.6$  was applied. This value is validated at least for the Milibach catchment, where reconstructions of the 2024 event yielded a modelled peak runoff coefficient of  $C = 0.63$  (Niederer und Pozzi Umwelt AG & GEOTEST AG, 2025).

Table 2 Distribution of land cover types in the five catchments based on the Arealstatistik by (Swisstopo, 2026).

|                        | Milibach | Schipfenbach | Selderbach | Altdorfbach | Buholzbach |
|------------------------|----------|--------------|------------|-------------|------------|
| Siedlungsflächen       | 1.8      | 0.9          | 0.5        | 2.4         | 0.6        |
| Landwirtschaftsflächen | 59.5     | 5.5          | 12.8       | 40.3        | 47         |
| bestockte Flächen      | 12.3     | 32.9         | 22.6       | 52.9        | 39.5       |
| unproduktive Flächen   | 26.4     | 60.8         | 64.1       | 4.4         | 12.8       |
| total                  | 100      | 100.1        | 100        | 100         | 99.9       |

The peak water discharge per catchment and return period derived from the modified rational method was subsequently converted into debris flow discharge by accounting for the sediment fraction within the flow. Debris flows consist of a mixture of water and solid material and peak discharge therefore exceeds pure water discharge due to the additional volumetric contribution of sediment. Following Bennett et al. (2014) debris flow discharge can be expressed as the combined contribution of the liquid and solid phases. In practical terms, the debris flow peak discharge was calculated by scaling the water discharge according to an assumed volumetric solid concentration. A solid fraction of 40% was assumed for all catchments. This value is consistent with reported sediment concentrations in Alpine debris flows. Reconstructions of sediment fractions in debris flows during the 1987 events indicated that solid fractions of approximately 30-60% (Bundesamt für Wasserwirtschaft & Bundesamt für Umwelt Wald und Landschaft, 1991). From the debris flow event in Brienz in 2024 a solid material fraction of about 35% was estimated (Niederer und Pozzi Umwelt AG & GEOTEST AG, 2025). Assuming a sediment fraction of 40% therefore represents a realistic estimate and a plausible basis for the scenarios.

In addition to the return period based discharge scenarios, an extreme flood scenario (EHQ) was defined. Several approaches can be applied according to the practical guide for flood estimations (Bundesamt für Umwelt (BAFU), 2025; Bundesamt für Wasser und Geologie, 2001, 2003) to estimate the EHQ:

- Multiplication of the 100-year discharge (HQ100) by a factor between approximately 1.2 and 2, depending on catchment characteristics and associated uncertainties. The multiplication factor can be up to 2.25 for catchments with hydropower dams.
- Use of the gradient between HQ100 and HQ2.33 as an indicator to define an appropriate multiplication factor
- Definition of a discharge scenario that is larger than the 300-year event but smaller than the 1000-year event

In this study a 1000-year precipitation and discharge scenario was initially calculated, however the resulting HQ1000 values were only moderately larger than the HQ 300 values. Further, for a return period of 1000 years based on 100 years of data uncertainty are too large to consider the results robust enough for scenario definition. The alternative approach based on the HQ100/HQ2.33 gradient was not applied, as the discharge calculations in this study are derived from precipitation scenarios rather than directly from observed discharge series and HQ2.33 was not determined. This method is more suitable for larger catchments with discharge measurements.

Therefore the method where the HQ100 is multiplied by a factor to approximate the EHQ is applied. A multiplication factor of 2 was chosen, as suggested by the practical guide for flood protection for rivers and streams (Bundesamt für Wasser und Geologie, 2001) for small catchments to account for increased uncertainties.

Total debris flow volumes are then estimated using the Rickenmann relation, an empirical discharge-volume relationship derived from documented debris flow events around the world (Rickenmann, 1999, 2016a). The relation distinguishes between granular debris flows given by:

$$Q_{max} = 0.135 \cdot M^{0.78}$$

whereas for muddy debris flows it is expressed as:

$$Q_{max} = 0.0188 \cdot M^{0.79}$$

with  $Q_{max}$  representing the peak debris flow discharge [ $m^3/s$ ] and  $M$  the total debris flow volume [ $m^3$ ]. These equations were rearranged to estimate event volumes from the calculated peak debris flow discharges. Rickenmann (2016a) notes that classification of debris flows are not always straightforward and Swiss catchments produce both granular and muddy debris flows. The analysed debris flows from 1987 lean more towards granular flows, while the highly studied Illgraben in Valais, Switzerland produces more muddy flows. The classification of the investigated catchments was therefore based on documented past events, photographic evidence, available reports as well as observations from the field.

Selderbach and Schipfenbach in Silenen have shown predominantly matrix-supported, fine-grained debris flows in recent years, similar to those observed at Illgraben. For Altdorfbach in Vitznau, the classification was based on smaller debris flows released from the Gassrübi landslide area, which exhibited characteristics typical of muddy debris flows. For Milibach in Brienz, discharge and volume estimates provided by the Canton of Bern for the 2024 event were used for plausibility checks and suggested a more muddy debris flow. For Buoholzbach in Nidwalden, the classification was less clear. Photographs from the 2005 event and deposits from the fan suggests characteristics of a muddy debris flow, while channel deposits above the fan area indicate that a more granular flow type would also be possible. Given this mixed evidence both flow types appear plausible, but the muddy debris flow relation was applied, as they yield higher event volumes corresponding to a more conservative scenario.

The resulting debris flow volumes in combination with the debris flow discharges were then used as input parameters for the debris flow simulations with RAMMS.

### 3.1.3 Climate Change Scenarios

Even though mean annual precipitation is not expected to change significantly with climate change, seasonal distribution is likely to change towards overall drier summer and wetter winters. However, with climate change an increase in precipitation extreme events is expected, with an increase in the event intensity and especially frequency.

The CH2025 climate scenarios indicate that under a global warming level of 3°C short duration extreme precipitation intensities are projected to increase substantially in Switzerland compared to the reference period 1991–2020. The projected mean increase for heavy 1-hour precipitation lies near the upper interval of the present day uncertainty range derived from observational extreme value analyses (Figure 13). This implies that the upper confidence interval of current statistical return level estimates corresponds to a plausible future climate state under continued warming (MeteoSwiss & ETH Zürich, 2025).

To account for the influence of climate change on short duration extreme precipitation, which acts as a main trigger to debris flows, "future scenarios" with consideration for intensification of extreme precipitation events are included in this thesis. For each scenario the precipitation values of the upper confidence interval from the extreme value statistics are used as the basis for the "future scenarios" and are processed into debris flow scenarios applying the method explained above.

It is important to note that this approach does not represent a dynamic extreme value model, which might represent climate induced changes of natural hazards more accurately. Instead it provides a scenario that reflects the magnitude of change as suggested by CH2025 with a global mean temperature increase by 3°C while remaining grounded in the observational record.



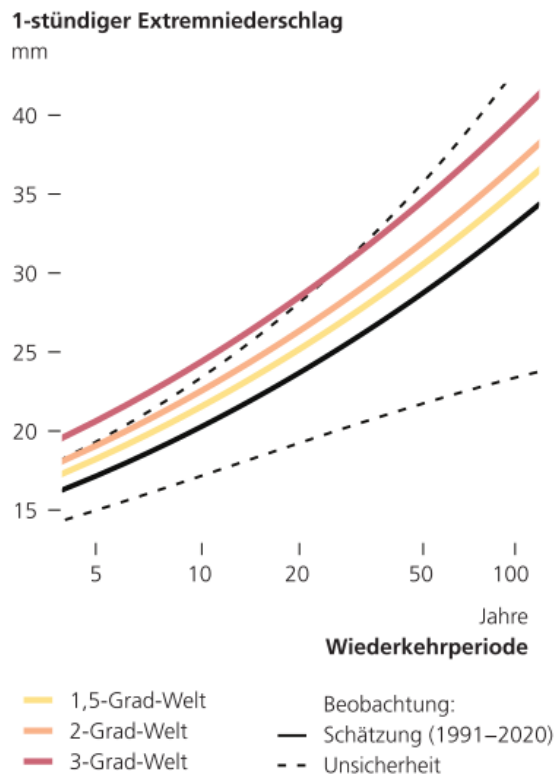


Figure 13 Example of the shift of the mean for extreme 1 hour precipitation intensity towards the upper confidence interval of extreme value statistics with current observations with increased global warming (MeteoSchweiz & ETH Zürich, 2025).

## 3.2 Field visits

Field visits were conducted in all investigated catchments to complement the desk-based analyses and to improve the understanding of geomorphological and hydrological conditions and ground assumptions on sediment availability or deposition compositions of past events in observations in the catchment.

Key locations were identified in advance based on topographic and geologic maps, orthophotos and documentations of past events. During the field visits particular attention was paid to sediment sources, signs of previous debris flow activities such as areas of deposition or erosion, channel morphology and mitigation structures such as check dam, retention basins or channel stabilisation work. Observations included geomorphological indicators of recent erosion, vegetation disturbances, exposed fresh sediment surfaces and base flow conditions. In the fan area special attention was given to channel depth or bridges and underpasses. These observations provided essential information for assessing sediment supply conditions and interpreting model results.

Prior to the field visits each catchment was explored using digital elevation models and hydrological datasets by Swisstopo. The official catchment boundaries were used to delineate the catchment as these datasets offer high spatial accuracy. Longitudinal channel profiles were derived from the digital terrain model to help identify areas of possible erosion or deposition. The profiles were drawn in the Swisstopo environment and exported as CSV files for further processing. All channel segments exceeding a slope angle of 25° were highlighted, as such gradients are commonly associated with potential debris flow initiation zones. Relevant landmarks were included in the profile plots to facilitate spatial orientation during fieldwork.

Fieldwork logistics were planned in advance. Hiking trails, cable car access, roads, position and access to structures and other potential access constraints were identified using the Swiss topographic map. Travel planning included transportation mode (car or public transport), estimated walking time and required equipment. The planned inspection routes were digitised in the Swisstopo app to obtain a preliminary estimate of time requirements and terrain conditions. For safety reasons company for most of the field visits was organised.

Field visits were conducted primarily along established hiking trails to ensure safety and efficiency. Where conditions permitted and where it was considered safe and responsible, off trail routes were taken to access relevant channel reaches or sediment sources.

Within the torrent channels, sediment depth was visually estimated. Areas of recent erosion and deposition were mapped, and unstable slopes adjacent to the channel were identified. Particular attention was paid to the nature of the channel bed, distinguishing between exposed bedrock and unconsolidated material as this influences sediment accumulation in the transition zone. Indicators of past debris flow activity were documented, including erosional scarps, levee deposits and disturbed or abrupt changes of vegetation composition. The general geomorphological character of each catchment was assessed, including slope morphology, valley confinement, channel pattern and potential sediment supply areas. Existing mitigation structures such as check dams, retention basins and other structures influencing flow within the channel, such as bridges were recorded. Their structural condition and potential interaction with extreme discharge scenarios were noted.

Each field day was documented systematically. GPS tracks were recorded and exported as GPX files and subsequently plotted on maps to provide a spatial reference of the inspected areas. Photographs were taken to document geomorphological features, sediment characteristics, erosion and deposition zones, and protective structures. Observations were summarised in written descriptions immediately after each field visit.

Maps showing inspection routes, together with selected photographs and observation summaries, are provided in the appendix.

### 3.3 Debris Flow Simulations

#### 3.3.1 Data preparation

All spatial input data required for the debris-flow simulations were obtained from Swisstopo. The datasets included the Swiss digital elevation model (SwissALTI3D), orthophotos of the catchments (SwissIMAGE) and the National map (Landeskarte) for orientation and the topographic landscape model (SwissTLM3D) and SwissBUILDINGS3D for information and exact location on roads, houses dams and other structures. The digital elevation model SwissALTI3D with a spatial resolution of 0.5 m formed the basis of the terrain representation and was used as the input elevation model in RAMMS.

Since the original data of the SwissALTI, SwissIMAGE and the national topographic map are provided as  $1 \times 1$  km tiles, the relevant tiles for each catchment were downloaded and merged using the GDAL merge tool in QGIS to create a single continuous layer suitable for use in RAMMS, which allows only one elevation file per simulation domain. Orthophotos from SwissIMAGE were used for visual validation and spatial orientation. To ensure compatibility with RAMMS the TIFF files were loaded into QGIS and exported again to create the corresponding TFW world file required for georeferencing in RAMMS.

The SwissALTI3D digital elevation model (DEM) includes major earth dams but does not represent concrete retention walls or outlet structures of retention basins. These elements were therefore manually incorporated into the elevation model. Using topographic maps and orthophotos polygons were drawn at the exact locations of the respective structures in Swisstopo. Their spatial extent was delineated as accurately as possible based on available imagery and map data. To ensure reliable representation within the computational grid, the structures were drawn with an increased thickness of approximately 5 m in the downstream direction. The polygons were exported to QGIS, where an absolute elevation in metres above sea level was assigned to each feature corresponding to the mean crest height of the respective structure. The mean crest height were determined by adding the height of the structure to the elevation above sea level as read from the DEM at the location of the structure. Crest height for the Dams in Vitznau were provided by the Canton of Luzern, while for the other catchments crest heights as measured in the field were used. The polygons were then integrated into the DEM, modifying the terrain elevation of the polygon area to the assigned elevation. The updated elevation model, now including all relevant retention structures, was exported and used as the final input DEM for the RAMMS simulations.

Vector datasets from SwissTLM were clipped to the respective catchment extents and used to identify infrastructure, torrent control structures and transportation networks. The SwissBuildings3D dataset required preprocessing due to complex geometries as houses are represented in the dataset including overhangs from roofs or balconies and the shape of roofs. To simplify the geometry convex hull operations were applied to reduce a house to single building footprint polygon. Data from the SwissTLM and SwissBUILDINGS were used for calibration of the simulations but are not used in the final scenario simulations.

### 3.3.2 Simulations in RAMMS

For each catchment debris flow simulations were conducted for the 30-, 100- and 300-year scenarios as well as for the extreme flood scenario (EHQ), both under present day conditions and under future climate conditions. All simulations were performed using a release hydrograph approach in RAMMS Debris Flow.

The required input data for each simulation included the digital elevation model (DEM), a calculation domain and a release area polygon. In addition general simulation parameters had to be specified to run a simulation, including spatial resolution, total simulation time (end time), output interval (dump step), material density and optionally an obstacle file representing buildings or infrastructure as no flux areas. Friction parameters ( $\mu$  and  $\xi$ ) and release parameters for the three-point hydrograph including total volume, peak discharge, time lag between onset and peak, initial flow velocity, and inflow direction have to be defined. The inflow direction was determined from topographic maps using a navigational rapporteur, as it is not defined in cardinal directions within RAMMS.

Spatial resolution has a significant influence on the accuracy with which terrain features are represented. A review by Mikoš & Bezak (2021) indicates that most debris flow simulations are conducted with grid resolutions between 2 m and 5 m. Coarser resolutions can lead to substantial deviations in inundation extent. Fan & Galoie (2025) demonstrate that increasing cell size from 1 m to 20 m can cause extreme distortions, increasing the inundation area by 724%, possibly indicating simulation errors in the simulation process. Based on these findings, a resolution of 2 m was selected for the final simulations, as it represents an appropriate compromise between computational efficiency and spatial accuracy.

The friction parameters  $\mu$  (dry Coulomb friction) and  $\xi$  (turbulent or viscous friction) strongly influence flow behaviour and runout. Reported values in the literature cover wide ranges, with  $\mu$  typically between approximately 0.05 and 0.4 and  $\xi$  commonly between 100 and 500 m/s<sup>2</sup>, but values outside these ranges have been documented (Mikoš & Bezak, 2021). The coefficient  $\mu$  primarily controls deceleration and final runout distance, particularly when the flow approaches standstill, whereas  $\xi$  plays a more dominant role at higher velocities (Gan & X. Zhang, 2019). Studies indicate that variations in  $\mu$  generally have a stronger effect on simulation results than variations in  $\xi$  (Fan & Galoie, 2025). For granular flows,  $\xi$  values are often below 200 m/s<sup>2</sup>, while muddy flows typically exhibit  $\xi$  values above 200 m/s<sup>2</sup>. When flow type is uncertain, initial values of  $\mu = 0.2$  and  $\xi = 200$  m/s<sup>2</sup> are commonly recommended for calibration (Mikoš & Bezak, 2021).

To determine suitable friction parameters for the study area a documented past event was used for calibration. The 2024 debris flow event in Brienz provided the most reliable documentation of runout extent and deposition patterns and was therefore selected for parameter calibration. A series of simulations was conducted using  $\mu$  values between 0.1 and 0.5 and  $\xi$  values between 100 and 400 m/s<sup>2</sup>. The parameter combination  $\mu = 0.2$  and  $\xi = 200$  m/s<sup>2</sup> produced the best agreement with the observed runout. Although minor discrepancies remained, possibly due to bridge obstructions or morphological changes of the channel, this parameter set was considered appropriate.

For the Selderbach, Schipfenbach and Buholzbach a past event was simulated as well, using the above defined friction parameters to assess whether they can also be applied in these catchments. Based on the limited information available of past event in the three catchments the adopted parameters provided plausible results when considering all the uncertainties influencing the scenario simulations. Because no information on volume or extent of sediment deposition of a past event was available, no such parameter testing could be done for the Altdorfbach. A test simulation was done anyway and the results seemed to be plausible even though they could not be compared to anything.

After initial parameter definition the scenarios were simulated. For each catchment, the first simulation served as a test run to verify all input parameters and model stability. The initial calculation domain encompassed the entire debris flow fan. The future EHQ scenario was used for this first run, as it represented the largest scenario. The release hydrograph was defined using the estimated total debris flow volume and corresponding peak discharge of the EHQ with a time lag of 10 seconds and an initial velocity of 10 m/s. The first simulation was executed at a resolution of 5 m to reduce computation time. The simulation end time was set to 2000 s, the dump step to 5 s (default), and the bulk density to 2000 kg/m<sup>3</sup> (default).

After verifying that the results were plausible, the runout envelope shapefile was exported and used as the calculation domain for the following simulation. The EHQ scenario was then simulated again within the reduced domain at a resolution of 2 m. Where necessary, minor adjustments to initial flow velocity were applied. Subsequently, the remaining scenarios were simulated in decreasing order of magnitude. For each scenario the runout envelope of the next larger scenario was used as the calculation domain. Input parameters were kept consistent wherever possible with only total volume, peak discharge being adjusted per scenario and if necessary initial velocity was decreased for smaller scenarios.

In catchments where none of the predefined design scenarios resulted in overload of retention structures additional simulations were performed with incrementally increased release volumes until overload occurred.

For each simulation RAMMS generated a database file (.db2) and compressed output files (.out.gz) containing the full model results. Raster outputs were exported in GeoTIFF format and included maximum flow height, maximum velocity, maximum momentum, maximum dynamic pressure, maximum shear stress, maximum erosion depth and maximum deposition height. These spatial datasets formed the basis for intensity mapping and hazard classification

## 3.4 Comparison Hazard maps

### 3.4.1 Intensity maps

To compare the HQ30, HQ100, HQ300, EHQ scenarios calculated here, an intensity map and from the intensity map a hazard map is created for each catchment. The intensity and hazard maps are created following the process proposed by BAFU with their enforcement aid from 2001 and 2025 (Bundesamt für Umwelt (BAFU), 2025; Bundesamt für Wasser und Geologie, 2001).

Intensity maps are thematic spatial representations that depict the spatial distribution of process intensity within an affected area and focus exclusively on the physical magnitude of the process at a given location and for a defined scenario. Intensity maps distinguish four intensity classes that represent increasing levels of process magnitude and associated damage potential, as described in Table 3. Not affected areas are locations where no relevant process influence is expected. Weak intensity characterises areas with low process magnitude and superficial damage, such as sediment deposition, water intrusion or non-structural damage to infrastructure elements. Endangerment for people is not expected. Medium intensity describes conditions with moderate to high process magnitude where structural damage to infrastructure must be expected and people outside of buildings are at risk. Strong intensity represents the highest level of process magnitude and is associated with severe damage or complete destruction of infrastructure, and a high risk for people inside and outside of buildings (Bundesamt für Umwelt (BAFU), 2025).



Table 3 Table of the four intensity classes presented and described in the enforcement aid by BAFU (2025).

| Intensitätsklasse<br>Intensity classes  | Bedeutung / Schadeneinwirkung<br>Meaning / Damage impact                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
|-----------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| keine Einwirkung<br>no effect           | Gebiet ist nicht von Einwirkung betroffen<br>Area is not exposed                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
| schwache Intensität<br>weak intensity   | Gebiet ist von Prozess betroffen, Personen sind sowohl innerhalb als auch ausserhalb von Gebäuden i. d. R. nicht gefährdet*. Gebäude** sind in ihrer Struktur i. d. R. nicht gefährdet; es können jedoch erhebliche Sachschäden am und im Gebäude auftreten.<br>The area is affected by the process, but people inside and outside buildings are generally not at risk*. Buildings** are generally not at risk in terms of their structure, but significant damage to property may occur on and inside the building. |
| mittlere Intensität<br>medium intensity | Personen sind ausserhalb von Gebäuden gefährdet, innerhalb von Gebäuden** i. d. R. jedoch nicht*. Gebäude erfahren in der Regel strukturelle Schäden.<br>People are at risk outside buildings, but generally not inside buildings. Buildings usually suffer structural damage.                                                                                                                                                                                                                                       |
| starke Intensität<br>strong intensity   | Personen sind sowohl ausserhalb als auch innerhalb von Gebäuden gefährdet. Gebäude können unmittelbar zerstört werden.<br>People are at risk both outside and inside buildings. Buildings may be destroyed immediately.                                                                                                                                                                                                                                                                                              |

Debris flows are categorized as a subprocess under the main process water. Other subprocesses include flood, channel erosion, surface runoff, groundwater upwelling, tsunami. Specifically for the subprocess debris flow the intensity classes are defined using thresholds of the values deposition height, specific discharge and erosion depth (Table 4). The debris-flow height  $h_A$  represents the maximum flow depth or sediment deposition thickness within the flow zone. It is defined as the vertical distance from the channel bed or local terrain surface. Higher  $h_A$  values correspond to higher intensity with anything greater than  $h_A = 2 \text{ m}$  classified as strong intensity. The specific discharge  $q = v \cdot h_A$  combines flow velocity  $v$  and flow depth  $h_A$ . This parameter describes the dynamic component of the flow and it captures both the kinematic energy of the flow and its capacity to exert dynamic impact forces on obstacles. Increasing values of  $q$  indicate an increasing damage potential with  $q > 2 \text{ m}$  being classified as strong intensity. As an accompanying process of debris flows erosion depth is the third characteristic value used to define process intensity. The erosion depth  $h_{ER}$  characterises the vertical lowering of the terrain surface caused by the debris flow, with  $h_{ER} > 2 \text{ m}$  classified as strong intensity (Bundesamt für Umwelt (BAFU), 2025).

Table 4 Table of the characteristic values used for debris flow intensity maps and their threshold to define the intensity class as described in the enforcement aid by BAFU (2025).

| Hauptprozess<br>Main process | Teilprozess<br>Subprocess | Kennwerte<br>Characteristic values                                                                                                                                                                                                                                   | Intensitätsklasse<br>Intensity classes |                                                        |                            | Intensitätsbestimmung<br>für den Teilprozess<br>Intensity determination<br>for the subprocess                                                                                                                                                                                                                                              |
|------------------------------|---------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------|--------------------------------------------------------|----------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                              |                           |                                                                                                                                                                                                                                                                      | schwach<br>weak                        | mittel<br>medium                                       | stark<br>strong            |                                                                                                                                                                                                                                                                                                                                            |
| Wasser<br>Water              | Übermuring<br>Debris flow | Mächtigkeit der Murgangablagerung oder Murganghöhe in der Fließzone: $h_A$<br>Thickness of debris flow deposits or debris flow height in the flow zone: $h_A$                                                                                                        | $\leq 0.5 \text{ m}$                   | 0.5 m bis 2 m                                          | $> 2 \text{ m}$            | Die höchste Einstufung für die Intensitätsklassen der drei Kennwerte ( $h_A$ , $v \cdot h_A$ , und $h_{ER}$ ) ist für die Intensität des Teilprozesses massgebend<br>The highest classification for the intensity classes of the three parameters ( $h_A$ , $v \cdot h_A$ , and $h_{ER}$ ) is decisive for the intensity of the subprocess |
|                              |                           | spezifischer Abfluss des Murgangs: $v \cdot h_A$<br>[mit $v$ = Fließgeschwindigkeit und $h_A$ = Murganghöhe in der Fließzone]<br>Specific discharge of the debris flow: $v \cdot h_A$<br>[where $v$ = flow velocity and $h_A$ = debris flow height in the flow zone] | $\leq 0.25 \text{ m}^2/\text{s}$       | 0.25 $\text{m}^2/\text{s}$ bis 1 $\text{m}^2/\text{s}$ | $> 1 \text{ m}^2/\text{s}$ |                                                                                                                                                                                                                                                                                                                                            |
|                              |                           | Begleitprozess:<br>Erosionstiefe: $h_{ER}$<br>[lotrechte Distanz ab Oberkante der Bodenoberfläche]<br>Accompanying process:<br>Erosion depth: $h_{ER}$<br>[vertical distance from the upper edge of the soil surface]                                                | $\leq 0.5 \text{ m}$                   | 0.5 m bis 2 m                                          | $> 2 \text{ m}$            |                                                                                                                                                                                                                                                                                                                                            |
|                              |                           | Fließgeschwindigkeit: $v$<br>Flow velocity: $v$                                                                                                                                                                                                                      |                                        |                                                        |                            | nur relevant gemäss Datenmodell, nicht für Intensitätseinstufung<br>Only relevant according to data model, not for intensity classification                                                                                                                                                                                                |

In this thesis, the intensity maps are created from the scenario-based simulations using RAMMS Debris Flow. For each catchment and each of the four defined scenarios, the model outputs of maximum deposition height  $h_A$  and maximum flow velocity  $v$  are extracted. Based on these outputs, the corresponding characteristic values, deposition height and specific discharge, are computed and classified into intensity classes according to predefined threshold criteria. The spatial layers representing maximum deposition height and flow velocity are subsequently overlaid to generate intensity maps for each characteristic value.

This procedure results in one intensity map per scenario and per characteristic value. In addition, a synoptic intensity map is created for each scenario by assigning, at every spatial location, the highest intensity class derived from the relevant parameters. The synoptic intensity map therefore represents the maximum relevant process per scenario. The resulting intensity maps provide the methodological basis for the subsequent derivation of hazard maps, where intensity information is combined with the corresponding probability of occurrence.

### 3.4.2 Hazard maps

Hazard maps represent the synthesis of the hazard assessment and constitute the central product for spatial planning, risk management and risk communication. They answer the key question of hazard assessment: Where does a process occur, with which intensity, and with which probability. In Swiss practice hazard levels are derived by systematically combining intensity and occurrence probability within a defined assessment perimeter using an intensity-probability matrix (Bundesamt für Umwelt (BAFU), 2025; Bundesamt für Wasser und Geologie, 2001).

In this thesis two sets of hazard maps are created per catchment, one based on scenarios without considering climate change and the other with climate change adjusted scenarios. The debris flow simulations for the 30-, 100-, 300-year and EHQ scenarios under current and future climate conditions form the basis of the analysis. For each scenario spatial intensity distributions were already classified in the preceding step during the creation of intensity maps. These intensity maps assign each raster cell to one of three intensity classes (weak, medium, strong) based on the simulated maximum process parameters. The probability classification is defined by the selected return periods. The HQ30 scenario corresponds to high probability, the HQ100 scenario to medium probability, the HQ300 scenario to low probability and the EHQ scenario to very low probability.

The hazard level for each raster cell was determined by combining the previously classified intensity with the corresponding probability class using an intensity–probability matrix as shown in Table 5. This matrix systematically links the three intensity classes with the four probability classes and assigns a hazard level. Higher hazard levels result from combinations of high intensity and high probability, whereas low intensity combined with low probability leads to low hazard levels. The classification was implemented in a raster based workflow in R. For each scenario the intensity raster was reclassified according to the intensity–probability matrix, resulting in a hazard raster. The final hazard maps were visualised using the standard Swiss hazard colour scheme.

The resulting hazard maps for the 30-, 100-, 300-year and EHQ scenarios were subsequently compared with the publicly available official hazard maps for each catchment. This comparison allows assessment of whether the simulated hazard levels correspond to those assumed in existing hazard assessments and provides an indication of potential spatial shifts in hazard zones under future climate scenarios, as well as possible under- or overestimation of debris flow hazards in the catchment.

Table 5 Matrix after which the hazard maps were coloured, based on the enforcement aid by BAFU (Bundesamt für Umwelt (BAFU), 2025; Bundesamt für Wasser und Geologie, 2001).

|           |        | HQ30                   | HQ100  | HQ300 | EHQ      |
|-----------|--------|------------------------|--------|-------|----------|
| intensity | strong | 9                      | 8      | 7     |          |
|           | medium | 6                      | 5      | 4     |          |
|           | weak   | 3                      | 2      | 1     |          |
|           |        | high                   | medium | low   | very low |
|           |        | occurrence probability |        |       |          |

The obligation to consider natural hazards in spatial planning was introduced with the revision of the Swiss Federal Act on Spatial Planning (Bundesamt für Raumentwicklung et al., 2000). Since then the cantons have been responsible for preparing and publishing hazard maps for developed areas. While the Confederation provides guidelines and financial support, the implementation and public accessibility of hazard maps lie within cantonal authority (Bundesamt für Umwelt (BAFU), 2025). The aim was to achieve comprehensive hazard map coverage for inhabited areas by around 2005 (BAFU, 2008a) and regularly revised and updated when new events, improved data or methodological developments require adjustments after initial creation.

For the comparison with existing hazard assessments officially published cantonal hazard maps were used for each catchment. For the Schipfenbach and Selderbach, the hazard maps are published by the Canton of Uri and were first created in 2006 with a spatial resolution of 5 m (Kanton Uri, 2026). The hazard map for the Altdorfbach in the Canton of Lucerne was originally created in 2004 and revised in 2012. (Kanton Luzern, 2026; Keller + Lorenz AG & beffa tognacca gmbh, 2012). In the Canton of Bern the hazard map for the Milibach was first established in 2005 and partially revised in 2010 and fully revised in 2012 and 2025 (Liener & Zimmermann, 2013; Niederer und Pozzi Umwelt AG & GEOTEST AG, 2025). For the Buoholzbach in the Canton of Nidwalden, the original creation date is not documented, but a recent revisions were completed in 2025 because of the construction of a new retention basin in the Buoholzbach (Schubiger Bauingenieure AG & Kanton Nidwalden, 2025).

### 3.5 Mitigation measures

Mitigation measures for the protection of settlement areas against natural hazards are a central component of the IRM applied in Switzerland (Bundesamt für Raumentwicklung et al., 2000). In the case of debris flows structural measures typically consist of retention basins, check dams and sediment trapping structures designed to retain or temporarily store mobilised material before it reaches vulnerable areas (Piton et al., 2017). Such measures are dimensioned on the basis of a defined design scenario, which specifies the event magnitude that the structure must safely withstand. The selection of the design scenario depends on the defined protection goal, which is determined according to the value and vulnerability of the protected assets (Bundesamt für Wasser und Geologie, 2001).

The protection goal of an area depends on what it is used for. A matrix as in Figure 14 is used to determine what the protection goal is for chosen area. To determine protection goals five main object categories are differentiated. The main object categories include residential areas, industrial and commercial zones, infrastructure, agricultural land and special objects. Closed settlements as well as industrial and commercial areas are generally to be protected against rare events, while protection goals for infrastructure depend on its national, regional, or local importance, with nationally important infrastructure having a higher protection goal. Agricultural land is protected according to its value and vulnerability, with higher standards applied to high-quality farmland and special objects are to be evaluated on a case to case basis (Bundesamt für Wasser und Geologie, 2001).

Overall, the defined protection goal determines how strongly an area should be protected and therefore directly influences the design of mitigation measures. It provides a clear and consistent basis for deciding which level of risk is considered acceptable.

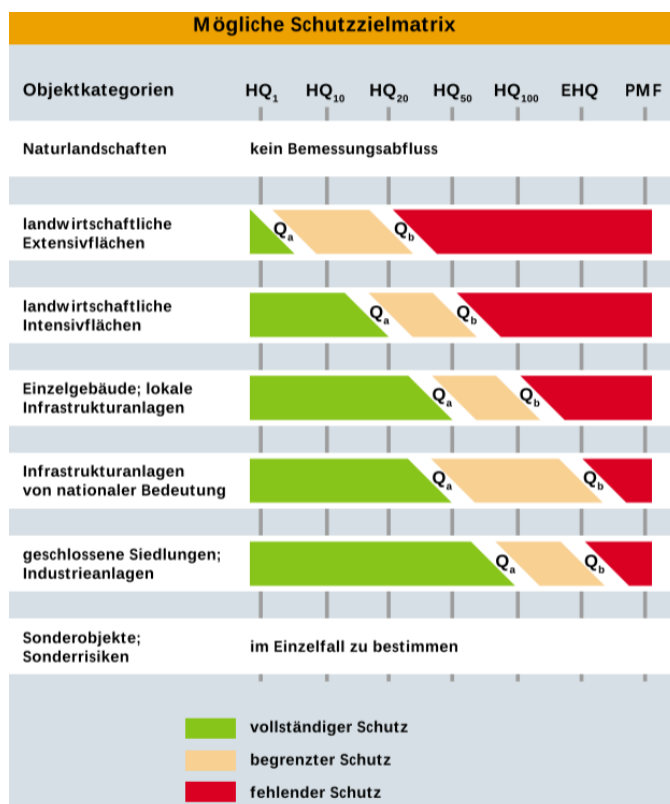


Figure 14 An example of a possible object categorisation for a protection goal matrix as it is used to determine the design scenario for which mitigation measures must be effective against. (Bundesamt für Wasser und Geologie, 2001).



## 4 Results

### 4.1 Scenarios

The first research question can be answered in three parts. First the results of the extreme values statistics are presented, showing the precipitation scenarios, which are the basis of all further scenario calculations. Second the scenarios under the influence of climate change are presented and lastly the discharge and debris flow scenarios both without climate change adjustment and with climate change adjustment.

#### 4.1.1 Precipitation scenarios

To address research question 1) *“What are the 30-, 100- and 300-year debris flow scenarios in the chosen catchments and how might these scenarios change under the influence of climate change?”* extreme precipitation statistics were derived for the two to three automatic MeteoSwiss weather stations that were closest to the five chosen catchments.

For each station, extreme value statistics were calculated using both the Generalized Extreme Value (GEV) approach and the Peaks-Over-Threshold (POT) method to find the precipitation amounts corresponding to return periods of 30, 100 and 300 years. While both approaches provide estimates for defined return periods, the POT method was selected as the reference for subsequent discharge and debris-flow volume calculations. Compared to GEV, which is limited to one maximum per block, in this case per year, the POT method captures multiple independent extreme events above a defined threshold. This is particularly relevant for stations such as Gersau (GES), Bristen (BRT) and Stans (SNS), which provide less than 50 years of observational data and therefore benefit from the larger sample size inherent to the POT approach. It also better represents the reality that more than one extreme precipitation event can occur per year.

The 24-hour precipitation sums for the three defined return periods show substantial differences between GEV and POT methods (Table 6). Across all catchments and stations, return levels using the POT method are consistently higher than those derived from the GEV method. For example, for the 100-year return period, GEV estimates range roughly between 90 mm and 180 mm, whereas POT estimates reach values between approximately 120 mm and 260 mm, depending on station and location. The same trend can be observed with the upper confidence interval (upper ci) where values resulting using the GEV methods are considerably lower than values using the POT method.

Table 6 Results of the extreme value statistic of the 24-hour precipitation sums recorded at the MeteoSchweiz weather stations close to the five catchments studied.

| 24-hour precipitation [mm]   |          |       |       |             |       |                             |       |       |             |       |
|------------------------------|----------|-------|-------|-------------|-------|-----------------------------|-------|-------|-------------|-------|
| Catchment                    | Milibach |       |       | Altdorfbach |       | Selderbach and Schipfenbach |       |       | Buoholzbach |       |
| Meteo-Station                | BRZ      | MER   | INT   | GES         | LUZ   | BRT                         | ALT   | GOS   | SNS         | ENG   |
| return period - GEV          |          |       |       |             |       |                             |       |       |             |       |
| 30-year                      | 86.1     | 80.8  | 85.6  | 140.6       | 88.0  | 115.4                       | 97.4  | 120.1 | 110.4       | 109.4 |
| 100-year                     | 101.4    | 93.8  | 103.3 | 174.1       | 106.0 | 138.8                       | 116.5 | 144.8 | 140.3       | 134.8 |
| 300-year                     | 116.0    | 105.9 | 120.8 | 208.4       | 124.0 | 161.7                       | 134.7 | 169.2 | 174.3       | 160.7 |
| return period - GEV upper ci |          |       |       |             |       |                             |       |       |             |       |
| 30-year                      | 95.6     | 95.9  | 88.4  | 183.8       | 97.9  | 139.5                       | 107.3 | 135.9 | 137.9       | 123.2 |
| 100-year                     | 118.3    | 122.0 | 107.0 | 256.0       | 124.2 | 182.6                       | 133.7 | 174.9 | 195.7       | 161.2 |
| 300-year                     | 142.2    | 150.5 | 125.9 | 342.8       | 153.1 | 231.1                       | 161.1 | 218.0 | 268.9       | 204.4 |
| return period - POT          |          |       |       |             |       |                             |       |       |             |       |
| 30-year                      | 142.5    | 114.7 | 139.3 | 200.1       | 144.1 | 221.7                       | 166.2 | 216.0 | 207.8       | 168.4 |
| 100-year                     | 161.0    | 124.4 | 157.8 | 221.4       | 162.9 | 259.9                       | 191.9 | 248.0 | 247.2       | 193.2 |
| 300-year                     | 178.8    | 133.0 | 175.5 | 240.8       | 180.9 | 298.4                       | 217.3 | 279.1 | 288.0       | 217.4 |
| return period - POT upper ci |          |       |       |             |       |                             |       |       |             |       |
| 30-year                      | 177.1    | 134.8 | 172.0 | 281.9       | 176.9 | 339.8                       | 211.7 | 277.8 | 307.0       | 211.4 |
| 100-year                     | 207.7    | 150.0 | 201.8 | 327.8       | 207.0 | 425.7                       | 254.7 | 332.4 | 389.0       | 252.1 |
| 300-year                     | 238.6    | 164.1 | 231.9 | 372.6       | 237.2 | 518.7                       | 299.3 | 388.4 | 479.3       | 294.1 |

The upper confidence interval estimates is additionally presented, as it is used to define an intensified precipitation scenario representing potential future climate conditions. In contrast, the lower confidence interval is not considered further, since the objective of this study is to assess a possible increase in debris-flow magnitude under increased precipitation extremes rather than reduced extremes .

The large difference between mean values und the upper confidence interval indicates large uncertainty, particularly for higher return periods, demonstrating the statistical sensitivity of extrapolation for rare events. This uncertainty increases with higher return periods, reflecting the limited observational record of very extreme event and the length of the observation period relative to the extrapolation length.

Spatially, the results of the extreme value statistics for the precipitation data somewhat represent the general precipitation distribution in Switzerland (Figure 15). The Stations BRZ, MER, INT and LU are located in comparatively drier areas, characterised by lower annual precipitation totals. In contrast, GOS, BRT, ENG and GES are situated in zones of enhanced orographic precipitation along the Alpine rim and higher elevation regions.

This spatial pattern is largely reflected in the extreme value statistics, but with notable differences between the two methods (GEV and POT). For the GEV approach, the lowest return levels are obtained for BRZ, MER, INT and LU broadly following the annual precipitation distribution. The highest values are obtained for GES, which not entirely follows the annual precipitation distribution, possibly due to an overestimation because of the stations relatively short operation period.

The POT method reveals a slightly different picture. Again, BRZ, MER, INT and LU remain the stations with the lowest extreme precipitation estimates. The highest extreme return levels are found at BRT and GOS (followed by GES and SNS), while ENG and ALT show intermediate values. The divergence between the GEV and POT results can be explained by the number of extreme events considered for the statistic, with the POT method considering multiple event per year, whereas the GEV method only considers the single largest event per year. The spatial divergence between the extreme value statistics results and the annual precipitation distribution suggests that some stations with moderate mean precipitation experience particularly intense short duration extreme events.

Compared with past events, the values derived from the POT method seem to fit observed values better. For example during the 1987 flood 24-hour precipitation sums of 120-160 mm were measured and estimated to equal values with a return period of 10-30 years (Zeller & Röthlisberger, 1988). During the 2005 flood 24-hour sums of 100-130 mm were measured, with some stations measuring up to 240 mm in 24 hours (BAFU, 2007). Those high measurements were estimated to correspond to return periods of 300 years or more. Comparing the observed values and their estimated return periods to the values of Table 6 the POT method seems to better represents return periods of extreme precipitation. For the 30-year return period values calculated using the POT method lie in the same range as observed in 1987 and values of 240 mm/24h correspond to a return period of 300 years or more. The values generated using the GEV method all lie well below observed values.

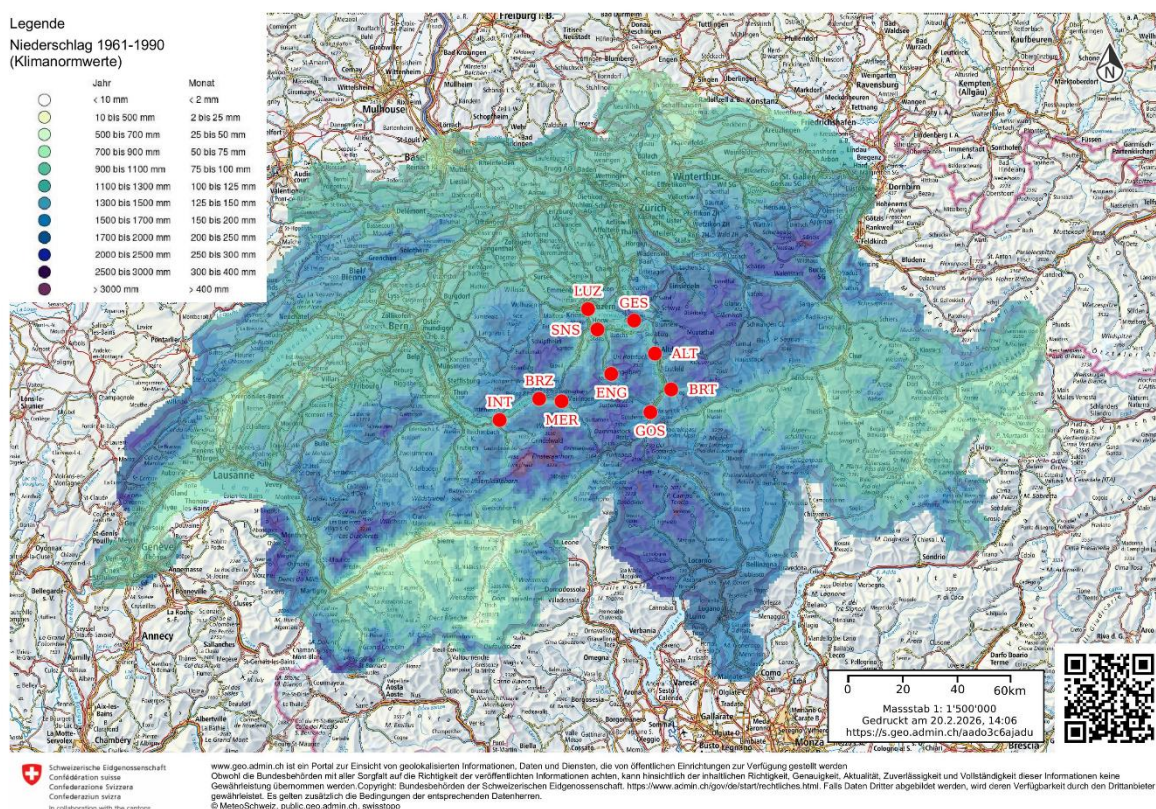


Figure 15 Map of the annual precipitation distribution in Switzerland for the period 1961-1990. As red points are the location of the MeteoSwiss weather station used for this thesis.

In addition to 24-hour precipitation totals, 1-hour precipitation intensities were derived for all stations and return periods. The calculation of short-duration intensities is required for the subsequent discharge estimation using the modified rational method (modifiziertes Fließzeitverfahren).

As for the 24-hour totals, POT based intensity levels consistently exceed GEV estimates across all return periods. For the 100-year return period, 1-hour precipitation intensities generally range between approximately 50–90 mm/h with the POT method, whereas GEV values mostly range around 30–50 mm/h, except for the values derived from the station in Gersau. However this observation matches with those calculated for 24-hour precipitation sums and can most likely be attributed to the short observation period of this station. For the intensities based on 24-hour POT analysis values locally exceed 100 mm/h, especially in the values derived from the upper ci.

Compared with observed precipitation intensities the same trend as with the 24 hour precipitation sums can be observed, where values based on the POT statistic match observed values better. In 1987 precipitation intensities of about 80 mm/h (Bundesamt für Wasserwirtschaft & Bundesamt für Umwelt Wald und Landschaft, 1991) and during in 2024 intensities of 70–100 mm/h were observed. The event in 2024 was determined to correspond to a “very rare” event (Niederer und Pozzi Umwelt AG & GEOTEST AG, 2025), which translates to a return period of 300 years or more. In Table 7 Values in the range of 70–100 mm/h are all produced using POT statistic as a basis and they lie in the range of a 300-year return period or above.

*Table 7 Results of the 1 hour precipitation intensities for each return period calculated from the 24-hour precipitation sums per MeteoSchweiz weather station and catchment.*

| 1-hour precipitation intensity [mm]                    |          |      |      |             |      |            |      |       |              |      |       |             |       |
|--------------------------------------------------------|----------|------|------|-------------|------|------------|------|-------|--------------|------|-------|-------------|-------|
| Catchment                                              | Milibach |      |      | Altdorfbach |      | Selderbach |      |       | Schipfenbach |      |       | Buoholzbach |       |
| Meteo-Station                                          | BRZ      | MER  | INT  | GES         | LUZ  | BRT        | ALT  | GOS   | BRT          | ALT  | GOS   | SNS         | ENG   |
| return period - GEV                                    |          |      |      |             |      |            |      |       |              |      |       |             |       |
| 30-year                                                | 34.6     | 32.5 | 34.4 | 55.9        | 35.0 | 31.2       | 32.5 | 26.3  | 31.5         | 32.7 | 26.6  | 38.5        | 38.2  |
| 100-year                                               | 40.8     | 37.7 | 41.6 | 69.3        | 42.2 | 37.5       | 39.2 | 31.5  | 37.9         | 39.5 | 31.8  | 49.0        | 47.1  |
| 300-year                                               | 46.7     | 42.6 | 48.6 | 82.9        | 49.3 | 43.7       | 45.7 | 36.4  | 44.1         | 46.1 | 36.7  | 60.9        | 56.1  |
| return period - GEV upper ci (climate change scenario) |          |      |      |             |      |            |      |       |              |      |       |             |       |
| 30-year                                                | 38.5     | 38.6 | 35.6 | 73.1        | 38.9 | 37.7       | 29.0 | 36.7  | 38.0         | 29.3 | 37.1  | 48.1        | 43.0  |
| 100-year                                               | 47.6     | 49.1 | 43.0 | 101.8       | 49.4 | 49.4       | 36.1 | 47.3  | 49.8         | 36.5 | 47.7  | 68.3        | 56.3  |
| 300-year                                               | 57.2     | 60.6 | 50.7 | 136.4       | 60.9 | 62.5       | 43.6 | 58.9  | 63.0         | 44.0 | 59.5  | 93.9        | 71.4  |
| return period - POT                                    |          |      |      |             |      |            |      |       |              |      |       |             |       |
| 30-year                                                | 57.3     | 46.2 | 56.1 | 79.6        | 57.3 | 59.9       | 44.9 | 58.4  | 60.5         | 45.3 | 58.9  | 72.5        | 58.8  |
| 100-year                                               | 64.8     | 50.1 | 63.5 | 88.1        | 64.8 | 70.3       | 51.9 | 67.1  | 70.9         | 52.3 | 67.6  | 86.3        | 67.4  |
| 300-year                                               | 71.9     | 53.5 | 70.6 | 95.8        | 72.0 | 80.7       | 58.7 | 75.5  | 81.4         | 59.3 | 76.1  | 100.5       | 75.9  |
| return period - POT upper ci (climate change scenario) |          |      |      |             |      |            |      |       |              |      |       |             |       |
| 30-year                                                | 71.2     | 54.2 | 69.2 | 112.1       | 70.4 | 91.9       | 57.3 | 75.1  | 92.7         | 57.8 | 75.8  | 107.2       | 73.8  |
| 100-year                                               | 83.6     | 60.4 | 81.2 | 130.4       | 82.3 | 115.1      | 68.9 | 89.9  | 116.1        | 69.5 | 90.7  | 135.8       | 88.0  |
| 300-year                                               | 96.0     | 66.0 | 93.3 | 148.2       | 94.3 | 140.3      | 80.9 | 105.0 | 141.5        | 81.6 | 105.9 | 167.3       | 102.7 |



### 4.1.2 Discharge scenarios

The peak discharges are derived using the modified rational method (modifiziertes Fliesszeitverfahren) and show a clear scaling with catchment size and precipitation scenario.

For the current climate scenarios, peak discharges (HQ30–HQ300) range between 12–16 m<sup>3</sup>/s for the smallest catchments (Schipfenbach, Selderbach), 31–53 m<sup>3</sup>/s for Milibach and Altdorfbach, and up to 150–205 m<sup>3</sup>/s for Buoholzbach, the largest catchment. The extreme scenario (EHQ) results in substantially higher values and the same scaling dependent on catchment size, which is logical as it was calculated by doubling the HQ100. The same is true for the peak discharge calculations using the intensified precipitation scenarios.

The reconstructed peak discharge of 35–45 m<sup>3</sup>/s for the Milibach event of the 12. August 2024 lies between the calculated HQ30 and HQ100 values under present day conditions. This indicates that the scenarios in Table 8 might overestimate the pure water discharge slightly as the event was estimate to correspond to a 100-300-year event. However, as there are no other records or estimates of pure water discharge for any of the other catchments this statement cannot be verified further.

*Table 8 Results for pure water discharge for each catchment derived from precipitation intensities based on the POT analysis. The discharge values were first calculated per intensity of each station per catchment and then averaged.*

| pure water discharge [m <sup>3</sup> /s] |          |             |            |              |             |
|------------------------------------------|----------|-------------|------------|--------------|-------------|
| catchment                                | Milibach | Altdorfbach | Selderbach | Schipfenbach | Buoholzbach |
| scenario without climate change          |          |             |            |              |             |
| HQ30                                     | 42.8     | 31.6        | 16.1       | 12.3         | 152.3       |
| HQ100                                    | 47.9     | 35.3        | 18.6       | 14.2         | 178.2       |
| HQ300                                    | 52.7     | 38.7        | 21.1       | 16.2         | 204.6       |
| EHQ                                      | 95.8     | 70.6        | 37.2       | 28.4         | 356.5       |
| scenario with climate change             |          |             |            |              |             |
| HQ30                                     | 52.3     | 29.8        | 22.1       | 16.9         | 209.8       |
| HQ100                                    | 60.5     | 36.0        | 27.0       | 20.6         | 259.5       |
| HQ300                                    | 68.6     | 42.5        | 32.1       | 24.5         | 313.0       |
| EHQ                                      | 120.9    | 72.0        | 53.9       | 41.2         | 518.9       |

### 4.1.3 Debris flow scenarios

The debris flow scenarios were derived from the previously calculated peak discharges. To represent debris flow conditions, a sediment fraction of 40% was added to the pure water discharge. The resulting peak discharges were then used to estimate debris-flow volumes based on the empirical relationship proposed by Rickenmann.

Under conditions without increased precipitation (Table 9 and Table 10) expected debris flow volumes increase consistently with return period across all catchments. The same is true for the debris flow volumes calculated from the increased precipitation scenarios (Table 11 and Table 12).



For Milibach, volumes range from approximately 34,000 m<sup>3</sup> (HQ30) to 94,000 m<sup>3</sup> (EHQ). Altdorfbach shows comparable behaviour with volumes between 23,000 m<sup>3</sup> (HQ30) and 64,000 m<sup>3</sup> (EHQ). The smaller catchments (Selderbach and Schipfenbach) produce volumes below 15'000 m<sup>3</sup> (HQ300) with EHQ smaller than 30,000 m<sup>3</sup>, whereas Buholzbach reaches substantially larger values between 1700'000 m<sup>3</sup> (HQ30) and 250'000 m<sup>3</sup> (HQ300) with the EHQ reaching about 500'000 m<sup>3</sup>.

Including the intensified scenarios (Table 11 and Table 12), representing a warmer climate, a systematic increase in both peak discharge and estimated debris-flow volumes can be observed. For Milibach, volumes range between 45'000 m<sup>3</sup> (HQ30) and 125'000 m<sup>3</sup> (EHQ) and Selderbach and Schipfenbach have volume ranges of 10'000 m<sup>3</sup> to 25'000 m<sup>3</sup>. The strongest increase occurs in Buholzbach, where the EHQ volume increases from roughly 500,000 m<sup>3</sup> to more than 800,000 m<sup>3</sup>.

Overall, the results show a non-linear amplification of debris-flow volumes with increasing peak discharge, reflecting the exponential nature of the Rickenmann relation. The climate adjusted scenarios therefore lead to considerably larger debris flow volumes.

The estimated debris-flow volumes are within a realistic range when compared to documented Swiss events: during the summer of 1987, around 600 debris flows were mapped, including more than 100 events exceeding 1,000 m<sup>3</sup>, about 20 larger than 10,000 m<sup>3</sup>, and three events exceeding 100,000 m<sup>3</sup> (Bundesamt für Wasserwirtschaft & Bundesamt für Umwelt Wald und Landschaft, 1991), which is consistent with the upper range of the simulated volumes in the larger catchments. While the overall magnitude of the calculated volumes is consistent with documented Swiss debris flow activity, a catchment-specific evaluation provides a more detailed assessment of their plausibility.

Table 9 Total maximum discharge values including sediment. The sediment share corresponds to 40% of the water discharge and is then added to the water discharge.

| Maximum Discharge [m <sup>3</sup> /s] - no climate change adjustment |           |             |            |              |            |
|----------------------------------------------------------------------|-----------|-------------|------------|--------------|------------|
|                                                                      | Catchment |             |            |              |            |
| Scenario                                                             | Milibach  | Altdorfbach | Selderbach | Schipfenbach | Buholzbach |
| HQ30                                                                 | 71.41     | 52.72       | 26.79      | 20.46        | 253.79     |
| HQ100                                                                | 79.82     | 58.86       | 31.03      | 23.70        | 297.08     |
| HQ300                                                                | 87.75     | 64.58       | 35.25      | 26.92        | 340.94     |
| EHQ                                                                  | 159.64    | 117.71      | 62.07      | 47.40        | 594.15     |

Table 10 Total volume of debris flows using the Ricknemann relation.

| Volume [m <sup>3</sup> ] - no climate change adjustment |           |             |            |              |            |
|---------------------------------------------------------|-----------|-------------|------------|--------------|------------|
|                                                         | Catchment |             |            |              |            |
| Scenario                                                | Milibach  | Altdorfbach | Selderbach | Schipfenbach | Buholzbach |
| HQ30                                                    | 34'024.43 | 23'240.54   | 9'845.46   | 6'998.54     | 169'454.60 |
| HQ100                                                   | 39'200.53 | 26'702.39   | 11'863.96  | 8'433.36     | 206'978.93 |
| HQ300                                                   | 44'225.59 | 30'016.38   | 13'941.08  | 9'909.86     | 246'577.62 |
| EHQ                                                     | 94'263.30 | 64'209.73   | 28'528.58  | 20'279.23    | 497'710.45 |

Table 11 Total maximum discharge values including sediment based on the increased precipitation scenarios. The sediment share corresponds to 40% of the water discharge and is then added to the water discharge

| Maximum Discharge [m³/s] - including climate change adjustment |           |             |            |              |             |
|----------------------------------------------------------------|-----------|-------------|------------|--------------|-------------|
|                                                                | Catchment |             |            |              |             |
| Scenario                                                       | Milibach  | Altdorfbach | Selderbach | Schipfenbach | Buoholzbach |
| HQ30                                                           | 87.14     | 70.27       | 36.78      | 28.09        | 349.69      |
| HQ100                                                          | 100.78    | 81.91       | 44.92      | 34.30        | 432.45      |
| HQ300                                                          | 114.28    | 93.40       | 53.51      | 40.86        | 521.67      |
| EHQ                                                            | 201.55    | 163.82      | 89.84      | 68.61        | 864.89      |

Table 12 Total volume of debris flows using the Ricknemann relation, based on the increased precipitation scenarios.

| Volume [m³] - including climate change adjustment |            |             |            |              |             |
|---------------------------------------------------|------------|-------------|------------|--------------|-------------|
|                                                   | Catchment  |             |            |              |             |
| Scenario                                          | Milibach   | Altdorfbach | Selderbach | Schipfenbach | Buoholzbach |
| HQ30                                              | 43'810.48  | 33'582.04   | 14'758.53  | 10'490.94    | 255'244.77  |
| HQ100                                             | 52'716.38  | 40'764.88   | 19'030.43  | 13'527.57    | 334'629.55  |
| HQ300                                             | 61'878.80  | 48'117.43   | 23'775.67  | 16'900.67    | 425'150.85  |
| EHQ                                               | 126'764.08 | 98'025.00   | 45'761.40  | 32'528.99    | 804'664.65  |

The Milibach catchment generally exhibits low debris-flow activity, with documented events only in 2022 and 2024, with the 2022 event being minor depositing approximately 2'500 m³ in the retention basin (Bundesamt für Umwelt BAFU, 2026). In contrast, the 2024 event mobilised the sediment depot below the waterfall and resulted in an estimated total deposition of approximately 65'000 m³. Based on hydrological reconstruction, this event was estimated to correspond to a very rare event (HQ300) or a smaller extreme scenario (EHQ) (Niederer und Pozzi Umwelt AG & GEOTEST AG, 2025). This assessment aligns well with the modelled debris-flow volumes, where the simulated HQ300 to EHQ range for the Milibach lies between about 45'000 m³ and 95'000 m³ under present day conditions, and between 62'000 m³ and 130'000 m³ when intensification due climate change is considered.

The Altdorfbach has also not exhibited frequent activity in the last decade with only one documented debris flow in 2005 (WSL, 2025), however without information on deposited volume or discharge. Therefore the results cannot be compared to past events.

The Selderbach catchment exhibits regular debris flow activity, however most historical events lack estimates of deposited volume or peak discharge. A major event recorded in 1882 is estimated to have deposited approximately 35'000 m³ of material. More recent events include the 2005 flood, during which around 27'000 m³ of sediment was deposited, and an event in 2023 with an estimated volume of 18'000 m³ (Bundesamt für Umwelt BAFU, 2026). These observed volumes are larger than the simulated debris flow volumes derived in this study for any of the return periods. As an example, the 2005 event, which was considered to be a 100-year flood would correspond to an extreme scenario (EHQ) under current climate or between the 300-year (HQ300) and extreme (EHQ) scenarios when climate change is considered. This discrepancy suggests that the applied method for estimating debris flow volumes might substantially underestimate actual debris flow volumes in the Selderbach catchment.

The Schipfenbach catchment exhibits regular debris flow activity. Smaller to medium-sized events have repeatedly occurred, such as in 1994 and 2000, with estimated deposition volumes of about 6'500 m<sup>3</sup> and 6'000 m<sup>3</sup>, respectively (Rickenmann et al., 2001). This would put them around a small 30-year event following the scenarios defined without climate adjustment. The medium sized event of 1968 deposited 10'000 m<sup>3</sup> and the events in 1991 and 2022 debris flows deposited around 15'000 m<sup>3</sup> (Bundesamt für Umwelt BAFU, 2026; Rickenmann et al., 2001). Without climate change adjustments they would correspond to 300-year to extreme event and with climate change adjustments they would lie between HQ30 and HQ300. The larger events in 1987, where 50'000 m<sup>3</sup> were deposited and the most significant historical event in 1977, with reported deposition volumes ranging between 50'000 m<sup>3</sup> – 80'000 m<sup>3</sup>, and in some sources even up to 9'000 m<sup>3</sup> (MeteoSchweiz, 2026b; Rickenmann et al., 2001) are both more than double the EHQ under current climate and also much larger than the EHQ with climate change. This comparison suggests that the calculated debris flow scenarios underestimate the debris flow potential of the Schipfenbach catchment, at least in relation to extreme events.

Known to generate devastating floods and debris flows the earliest account of an event in the Buoholzbach was documented in 1762, three events in the nineteenth century and four events in the twentieth century (Culman, 1864). In 1984 two events occurred with the first in July depositing 10'000 m<sup>3</sup> and the second in August depositing 15'000 m<sup>3</sup>. During the 100-year flood in August 2005 the Buoholzbach produced a debris flow depositing 70'000 m<sup>3</sup> sediment (WSL, 2025). All past events with estimates of deposition volumes are much smaller than any of the here estimated scenarios, with the HQ100 without climate change adjustment being nearly three times larger than what was measured in 2005. This suggests that the method applied here to estimate debris flow scenarios might overestimate the debris flow potential of the Buoholzbach.

## 4.2 Comparison Hazard maps

To answer the second question *“Do the hazard maps in the chosen catchments assume similar dimensions for the different debris flow scenarios?”* the hazard maps published by the cantons are compared to the hazard maps created using the simulation of the above presented scenarios. The hazard maps are compared for each catchment. Some variation in colour design of the hazard maps created by the cantons exist, but the same principles are applied everywhere, making them comparable even though they do not look the same.

For the Milibach in Brienz official hazard maps are published by the Canton of Bern and are publicly available on the Canton's GIS portal. The hazard map from the GIS portal are compared with the hazard maps created from the simulations of the debris flow scenarios for the Milibach. Figure 16 presents the debris-flow hazard maps derived from the simulations, a) without climate change adjustment and b) with climate change adjustment. Figure 17 shows the official cantonal hazard map for the process water, of which debris flow is considered a sub-process. Also included in the official cantonal hazard maps are dangers posed by the lake.

The hazard maps derived from the simulations show a spatial extent comparable to the official cantonal hazard map. Differences between the climate scenarios are primarily visible in the extent of the red zone (high hazard), with the climate change adjusted scenarios producing larger areas in red. Compared to the cantonal hazard map, the simulation based maps indicate a more extensive blue zone (medium hazard) between the lake and the railway line. In contrast, the official cantonal map displays a larger red zone, particularly towards the east along a road, whereas the simulation based

maps classify this area as blue or, in the case of the simulation without climate change adjustment, partly even as yellow zones (low hazard).

For the Altdorfbach in Vitznau the Canton of Luzern publishes the official hazard maps. They are publicly available on the cantonal GIS portal. For this catchment too, the official hazard maps are compared to the hazard maps created from the debris flow scenario simulations of the Altdorfbach. Figure 18 presents the hazard maps based on the debris flow scenario simulations with a) using current climate scenarios and b) using scenarios adjusted for climate change. Figure 19 presents the official cantonal hazard map for the process water, including the subprocess debris flow in pink outside of populated areas. The hazard map by the Canton does not exclusively show hazards associated with the Altdorfbach, but also by the surrounding torrents and the lake.

The hazard maps created from the scenario simulations show a slightly smaller spatial extent than the area attributed to the Altdorfbach on the official maps. Between the climate scenarios there is a considerable difference in the extent of the blue and yellow zone, both being considerably larger in b) than in a). The special extent of the area associated with the zone of residual risk (light yellow) does not change much between a) and b). Comparing the simulation based hazard maps to the official hazard map the red zone in the official map is especially larger and towards the lake both the red and the blue zone are considerably larger in the official map. In general the official map expects the Altdorfbach to flow further towards the north than the simulation based maps. It is possible that this difference is due to the official map displaying all the hazards categorised under the main process water, while the simulation based maps only display the subprocess debris flow.

For the Selderbach in Silenen the official hazard maps are published by the Canton of Uri on their GIS portal. The official hazard maps of this catchment are compared the hazard maps derived from the debris flow scenario simulation. In Figure 20 the hazard maps for the debris flow scenarios a) without climate adjustment and b) with climate adjustment are presented and in Figure 21 the cantonal hazard maps for the subprocess debris flow are presented. The Canton of Uri publishes separate hazard maps for the different subprocess to the main process water. They also use a slightly different colour scale, but still within the main colours associated with hazard maps in Switzerland.

Ignoring the colour scale, the hazard maps created from the debris flow scenario simulations show a similar spatial extent to the official hazard maps, especially the simulations using climate adjusted scenarios. However, what is classified as a red or blue zone in the official maps is only a yellow zone or zone of residual risk, showing a rather large discrepancy between the official scenarios and the scenarios created in this thesis. A difference in spatial extent is also visible between the hazard maps based on the simulations, with a) covering a smaller extent than b). For a) there are also no red or blue zones outside of the retention basin, whereas in b) the channel of the Selderbach below the retention basin is classified as a red or blue zone.

The Schipfenbach lies also in the municipality of Silenen in the Canton of Uri, therefore the official hazard map for this torrent is also published by the Canton Uri and publicly available on the GIS portal of the Canton. The hazard maps based on the debris flow scenario simulations are presented in Figure 22 showing a) the scenarios without climate adjustment and b) with climate adjustment and compared to the official hazard map for the subprocess debris flow in Figure 23.

The hazard maps based on the simulation show a clearly smaller extent than the official maps, as none of the simulated scenarios leave the retention basin. Compared to the official map large areas below the retention basin are either red or blue zone, areas with high or medium danger from debris flows. This discrepancy between the official hazard maps and the hazard maps based on the scenario simulations can only be explained by the difference in design scenarios. There is also not considerable difference between the hazard maps based on the simulations, only the area associated with residual risk being slightly larger in b) than a).

For the Buoholzbach the Canton of Nidwalden is responsible for the hazard maps and published them on their Geo portal, where they are publicly available. The hazard maps based on the debris flow scenario simulations are shown in Figure 24 including in a) scenarios under current climate and in b) scenarios affected by climate change. In Figure 25 the official hazard map of the areas affected by the Buoholzbach. The official map displays the hazards posed by the main process water including all subprocesses. It therefore also shows the hazards posed by the river Engelberger Aa as well as the surrounding torrents. It is not entirely clear which areas are affected by the Buoholzbach and which might also be affected by other sources.

The official hazard map and the maps based on the scenario simulations show more or less a similar extent this is especially true for the climate adjusted scenario based map b). The main difference in the overall extent between the maps is that the official map displays a larger red zone towards the north, where the Buoholzbach and the Engelberger Aa meet. This could be due to interactions of the two, as the official map includes all water based hazards. A difference between the hazard maps based on the scenario simulations can be found in the overall spatial extent with a) being slightly smaller than b). For the areas classified as red zone a) shows a considerably smaller extent than b).

In general it can be said that the hazard maps created from the scenario simulations for the Milibach, Altdorfbach and Buoholzbach seem to have a similar spatial extent with some differences in zone classification. This could be attributed to the spatial resolution. The simulation were made with a spatial resolution of two meters. The Canton of Luzern states that the spatial resolution of its hazard map is five meters (Kanton Luzern, 2026). Using a resolution of five meters for the simulations, the spatial extent of the affected areas are slightly larger than with a resolution of two meters, especially for the smaller scenarios which contribute to the red and blue zones.

For the Selderbach and Schipfenbach the official hazard maps cover a larger extent in general in addition to the extent being classified mostly as red and blue zones, whereas the hazard maps from the simulations either don't display any risk or only residual risks. This can most likely be attributed to the underlying scenarios for the simulations underestimating the potential hazard posed by the two torrents, as well as the spatial resolution. Simulations with a spatial resolution of five meters for the two torrents yield larger extents of affected areas than what is present in the hazard maps in Figure 20 and Figure 22.



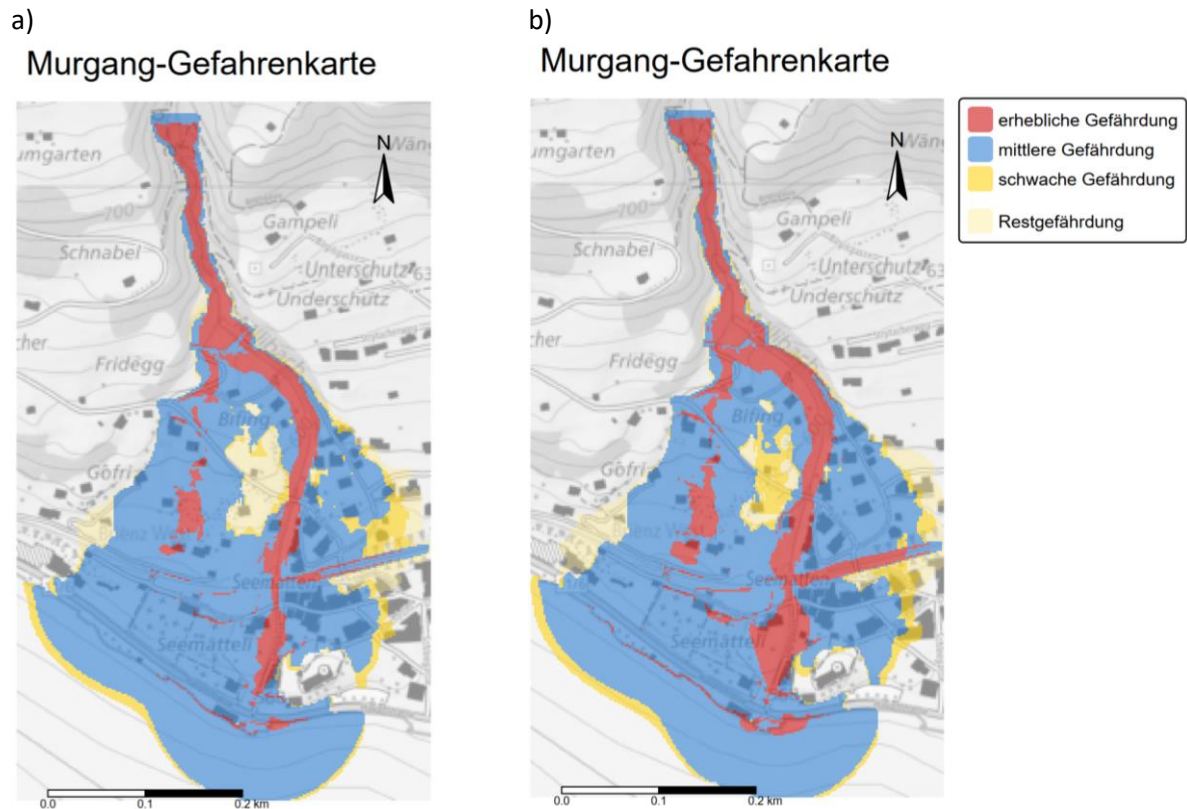


Figure 16 Debris flow hazard Maps of the populated areas affected by the Milibach derived from simulations based on the calculated scenarios. a) debris flow hazard map from scenarios without climate change adjustment b) debris flow hazard maps from scenarios with climate change adjustment.

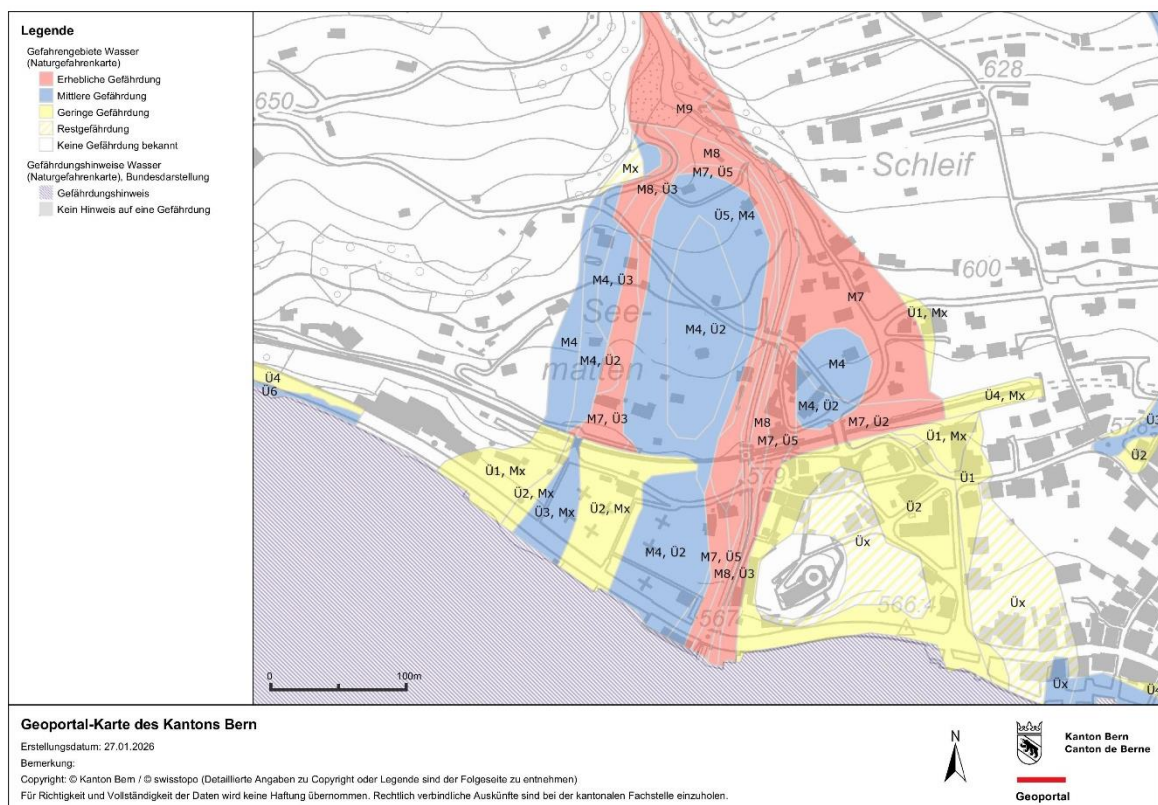
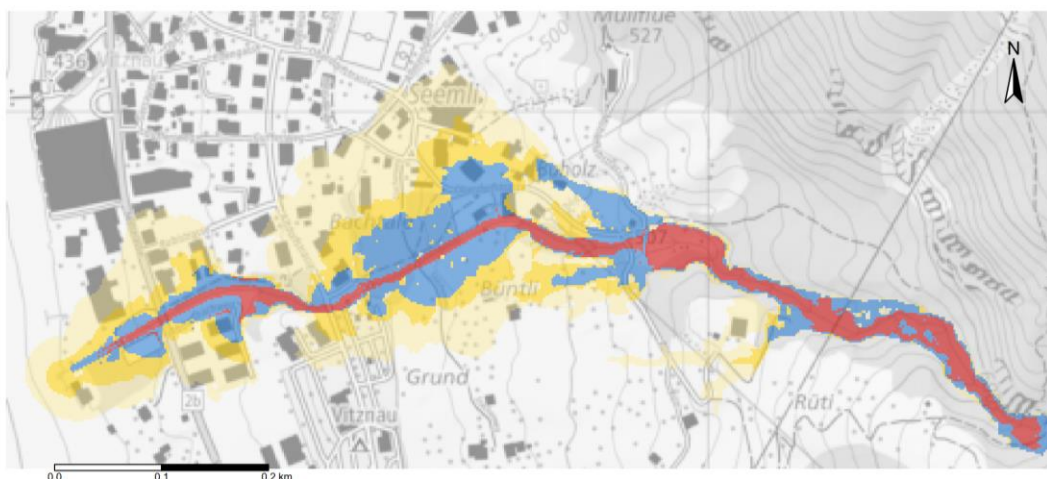


Figure 17 Water hazard map (including debris flow) for the populated areas affected by the Milibach, as published by the canton Bern (Kanton Bern, 2026).

## a) Murgang-Gefahrenkarte



## b) Murgang-Gefahrenkarte

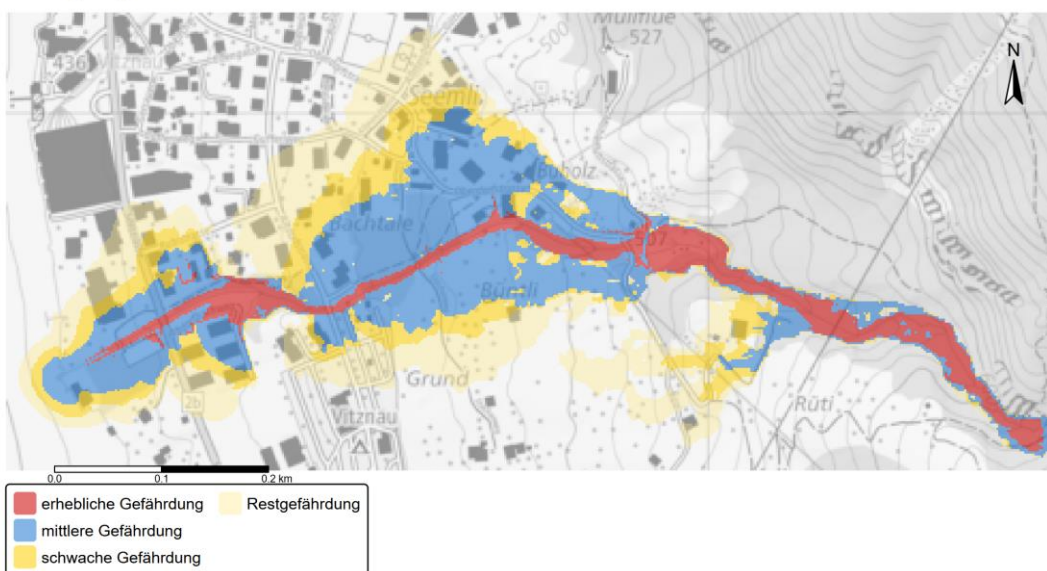


Figure 18 Debris flow hazard Maps of the populated areas affected by the Altdorfbach derived from simulations based on the calculated scenarios. a) debris flow hazard map from scenarios without climate change adjustment b) debris flow hazard maps from scenarios with climate change adjustment.

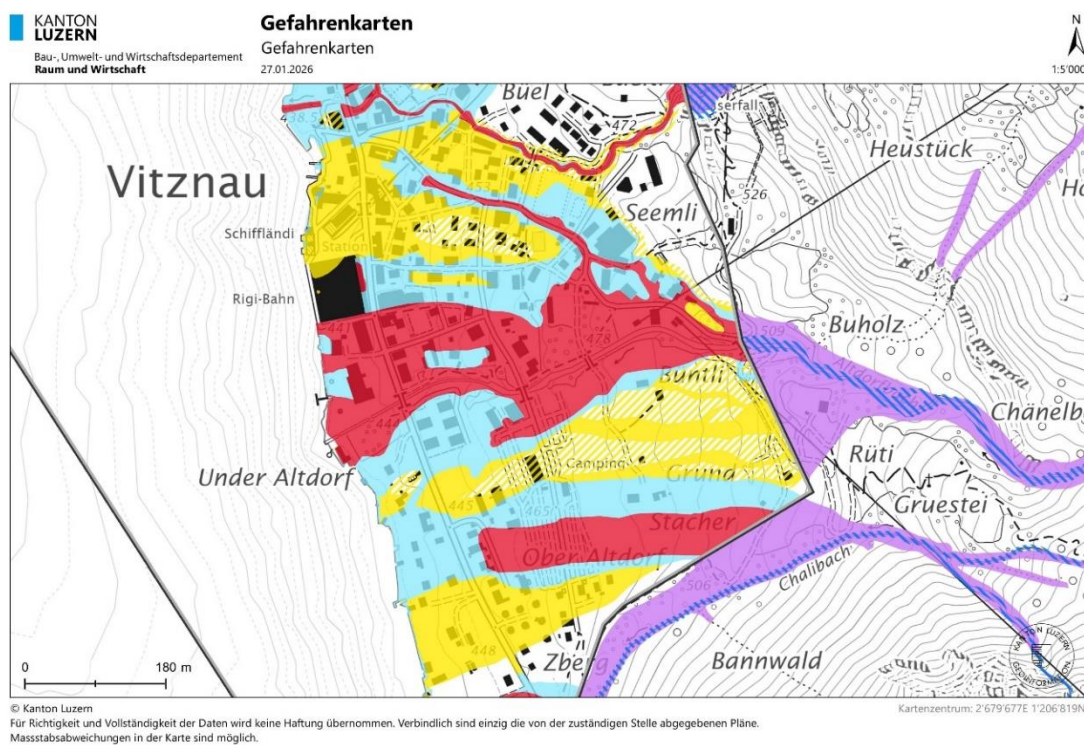
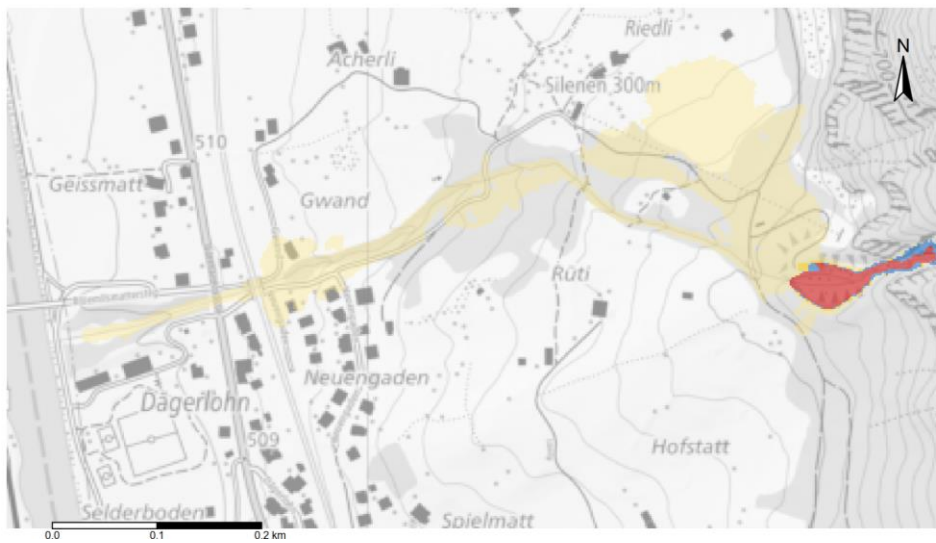


Figure 19 Water hazard map (including debris flow) for the populated areas affected by the Altdorfbach, as published by the canton Luzern (Kanton Luzern, 2026).



## a) Murgang-Gefahrenkarte



## b) Murgang-Gefahrenkarte

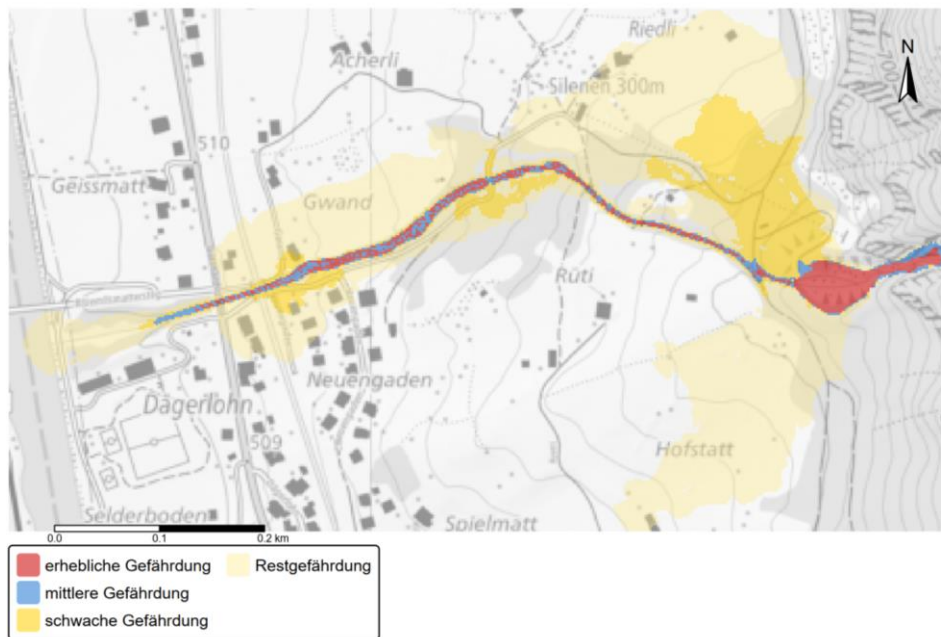


Figure 20 Debris flow hazard Maps of the populated areas affected by the Selderbach derived from simulations based on the calculated scenarios. a) debris flow hazard map from scenarios without climate change adjustment b) debris flow hazard maps from scenarios with climate change adjustment.

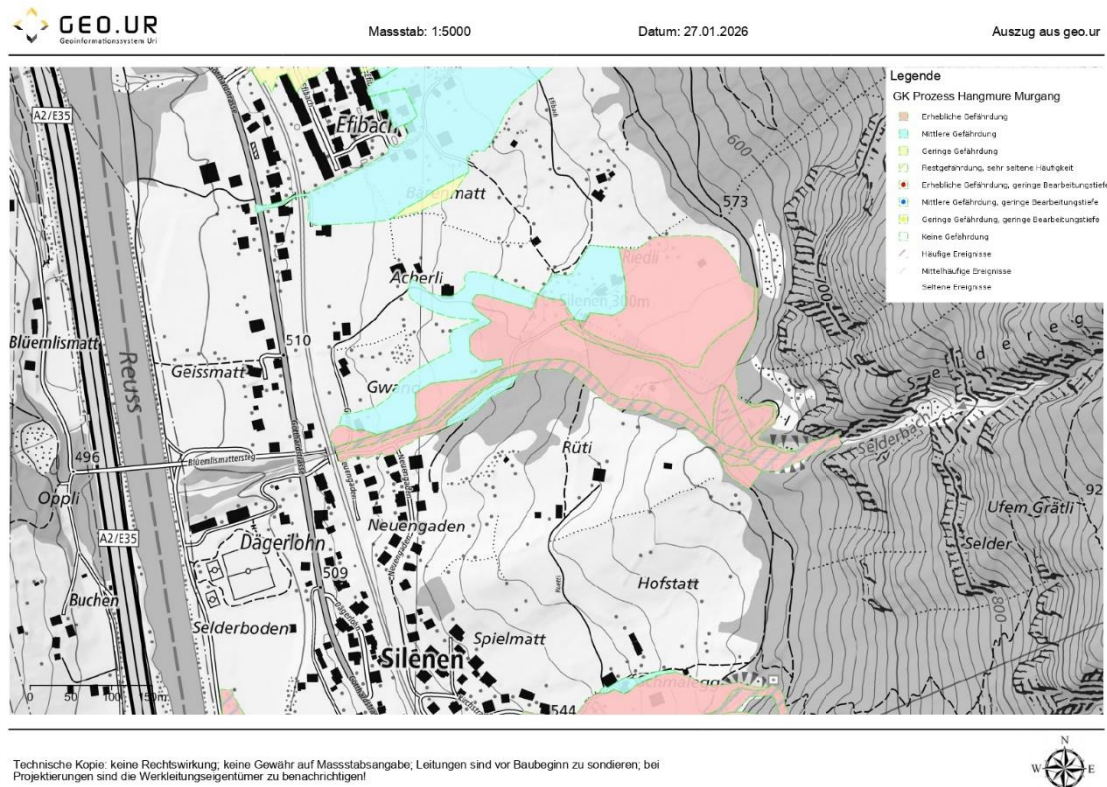


Figure 21 Debris flow hazard map for the populated areas affected by the Selderbach, as published by the Canton Uri (Kanton Uri, 2026).

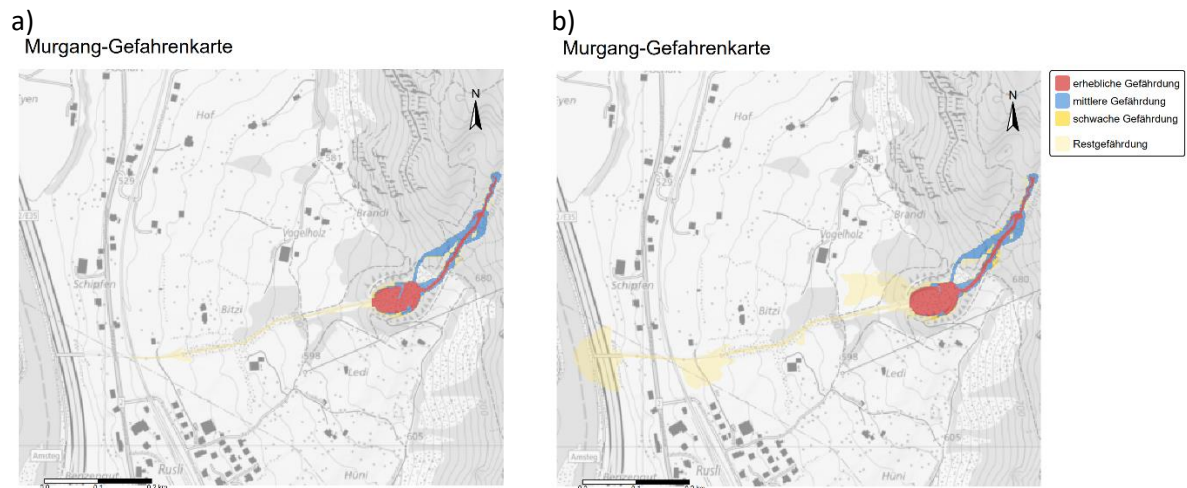


Figure 22 Debris flow hazard Maps of the populated areas affected by the Schipfenbach derived from simulations based on the calculated scenarios. a) debris flow hazard map from scenarios without climate change adjustment b) debris flow hazard maps from scenarios with climate change adjustment.



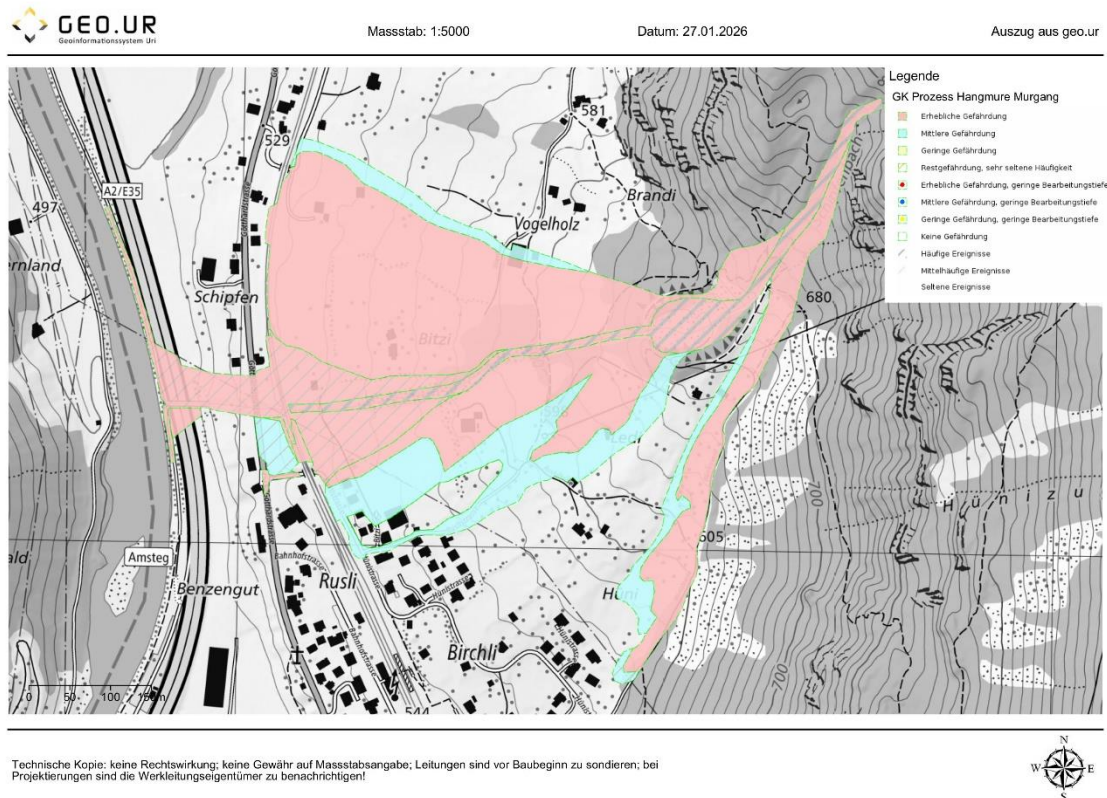


Figure 23 Debris flow hazard map for the populated areas affected by the Schipfenbach, as published by the Canton Uri (Kanton Uri, 2026).

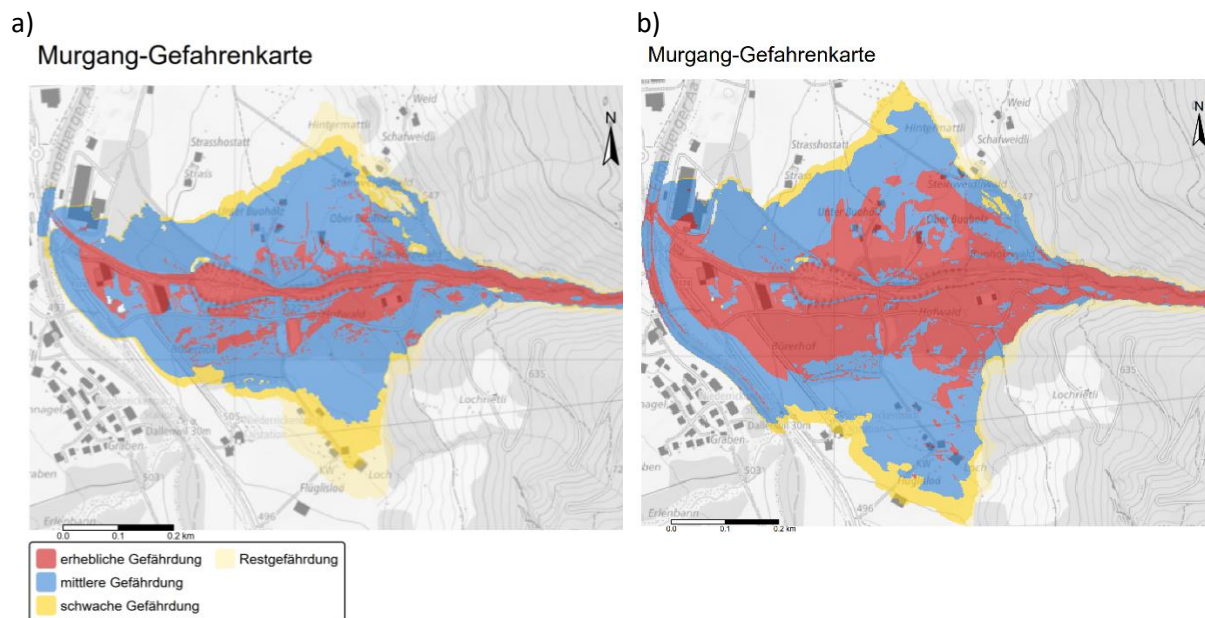


Figure 24 Debris flow hazard Maps of the populated areas affected by the Buoholzbach derived from simulations based on the calculated scenarios. a) debris flow hazard map from scenarios without climate change adjustment b) debris flow hazard maps from scenarios with climate change adjustment.

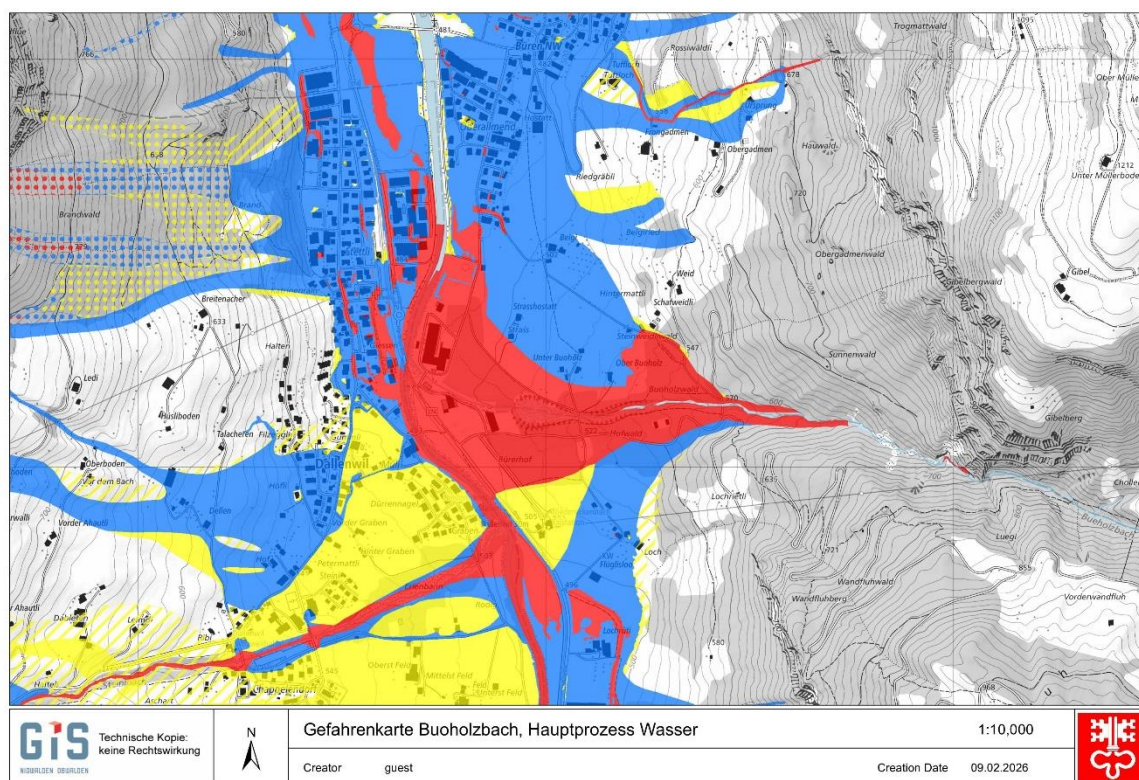


Figure 25 Water hazard map (including debris flow) for the populated areas affected by the Buholzbach, as published by the Canton Nidwalden (Kanton Nidwalden, 2026).

### 4.3 Protection measures

To answer the third research question “Are the protection measures (existing or planned) capable of sufficiently mitigating current and future scenarios?” the intensity maps of each catchment are looked at, as they show the by the process affected areas for each scenario.

The typical protection goal for populated areas is to ensure protection against an event with a 100-year return period. In this study, the 100-year scenario was therefore analysed both under present day conditions and with climate change adjustment. For catchments with plans to change the mitigation measures, both existing and future measures are looked at, however only for the plans in the Altdorfbach simulation for both structures were made, as it is the only catchment where exact plans were provided, allowing for implementation of the planned structure in RAMMS.

The intensity maps for the HQ100 scenario for the Milibach (Figure 26) indicate that the existing sediment retention basin reduces debris flow intensity but does not fully prevent flow propagation across the fan area. The highest intensities below the retention dam occur in along the main channel and in some areas to the west of the main channel in a straight line between retention dam and the lake. For the scenario considering climate change the train tracks crossing the Milibach channel also lie in areas of high intensity. This suggests that, although the basin attenuates peak discharge and sediment load to some extent, it does not entirely eliminate the hazard of a debris flow events with a return period of 100 years.



For a protection goal defined as complete protection against HQ100, the results are therefore not satisfactory. While some of the flow is controlled within the channel system, considerable hazard still remains in areas of the fan that are used for settlement and infrastructure. In particular, the presence of high and medium intensities outside of the retention basin and main channel indicates that material deposition and overbank spreading would still occur, implying potential danger to life and infrastructure.

Overall, the intensity maps demonstrate a substantial protection deficit with the current mitigation measures for both current and future climate conditions. Achieving full protection against a 100-year event would likely require either an increase in retention capacity, improved flow confinement, or additional guiding and overflow management measures to prevent lateral spreading into the settlement area.

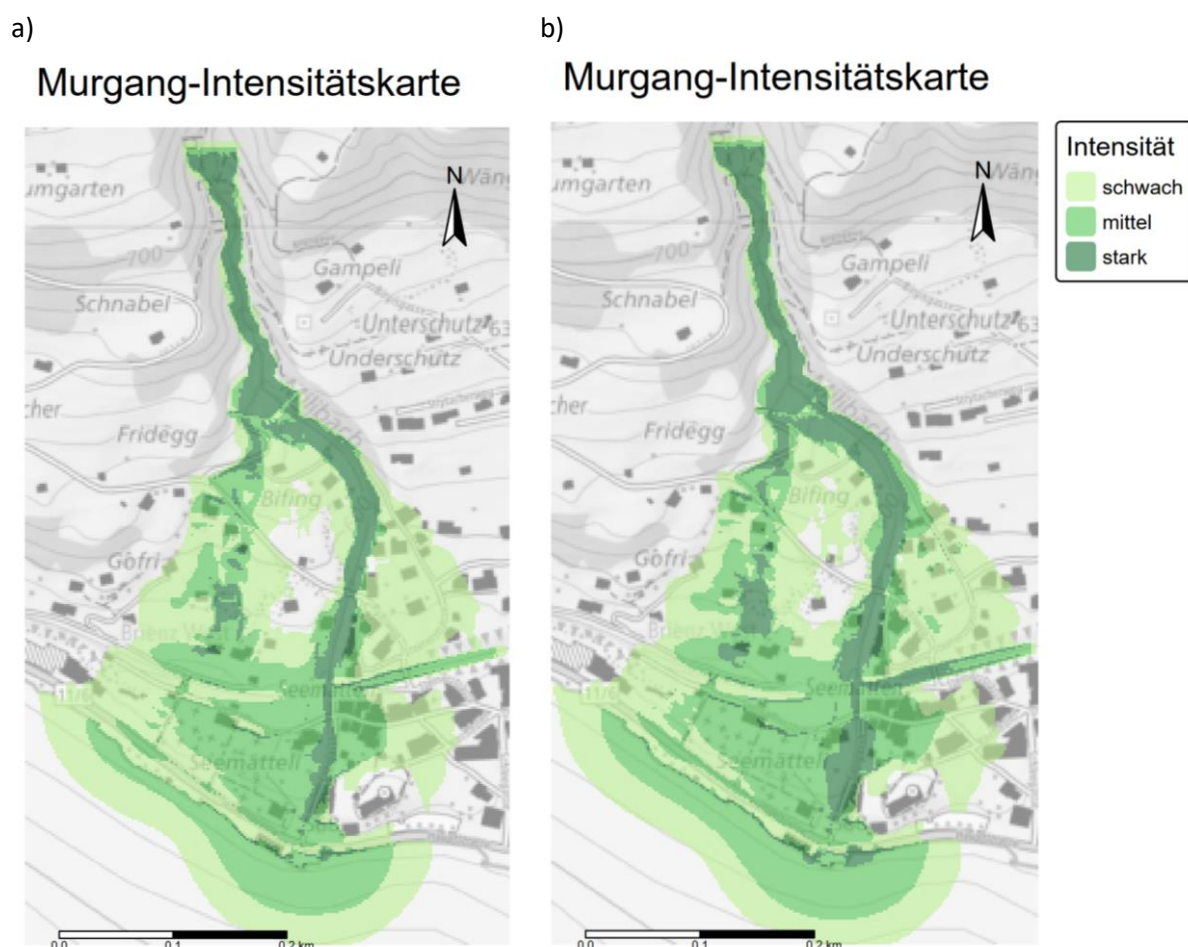


Figure 26 Synoptic intensity maps of the Milibach and Brienzer Aa for debris flow scenarios with a 100-year return period, a) under current climate and b) with climate change adjustment.

The 2024 debris flow event clearly demonstrated the urgent need to improve the protection measures along the Milibach. This is confirmed by the intensity map created from simulations. During the 2024 event, once the existing channel was filled, the flow abandoned the predefined course and spread over a wide area to both sides of the channel. The simulations indicate a similar tendency of the flow expanding laterally as well as preferably following the steepest and most direct path towards Lake Brienzer.

One possible mitigation strategy currently under discussion is the diversion of the Milibach towards the west, guiding the torrent more directly along the edge of the village into Lake Brienz as shown in Figure 27 (Niederer und Pozzi Umwelt AG & GEOTEST AG, 2025). Based on the experience of 2024 and the modelling results, such a diversion could be a valid solution. The event and simulations suggest that the Milibach naturally tends to seek the shortest and steepest route to the lake when the present channel is no longer functional. A shift of the torrent or reserved area in case of overload to the west would therefore align with observations and simulations. However, the asses the effectiveness of such a measure more research and further simulations including the planned measure are necessary. In 2024 the Milibach destroyed its channel which could also happen to the shifted channel, which must be considered.

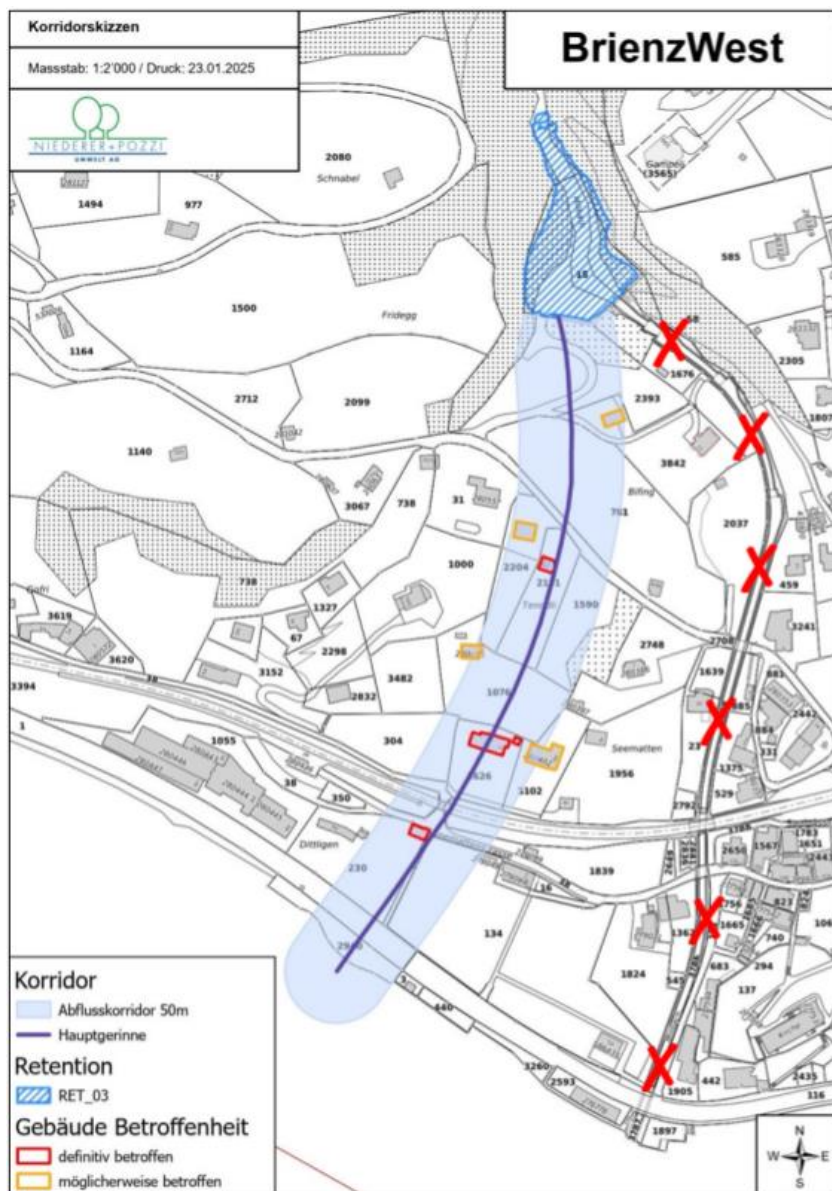


Figure 27 One possible option to better protect the village of BrienZ against the dangers posed by the Milibach, as suggested by the local solution-oriented event analysis (Niederer und Pozzi Umwelt AG & GEOTEST AG, 2025).

## a) Murgang-Intensitätskarte



## b) Murgang-Intensitätskarte

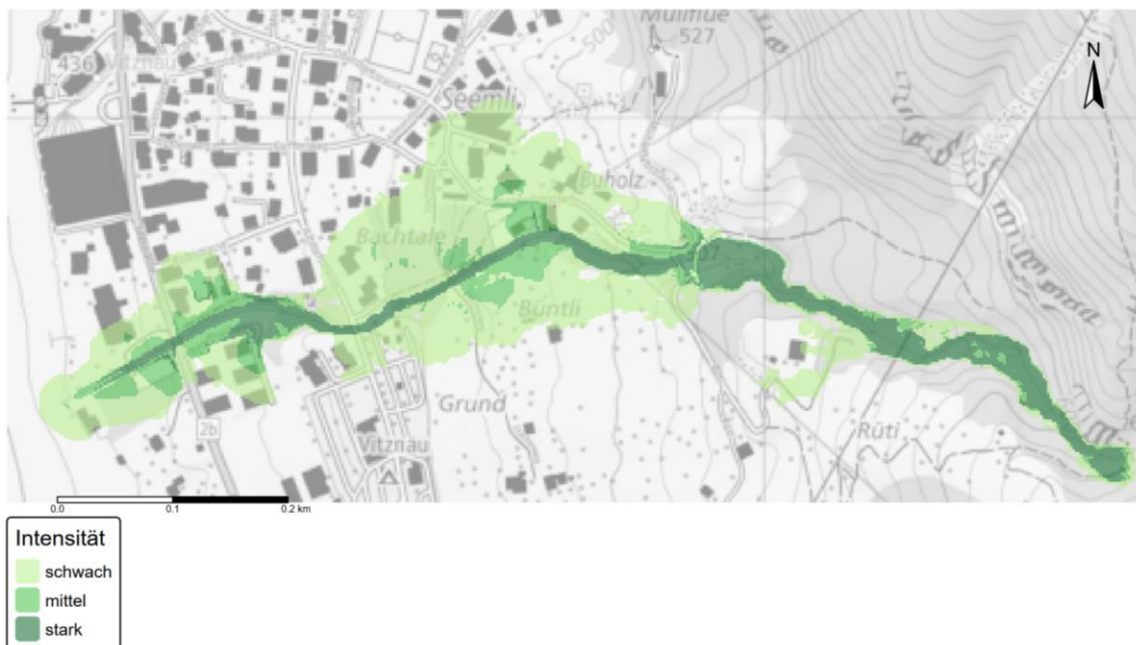


Figure 28 Synoptic intensity maps of the Altdorfbach and Vitznau for debris flow scenarios with a 100-year return period, a) under current climate and b) with climate change adjustment, simulated with the existing retention dam.

The intensity maps for the Altdorfbach and Vitznau for the HQ100 scenario (Figure 28) indicate that the existing sediment retention basin reduces debris flow intensity but does not fully stop a debris flow from accessing the fan area. With the HQ100 scenario without climate adjustment, the highest intensities below the retention dam seem to keep to the channel, with some areas outside of the channel experiencing low intensities and only very small areas experiencing medium intensities. For the HQ100 scenario with climate change considerations, the highest intensities are also expected in the channel with some areas affected by high intensities below the camp ground. In general areas affected by processes with low and medium intensities are larger in this scenario. Along the channel crossing the fan area, the most affected area in both scenarios is the residential area above the main road. It lies within the large area outside the channel affected by medium to high intensities.



Even though the basin and the channel below contain most of the debris flow, it does not entirely eliminate the hazard of a debris flow events with a return period of 100 years. The protection goal for a closed settlement defined as complete protection against an event with a 100-year return period, is therefore not met. Considerable hazard still remains in areas close to the channel used for housing. Material deposition and overbank spreading can be expected in such a scenario, implying potential danger to life and infrastructure. Overall, the scenario demonstrates a substantial protection deficit with the current mitigation measures.

To achieve full protection against a 100-year event would likely require either an increase in retention capacity, improved flow confinement, or additional guiding and overflow management measures to prevent lateral spreading into the settlement area. The Canton of Luzern has recognised the protection deficit and planned a second retention dam above the existing one, for which construction has begun in late 2025. The upper new retention dam is designed to work in combination with the lower older dam (Keller + Lorenz AG & beffa tognacca gmbh, 2012; Schubiger Bauingenieure AG & Kanton Luzern Verkehr und Infrastruktur, 2006). Exact plans for the new combined retention structure were provided by the Canton of Luzern, allowing for simulation of the scenarios with the new measure in place.

With the additional new retention dam an event with a 100-year return period (Figure 29) is mostly contained by the two structures with only slight overload to the south of the south of the upper retention basin. For the scenario without climate change consideration only a very small area is affected with low intensity, for the scenario adjusted for climate change a larger area is affected by mostly low intensity. The area affected is agricultural land with only some scattered houses or barns and the flow does not reach the village below. Areas used for agriculture are normally attributed with a lower protection goal and with low intensities single object protection measures could be considered in this case to achieve protection. It is also possible that this overload to the south can be attributed to inaccuracies of the simulations. In combination with the construction of the second dam, earth work is necessary, which is not represented here.

## a) Murgang-Intensitätskarte



## b) Murgang-Intensitätskarte



Figure 29 Synoptic intensity maps of the Altdorfbach and Vitznau for debris flow scenarios with a 100-year return period, a) under current climate and b) with climate change adjustment, simulated with the planned retention dam.

The intensity maps of the Selderbach in Silenen for the HQ100 scenario (Figure 30) indicate that the existing protection measures against debris flows, consisting of retention basin and reinforced channel over the fan area fulfil the intended protection goal. For the scenario without climate change considerations a debris flow with a 100-year return period is not able to overflow the retention basin. For the scenario with climate change consideration a 100-year event overflows the retention basin but is contained by the channel below. No areas outside the retention basin or the channel are expected to be affected by an event of this size.

Because the protection goal is met based on the here presented scenarios, no further action is needed. There is also no plans for changes to the mitigation measures.

## a) Murgang-Intensitätskarte



## b) Murgang-Intensitätskarte



Figure 30 Synoptic intensity maps of the Selderbach and affected areas of Silenen for debris flow scenarios with a 100-year return period, a) under current climate and b) with climate change adjustment.

## a) Murgang-Intensitätskarte



## b) Murgang-Intensitätskarte

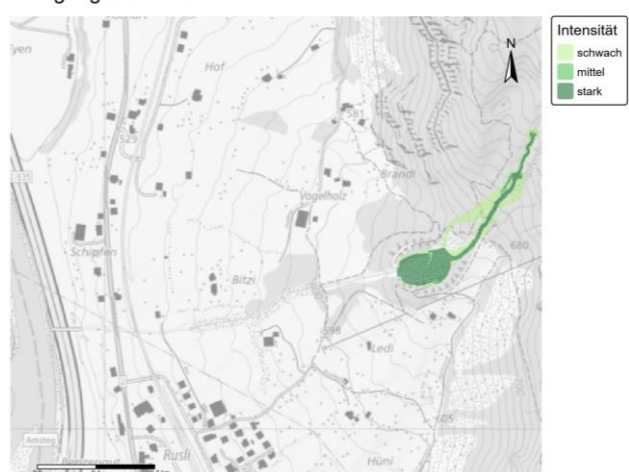


Figure 31 Synoptic intensity maps of the Schipfenbach and affected areas of Silenen for debris flow scenarios with a 100-year return period, a) under current climate and b) with climate change adjustment.

For the Schipfenbach the intensity maps for the HQ100 scenario (Figure 31) show a similar picture as in the Selderbach. The maps indicate that the existing protection measures against debris flows, a retention basin and reinforced channel over the fan area, that the protection goal is fulfilled. For both the scenarios, with b) and without a) climate change considerations a debris flow with a 100-year return period is not able to overflow the retention basin. No areas outside the retention basin or the channel are expected to be affected by an event of this size.

Because of the fulfilment of the protection goal based on the here presented scenarios, no further action is needed. For this catchment as well no changes to the mitigation measures are planned.

The intensity maps for the HQ100 scenario (Figure 32) indicate that the existing sediment retention basin reduces debris flow intensity for the scenario without considerations for climate change but does not prevent flow propagation across the fan area. In the scenario without climate change consideration areas of high intensities occur above the retention basin in areas mostly covered by forest, and below the retention basin to the south of the channel. A 100-year debris flow event seem to leave its channel already above the retention basin affecting large areas to the north and the south of the torrent with medium intensity.

For the scenario with climate change consideration the retention basin does not seem to affect the propagation of the debris flow much, as considerable overbank flow occurs already above the retention basin, leading to the flow mostly bypassing the retention basin to the south. Large areas of high and medium intensity occur to the north and the south of the torrent. The current retention basin does not protect against a 100-year event, the protection goal is not met.

Even though the affected area is not a closed settlement and therefore possibly attributed with a lower protection goal, a debris flow event of this size would reach the cantonal road and Zentralbahn rail way to Engelberg and the river Engelberger Aa over a considerable length. An event reaching the Engelberger Aa with this intensity might cause the river to be pushed out of its bed, which would then lead to major damages downstream of the Buholzbach affecting major parts of the valley bottom, impacting Dallenwil, Oberdorf, Stans and Stansstad, therefore warranting a protection goal of complete protection of at least an event with return period of 100 years.

During the flood in 2005 this scenario nearly became reality, as a debris flow reached the Engelberger Aa, but luckily did not push it out of its bed. This event sparked discussions of how this scenario can be avoided and initiated a long planning phase for improved mitigation measures containing large amounts of sediment delivered by the Buholzbach. In late 2024 construction for a much larger retention dam including guiding dams above the structure (Figure 33) began. Unfortunately detailed information of this new structure was available. This did not allow implementation of the new structures with enough accuracy to produce simulations with enough informative value. However, a comparison of sediment volume values allows for a placement of the structure in the scenarios. The new structure is designed to retain an event delivering of up to 250'000 m<sup>3</sup>, considered to be a 300-year event by the authorities. This would align with the here calculated scenarios, where a 300-year event would deliver just below 250'000 m<sup>3</sup>. However this is only true for the scenarios not considering climate change. With the scenarios considering climate change over 400'000 m<sup>3</sup> are delivered to the fan, which would overload the structure.



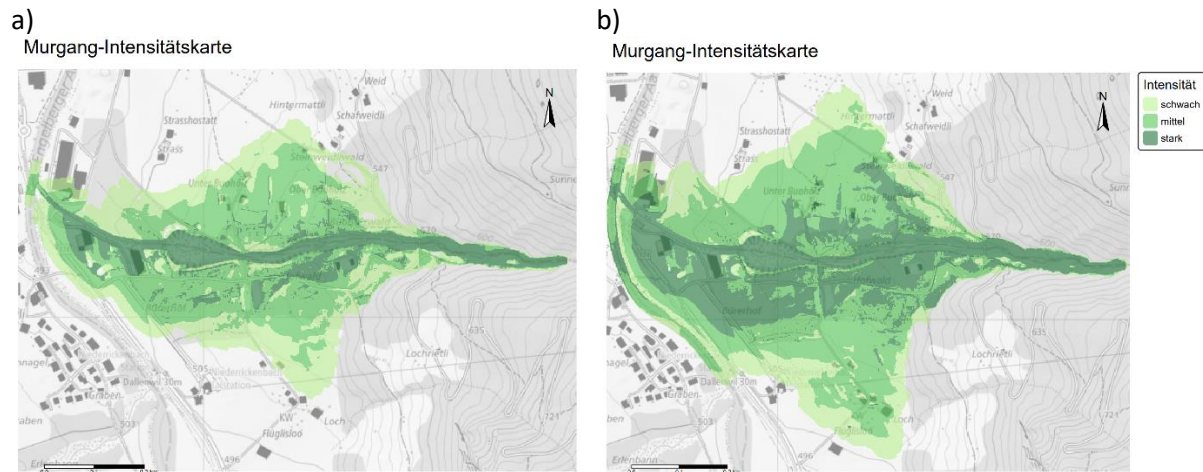


Figure 32 Synoptic intensity maps of the Buoholzbach for debris flow scenarios with a 100-year return period, a) under current climate and b) with climate change adjustment, simulated with the existing retention dam.

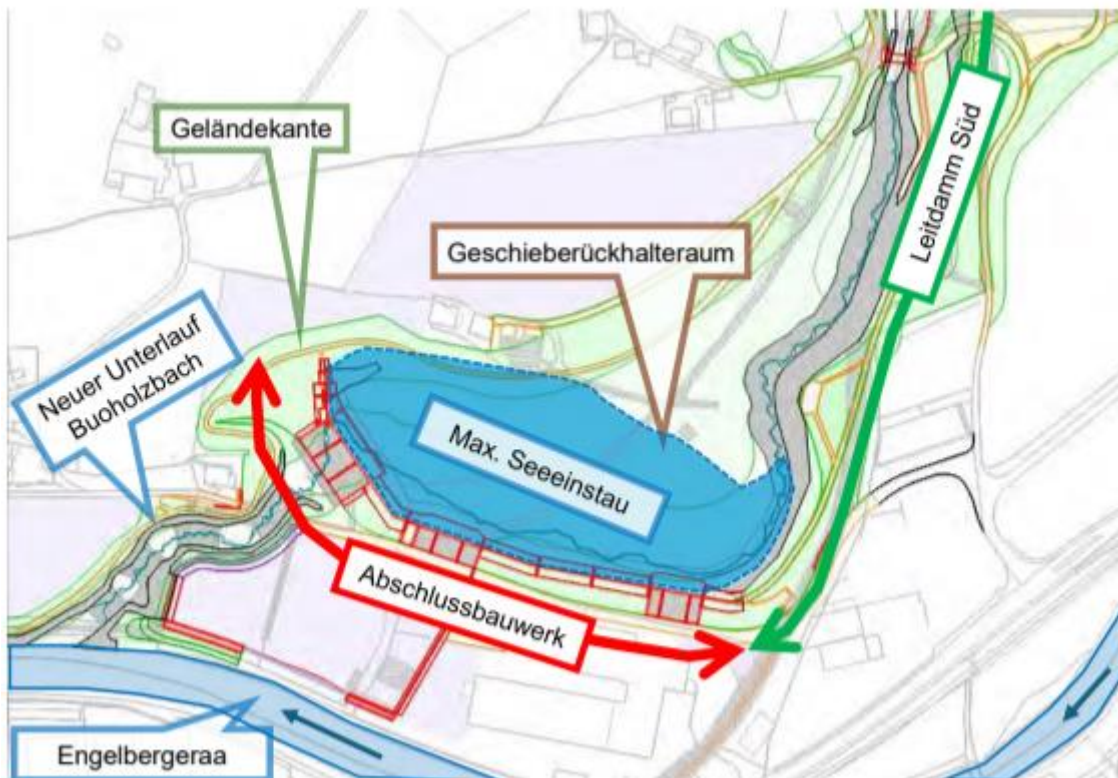


Figure 33 The new planned and under construction retention basin for the Buoholzbach which is designed to protect against a 300-year flood (Schubiger Bauingenieure AG & Kanton Nidwalden, 2025).



## 4.4 Overload scenario

To answer the fourth research question *“What are the consequences of an event exceeding the protection measure’s design scenario?”* the intensity maps are used again, but now the smallest scenarios that overloads the mitigation structures is analysed. For the catchments with plans for adjustment of mitigation measures but not enough information to produce valuable simulation results (Milibach and Buoholzbach), only scenarios including existing mitigation measures are discussed, even though construction is already in progress at the Buoholzbach. For the Altdorfbach, where information of the new mitigation measures were sufficient for scenario simulations, only the scenarios including the new measure are discussed, as construction has started.

The inundated area after overload is described and for catchments where none of the standard design scenarios lead to overload, an additional simulation was made increasing the debris flow volume to the point where overload occurs.

For the Milibach in Brienz, the 30-year return period scenario, without accounting for future climate change already results in overload of the existing retention basin and channel capacity. The intensity map (Figure 34) shows that once the retention basin and the channel is filled the flow spreads laterally across the debris fan. The affected areas are predominantly located within the dense settlement of Brienz, where buildings are closely spaced and infrastructure is highly concentrated. West of the channel, parts of the looser settlement structure are also impacted.

Three roads and their bridges over the Milibach channel including the cantonal road running along Lake Brienz, which serves as the main connection between the lakeside villages, are directly affected by medium to high intensities. Also affected with medium to high intensity is the railway line of the Zentralbahn linking Interlaken and Lucerne via the Brünigpass. The railway line to the east of the Milibach lies below surrounding terrain and enters a tunnel into which some of the flow is diverted, affecting the infrastructure with high intensity. Disruption of these infrastructures would therefore not only have local consequences but also regional implications for mobility and economic connectivity.

At least 20 residential buildings are exposed to medium to high debris flow intensities from an event with a return period of 30 year as, implying substantial structural damage potential and a considerable threat to human safety. In addition, the cemetery of Brienz lies within the zone affected with low to medium intensity, representing a socially and culturally sensitive area. Overall, the 30-year scenario would already cause considerable damage and potential harm to human and animal life.

For the Altdorfbach and Vitznau after the construction of the new retention structure the scenario with 100-year return period, with consideration for climate change results in a slight overload of the upper retention basin. The intensity map (Figure 35) shows that once the retention basin is filled the flow overloads the structure to the south and flows over mostly grassland with single trees. The affected area is used for agricultural purposes and contain few houses or barns spread across the area. One road connecting the spread out structures also lies in the affected area.

The village of Vitznau, especially the camping ground directly south to the retention basin, as well as major infrastructures are not expected to be affected by this scenario. However this overload scenario would cause the area south of the retention basin to be affected with mostly low intensity. Extensive damage to buildings must be expected, but the process is not expected to cause structural damage. Humans within and outside of structures are not expected to be harmed.

### Murgang-Intensitätskarte



Figure 34 Intensity map of the Milibach and Brienztal for the 30-year scenario without climate change adjustment.

### Murgang-Intensitätskarte



Figure 35 Intensity map of the Altdorfbach and Vitznau for the 100-year scenario including climate change adjustment after construction of the new dam and connection to the old structure.

For the Selderbach in Silenen only the extreme event scenario (EHQ) that include climate change adjustments causes a considerable overload of the retention basin stream channel, inundating surrounding areas. As shown in the intensity map (Figure 36), the highest intensities remain concentrated within the channel itself, however the debris flow spreads across parts of the fan with low to medium intensity.

In the upper section of the fan, the affected areas consist mainly of forested slopes and agricultural land to both sides of the retention basin. These zones are exposed predominantly with low to locally medium intensity. The access road to the retention basin is exposed over a long distance with locally high intensity, suggesting potential structural damage and loss of access to the retention dam after extreme events. Two agricultural buildings in the upper fan area are affected with low intensity, implying possible sediment deposition but limited structural failure or danger to human or animal life.

Further downstream, the debris flow reaches the more densely populated area of Silenen. Here, low to medium intensities extend laterally beyond the channel corridor, affecting residential areas. The cantonal road crossing the fan and running along the valley floor lies within the affected zone, as does the Gotthard railway line. Both would be affected with medium to high intensity. Disruption of these transport axes would have significant national consequences, as they are part of the north–south transit corridor. The debris flow is expected to extend to the confluence with the River Reuss, but only just and very locally. The amount of material reaching the Reuss is possibly insufficient to divert the Reuss.

In case of an overload scenario in the Selderbach major damage must be expected, especially to the Gotthard rail line and cantonal road. However with the new Gotthard base rail tunnel, a disruption of the Gotthard rail line would only have regional consequences, as it is only the secondary line and only minimally used for freight transport. However, should the Gotthard base tunnel be incapacitated somehow, an interruption of the rail line in Silenen would have national consequences.

Murgang-Intensitätskarte



Figure 36 Intensity map of the Selderbach in Silenen for the extreme event scenario (EHQ) with climate change adjustment.

For the Schipfenbach again only the extreme scenario (EHQ) with climate change adjustment leads to overload of the retention basin. In this scenario, areas affected by the overflow outside the channel corridor are limited to zones of low intensity. According to the intensity classification, these areas are not expected to experience structural damage to buildings and notably no residential or agricultural buildings are located within the affected overflow zones. The lateral spreading therefore primarily affects open land used for agricultural purposes.

A potential critical point is the crossing of infrastructure of the channel of the Schipfenbach. The cantonal road and the Gotthard railway line intersect the debris flow path and could be affected in the event of bridge obstruction and sediment accumulation. This could lead to bank overflow and sediment deposition along the road or railway.

At the intersection with the A2 highway the Schipfenbach is guided over the A2 via an overpass structure. The overpass was not included in the simulations, which leads to the A2 being affected by the overflow in the intensity map presented. Under normal functioning conditions of the overpass, direct impact on the A2 is unlikely. This does not mean however that the A2 cannot be affected. In the case where the debris flow were not fully contained within this overpass structure, larger damages must be expected on the A2.

Overall, the consequences of an overload scenario would primarily concern critical transport infrastructure rather than settlement areas. Disruption of the cantonal road, the Gotthard railway line, or the A2 highway would have regional to national implications, given their importance for north–south transit and regional connectivity. However this extreme scenario is most likely not as extreme as the results in this thesis might make it out to be, as past events in the Schipfenbach have been much larger than the here presented scenario (see chapter 1.3.4). In case of a larger event, the cantonal road, A2 highway and railway line are most likely affected with higher intensity and over a greater length, causing greater damages than the intensity map in Figure 37 suggests.

### Murgang-Intensitätskarte



Figure 37 Intensity map of the Schipfenbach in Silenen for the extreme event scenario (EHQ) with climate change adjustment

For the Buoholzbach the 30-year return period scenario without consideration of climate change already leads to an overload of the existing protection structures. As illustrated in the intensity map (Figure 38) the guiding dams above the retention basin are overtopped under this event magnitude. This results in high intensity flow affecting adjacent forested areas, the drinking water reservoir, and the access road to Niederrickenbach. In these zones, structural damage and direct risk to persons must be expected.

Further, across the upper and central parts of the fan, agricultural land is affected by low to medium intensity. Several residential and farm buildings located within this area are exposed to these intensities, implying potential structural damage and danger for humans and animals. While complete building destruction is not expected in areas with low intensity, substantial damages might still occur.

Below the retention basin an industrial area lies within a zone affected with high intensity. In this area, severe structural damage or immediate destruction of buildings is possible, endangering human life inside and outside of buildings. Additionally, the cantonal road and railway line connecting Engelberg to Lucerne is affected with medium intensity, possibly damaging the road, leading to an interruption.

The simulated deposits extend to the Engelberger Aa with low to medium intensity. While a complete diversion of the river is unlikely, sediment input at this scale could influence local flow conditions, potentially leading to temporary backwater effects or partial channel constriction.



## Murgang-Intensitätskarte

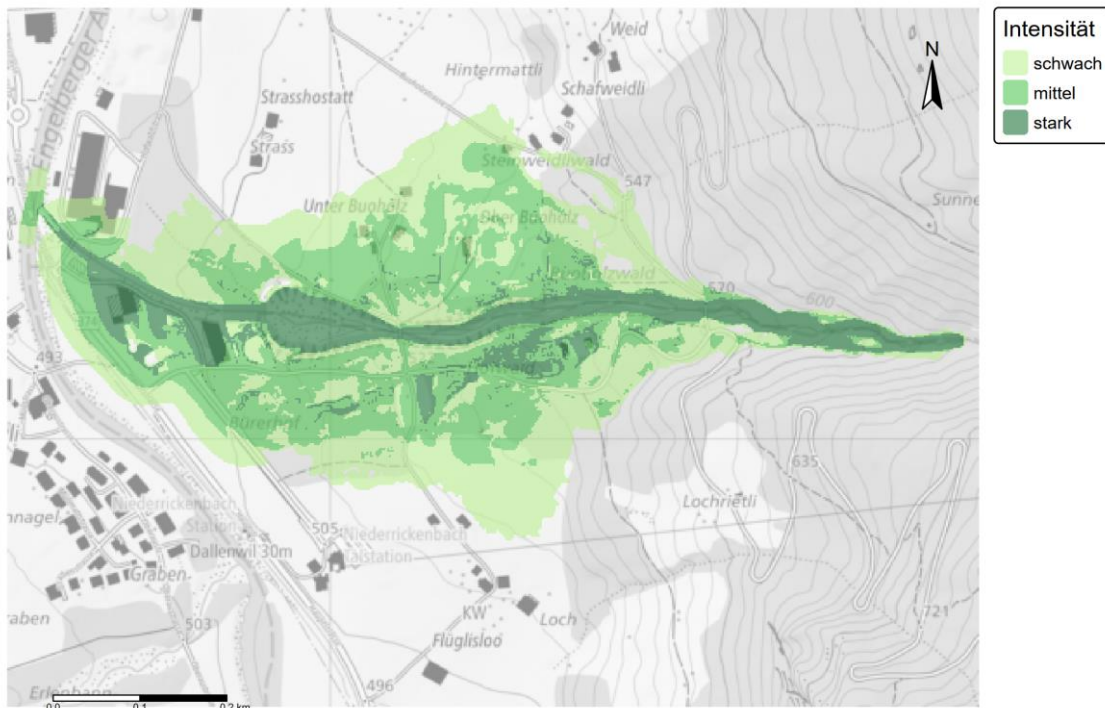


Figure 38 Intensity map of the Buoholzbach in Nidwalden for the 30-year scenario without climate change adjustment.

## 5 Discussion

### 5.1 Uncertainty

Scenario creation for natural processes is inherently associated with uncertainty. It arises from limited observational records, statistical parameter estimates (Coles, 2001) and assumptions about process driving factors (Rickenmann, 2016a). Further uncertainties are introduced because of the possibly limited transferability of past observations to future climate conditions (Gallina et al., 2016).

In practice, the question inevitably arises as to which scenarios are sufficiently representative to serve as a reliable basis for planning and decision making. While the classification of observed events, regarding their probability or return period, that lie outside the range of previous experience is already challenging, rare slope processes are especially difficult to capture statistically, and their likelihood and magnitude can usually only be expressed as ranges. These uncertainties in hazard and risk assessment directly affect the resulting planning and decision frameworks, which inherently contain a certain degree of imprecision that must be acknowledged and clearly communicated in practice (BAFU, 2008a).

### 5.1.1 Uncertainty in extreme value statistics

The estimation of precipitation extremes using extreme value statistics is inherently associated with multiple sources of uncertainty. A fundamental limitation is the typically short duration of instrumental precipitation records relative to the return periods of interest. Estimating 100- or 300 - year events from records spanning only a few decades involves substantial extrapolation beyond the observed data range. In extreme value theory, parameter estimates represent conditional best estimates given the available sample and are therefore subject to considerable sampling uncertainty (Coles, 2001). This uncertainty increases rapidly for higher return levels but is mitigated by longer observation periods regardless of the applied method (Wehner et al., 2024). In this context, using extreme values derived from Swiss weather stations with observational records of up to 100 - 150 years allows for a somewhat statistically robust extrapolation for values with a return period of 300 years. However, even extreme value statistics bases on very long measurement series exhibit large range of uncertainty (BAFU, 2008b).

Additional uncertainty arises from modelling assumptions and methodological choices. The selection of the statistical framework, whether based on block maxima using the Generalized Extreme Value (GEV) distribution or on peaks-over-threshold (POT) methods employing the Generalized Pareto Distribution (GPD), can lead to different parameter estimates and return level calculations (Coles, 2001; Katz et al., 2002).

The choice between the Generalized Extreme Value (GEV) approach and the Peaks over Threshold (POT) method involves several trade-offs in the analysis of extreme precipitation. The GEV approach based on annual or seasonal maxima is conceptually simple and avoids the need for threshold selection, which makes it robust and transparent in application. However, it uses only one maximum per block, in this case one maximum per year. This leads to potentially discarding additional relevant extreme events within the same year. This limitation may reduce statistical efficiency, particularly for shorter observation records. In contrast, the POT method utilises all exceedances above a defined threshold and therefore often provides more information on tail behaviour, especially in relatively short time series. This can lead to more stable estimates of high return levels (Coles, 2001). However, in the POT approach, the choice of threshold influences the number of events used for the statistics. A threshold that is set too low may include values that do not truly represent extreme behaviour, while a threshold that is set too high leaves too few data points for a reliable estimation. Further, precipitation extremes frequently exhibit temporal clustering and spatial dependence, especially during large scale weather patterns. Such dependence structures may conflict with the independence assumptions underlying classical extreme value models, thereby introducing additional uncertainty into parameter estimation and return level inference (Katz et al., 2002).

While the POT approach can provide a more efficient representation of tail behaviour when the threshold is carefully selected, the GEV block maxima method offers a conceptually simpler framework, as it avoids threshold selection and additional declustering procedures (Coles, 2001). The suitability of either method depends on data length, temporal resolution, and the specific objectives of the hazard assessment.

In the present analysis, the choice between the GEV and POT approaches is strongly influenced by the length of the available precipitation records. For long observation periods that exceed 100 years, the GEV method based on annual maxima provides a robust and conceptually straightforward framework, as a sufficiently large number of block maxima is available to ensure stable parameter estimation. However, for shorter records, the number of annual maxima is limited, which increases sampling uncertainty and may lead to unstable return level estimates for rare events with return periods of 100 or 300 years (Koutsoyiannis, 2004; Papalexiou & Koutsoyiannis, 2013). In such cases, the POT method can be advantageous because it incorporates multiple extreme events per year, thereby increasing the effective sample size and improving the representation of tail behaviour. This is particularly relevant when analysing short-duration precipitation extremes, where several intense events may occur within a single year.

It was ultimately decided to use the POT approach. Even though data from stations with 160 years of recorded precipitation was used, data from stations with less than 50 years of recorded precipitation was also used. The station in Gersau with records since 1998, Bristen since 1982 and Stans since 1976 are the closest MeteoSwiss stations to the Altdorfbach, Selderbach and Schipfenbach and Buoholzbach respectively and were therefore chosen despite the short record period. Given the short time series at these locations the POT framework allows for a more efficient use of available extreme observations and reduces the loss of information associated with the block maxima approach. Consequently, the method ensures greater consistency across stations with heterogeneous record lengths.

The inclusion of stations with comparatively short record lengths is a direct consequence of the limited spatial coverage of the observational network. In mountainous terrain, and particularly in small alpine catchments, the number of rain gauges that are spatially representative is often very limited. For none of the investigated catchments in this thesis was a meteorological station located within the catchment itself or in the immediate vicinity. Consequently, the selection of precipitation stations required a trade-off between record length and spatial representativeness.

In this context, stations with shorter time series were included because of their proximity to the respective catchments, even though this introduces additional sampling uncertainty (Frei et al., 2008). In complex terrain, rainfall can vary substantially over short distances, and rain gauges may not capture the local maximum intensities that ultimately trigger debris flows or flash floods (Nikolopoulos et al., 2014). Therefore spatial representativeness is critical in convective precipitation regimes where rainfall variability can be high over short distances and the incorporation of short records reflects the structural limitation of the monitoring network rather than a purely statistical choice.

A striking example of the influence that the distance between a rain gauge and a catchment can have on the representation of debris-flow triggering precipitation in observational records, and consequently on extreme value analyses, was observed during the 2024 event in Brienz. On the 12. August a convective cell hit the entire Milibach catchment with precipitation intensities of 70 - 100 mm/h for approximately 30 minutes triggering a large debris flow (Niederer und Pozzi Umwelt AG & GEOTEST AG, 2025). Only 5 km away from the catchment and an estimated 1.5 km from the line of highest intensity of the storm the MeteoSwiss weather station measured only a maximum 30.6 mm/h (Table 13). This highlights that the uncertainty associated with precipitation extremes in small catchments is not only statistical in nature, but also strongly influenced by the spatial distribution of the observational network.

Table 13 Excerpt from the recorded data at the weather gauging station Brienz around the time of the thunderstorm that triggered a debris flow in the Milibach (MeteoSchweiz, 2025).

| station | Reference timestamp | Atmospheric pressure at barometric altitude [hPa] | Wind speed scalar - hourly mean [km/h] | Gust peak (1s); hourly maximum [km/h] | Gust peak (3s); hourly maximum in [km/h] | Precipitation hourly total [mm] |
|---------|---------------------|---------------------------------------------------|----------------------------------------|---------------------------------------|------------------------------------------|---------------------------------|
| BRZ     | 12.08.2024<br>16:00 | 947.8                                             | 7.2                                    | 22                                    | 21.6                                     | 0                               |
| BRZ     | 12.08.2024<br>17:00 | 951                                               | 38.5                                   | 84.2                                  | 83.2                                     | 30.6                            |
| BRZ     | 12.08.2024<br>18:00 | 953.6                                             | 10.4                                   | 29.2                                  | 27.7                                     | 8                               |
| BRZ     | 12.08.2024<br>19:00 | 953.3                                             | 3.2                                    | 9                                     | 8.6                                      | 2.1                             |
| BRZ     | 12.08.2024<br>20:00 | 952.5                                             | 7.6                                    | 15.1                                  | 14.8                                     | 0.9                             |
| BRZ     | 12.08.2024<br>21:00 | 951.3                                             | 6.5                                    | 20.2                                  | 19.1                                     | 0                               |
| BRZ     | 12.08.2024<br>22:00 | 951.2                                             | 4                                      | 11.5                                  | 11.2                                     | 0                               |
| BRZ     | 12.08.2024<br>23:00 | 950.9                                             | 4.3                                    | 10.4                                  | 10.1                                     | 0                               |

### 5.1.2 Uncertainty in climate scenarios

In addition to statistical and spatial uncertainties, further uncertainty arises from the consideration of future climate conditions.

The climate-change scenarios applied in this thesis are not derived from dynamically downscaled climate model chains nor from non-stationary extreme value analyses. Instead, observed precipitation extremes are analysed under the assumption of stationarity, and projected intensification signals consistent with CH2025 warming levels are subsequently applied. By using the upper confidence interval derived from extreme value analysis based on observed precipitation data to represent precipitation patterns expected for Switzerland under 3°C warmer global average temperature (MeteoSwiss & ETH Zürich, 2025) potential future conditions are explored.

The scenarios with climate change developed in this thesis are therefore not derived from dynamically downscaled climate model chains nor from explicitly non-stationary extreme value models. This approach represents a pragmatic compromise between theoretical consistency and methodological feasibility. But the assumption of stationarity has been increasingly questioned in the hydrological and climate risk literature. Milly et al. (2008) argued that “stationarity is dead” for water management, as anthropogenic climate change alters the statistical properties of hydroclimatic variables. Under such conditions, return periods derived from historical data may no longer represent future exceedance probabilities. Sarhadi et al. (2016). further demonstrate that return periods can become explicitly time dependent in a changing climate. They imply that the traditional concept of a fixed 100-year event loses its statistical meaning when the underlying hazard distribution evolves.

In response non-stationary extreme value approaches have gained increasing attention within hydrology and other fields concerned with extreme events. These non-stationary models allow distribution parameters to vary as a function of time, temperature or other physically meaningful covariates (Coles, 2001). A comprehensive review by Twinomuhangi et al. (2025) shows that non-stationary frequency analysis is increasingly applied and often improves the representation of evolving extremes. However, it is also emphasised that substantial methodological challenges remain, including short and heterogeneous observation records, instability of parameter estimates, uncertainty in covariate selection and limited robustness when extrapolating to high return periods. These challenges are particularly relevant in mountainous regions, where precipitation records are often short and spatially sparse.

At the other hand, there is robust physical evidence that short duration extreme precipitation intensifies with warming climate. Multiple studies show that sub daily rainfall extremes tend to scale with atmospheric moisture availability, often following Clausius–Clapeyron scaling or even higher than the Clausius–Clapeyron rates for convective storms (Fischer & Knutti, 2016; Westra et al., 2014). However, translating physically projected intensification into fully non-stationary statistical models is complex and introduces additional layers of uncertainty, which is why most operational risk frameworks still rely on static hazard representations (Gallina et al., 2016).

Against this background, the approach adopted in this thesis should be interpreted as a structured sensitivity analysis. The resulting climate-adjusted scenarios therefore do not redefine return periods in a time varying probabilistic sense. Instead, they explore how debris flow magnitudes may respond under intensified precipitation conditions. This approach acknowledges the theoretical limitations of stationarity, recognises the growing evidence for evolving extremes, but avoids the additional structural uncertainties associated with fully non-stationary modelling, which would be beyond the scope of this thesis.

The second component represented in the climate scenarios is the effect climate change has on sediment availability. Already in the late twentieth century in the analysis of the flood in 1987 in Switzerland it was recognised that glacier retreat increases the availability of easy erodible, unconsolidated material. In fact they state that over 50% of release areas of the over 150 documented large debris flows were covered by glaciers only 150 years ago (Bundesamt für Wasserwirtschaft & Bundesamt für Umwelt Wald und Landschaft, 1991). The newly exposed periglacial zones provide considerable amounts of sediment to be mobilized by debris flows. As glaciers withdraw areas formerly covered and supported by ice become exposed and lose their stability. Additionally to glacier retreat, thawing permafrost in rock and scree slopes provides more loose material (Hock et al., 2019; Huggel et al., 2012). It is therefore likely that with further glacier retreat and permafrost degradation exposed, unconsolidated sediment becomes more abundant, which in turn could facilitate very large debris flows outside the range of previously documented events (Stoffel & Huggel, 2012). However at lower elevations the projected changes, such as a reduction in freeze-thaw cycles are expected to reduce the sediment yield and therefore also reduce the amounts and magnitude of debris flows (Hirschberg et al., 2021; Hock et al., 2019).



These changes in sediment availability were not considered in the climate change affected scenarios. A comparison of the catchment areas with old maps show that none of the five catchments contained glaciated areas within the last 150 years. In regards to the presence of permafrost only the catchments of the Selderbach and Schipfenbach are expected to contain permafrost, that with degradation could provide more loose sediment in the future (Swisstopo, 2026). For the analysed catchments sediment availability is more likely to be affected by a decrease in sediment input, due to their low elevation. Overall, this suggests that changes in sediment supply are unlikely to amplify future debris flow magnitudes in the studied catchments and might even counteract potential increases driven by more intense precipitation.

### 5.1.3 Uncertainty with debris flow scenarios

Uncertainties inherent in the precipitation scenarios propagate directly into the debris-flow scenarios and accumulate along the modelling chain from rainfall to runoff and from runoff to debris-flow discharge and volume.

The translation of rainfall into discharge in small and steep mountain catchments remains associated with considerable uncertainty, as errors in rainfall estimation cannot average out at the small spatial scales relevant for discharge generation (Borga et al., 2014). Already the determination of peak discharge values is subject to large uncertainty, and this uncertainty only increases when estimating sediment transport or debris flow magnitudes, due to process complexity and limited data availability (Bundesamt für Wasser und Geologie, 2001).

Small mountain catchments that produce flash floods and debris flows have often limited real time discharge observations (Borga et al., 2014). The few discharge values found in flash flood and debris flow databases are most often peak discharge estimates reconstructed from post event surveys in ungauged catchments (Marchi et al., 2010) and provide only a limited empirical basis.

To estimate peak discharge from precipitation observations a discharge coefficient has to be defined applicable to the catchment. Observations at Illgraben found a wide range of discharge coefficients, ranging from nearly 0 to close to 1 (Hirschberg et al., 2019), underlining that discharge coefficients show substantial variability and depend strongly on antecedent saturation conditions. A study by Marchi et al. (2010) on discharge coefficients of flash flood events conducted across Europe reported mean values around 0.35 but with significant regional differences. However, this study as well as most others on the topic are conducted in much larger catchments areas of several 100 km<sup>2</sup> with presumably a more mellow slope and overall flatter terrain, influencing land cover type.

In this study, a discharge coefficient of  $C = 0.6$  was applied to all catchments for the discharge calculations, mainly based on back calculated estimates from the Milibach event in 2024, for which the discharge coefficient was estimated at  $C = 0.63$  (Niederer und Pozzi Umwelt AG & GEOTEST AG, 2025). The application of a discharge coefficient of 0.6 to all analysed catchments, even though they have differing land cover type distribution, can be attributed to the lack of available data or studies, which would allow for a catchment specific adjustment. This uniform application of a discharge coefficient introduces considerable uncertainty as it was shown that discharge coefficients vary considerably between events and landscapes (Marchi et al., 2010).

The conversion from water discharge to debris flow discharge and volume introduces even more uncertainty. A constant sediment fraction of 40% was assumed, based on transport limited catchment concepts proposed by Bennett et al. (2014). The assumption of a 40% sediment fraction in debris flow discharge lies within the observed Swiss range of 30–60% reported for the analysed debris flows during the 1987 (Bundesamt für Wasserwirtschaft & Bundesamt für Umwelt Wald und Landschaft, 1991). Although this value lies at the lower end of the observed spectrum, it is consistent with estimates from the 2024 Milibach event where a sediment fraction of 35% was estimated (Niederer und Pozzi Umwelt AG & GEOTEST AG, 2025) and supports the assumption of muddy debris flows. Nevertheless, sediment concentrations are known to vary strongly between catchments and events. Debris flows observed by (McCoy et al., 2012) in US catchments exceeded a 20% solids fraction even outside the bulk front. By adding the sediment concentration to the water discharge, debris flow discharge was estimated which was then calculated into debris flow volumes using the empirical G-V relationship for muddy debris flows proposed by Rickenmann (2016b).

Analyses of the 1987 Swiss events demonstrate that empirical formulas show substantial scatter, particularly in small catchments and that differences between observed and calculated debris volumes can be large. Empirical estimation can therefore not replace field based hazard assessments and can only produce rough order-of-magnitude estimates (Bundesamt für Wasserwirtschaft & Bundesamt für Umwelt Wald und Landschaft, 1991). The presented debris flow scenarios are therefore to be interpreted as rough but plausible estimates.

The debris flow scenarios are largely based on a limited set of defining catchment characteristics, namely catchment size, torrent length, and channel steepness. The Schipfenbach and Selderbach catchments are comparatively short, straight, and steep, and do not contain significant tributaries. Their catchment areas are relatively small and narrow, covering approximately 1.3 km<sup>2</sup> and 1.8 km<sup>2</sup>, respectively. These morphological characteristics may contribute to an underestimation of potential peak discharge and corresponding debris-flow volumes with the applied method, compared to the magnitudes that could be expected from past events.

In contrast the Buoholzbach catchment is comparatively large with an area of approximately 14 km<sup>2</sup> and contains multiple tributaries. The channel is less steep and follows a more winding course. Along the torrent, several flatter sections are present allowing sediment deposition before the material reaches the fan. These characteristics suggest that sediment retention within the channel network may reduce the volume that is ultimately delivered to the depositional area. These characteristics possibly contribute to the overestimation of debris flow magnitudes calculated with this method when compared to the magnitudes of past events.

These observations highlight the importance of detailed, catchment specific assessments. Alternative estimation approaches for solid discharge, such as methods proposed in the Guide for estimating solids concentrations in torrents (Arbeitsgruppe für operationelle Hydrologie, 1996) may provide results that are better tailored to the morphological and sedimentological uniqueness of the individual catchments.

Within the framework of this thesis however, the most accessible and adjustable parameters to better reflect catchment characteristics are the runoff coefficient (C) and the assumed sediment concentration of the discharge. A short analysis was therefore conducted for the Selderbach and Schipfenbach catchments. Based on field observations, increased sediment fractions and increased discharge coefficient appear plausible for these catchments.

Increasing the assumed sediment concentration to 60% for the Selderbach and Schipfenbach scenarios results in a moderate increase in estimated debris flow volumes (Table 14). However, the resulting volumes still remain below those observed in past large events. This suggests that the substantial underestimation of debris flow volumes in small, straight, and steep catchments cannot be explained solely by the assumed sediment fraction in the discharge, but must be influenced by other processes as well.

*Table 14 Volume estimations for the Selderbach and Schipfenbach with increased sediment concentration of 60% under current climate and future climate assumptions.*

| Sediment concentration = 60%                            |            |              | Sediment concentration = 60%                                   |            |              |
|---------------------------------------------------------|------------|--------------|----------------------------------------------------------------|------------|--------------|
| Volume [m <sup>3</sup> ] - no climate change adjustment |            |              | Volume [m <sup>3</sup> ] - including climate change adjustment |            |              |
|                                                         | Catchment  |              |                                                                | Catchment  |              |
| Scenario                                                | Selderbach | Schipfenbach | Scenario                                                       | Selderbach | Schipfenbach |
| HQ30                                                    | 16'448.88  | 11'692.50    | HQ30                                                           | 24'657.19  | 17'527.29    |
| HQ100                                                   | 19'821.19  | 14'089.68    | HQ100                                                          | 31'794.28  | 22'600.61    |
| HQ300                                                   | 23'291.46  | 16'556.48    | HQ300                                                          | 39'722.18  | 28'236.07    |
| EHQ                                                     | 28'528.58  | 20'279.23    | EHQ                                                            | 76'453.89  | 54'346.41    |

A uniform discharge coefficient (C) of 0.6 for all catchments is not entirely realistic, as land cover distribution differs between the catchments. An analysis of approximate runoff coefficients based on land use types (settlement areas: C=0.9, agricultural areas: C=0.6, forested areas: C=0.4, unproductive areas: C=0.8) resulted in weighted mean values that broadly support the assumption of C=0.6. The calculated catchment specific coefficients varied only slightly around this value, with the lowest value estimated for the Altdorfbach (C=0.5) and the highest for the Schipfenbach (C=0.7).

A combined increase of the sediment fraction to 60% and the discharge coefficient to 0.7 yielded results that align more closely with past observations for the Selderbach and Schipfenbach catchments (Table 15). For the Selderbach, newly estimated debris flow volumes without climate change range between 20'000 m<sup>3</sup> and 35'000 m<sup>3</sup>, which corresponds well to observed magnitudes between 18'000 m<sup>3</sup> and 35'000 m<sup>3</sup> (Bundesamt für Umwelt BAFU, 2026; WSL, 2025). Under climate change scenarios, the estimated volumes increase to a range between 30'000 m<sup>3</sup> and 92'000 m<sup>3</sup>, which are mostly larger than past observations.

For the Schipfenbach, estimated volumes without climate change range from 14'000 m<sup>3</sup> to 25'000 m<sup>3</sup>, whereas documented past events range from less than 10'000 m<sup>3</sup> to more than 50'000 m<sup>3</sup> (Bundesamt für Umwelt BAFU, 2026; Rickenmann et al., 2001). The comparatively narrow range of modelled volumes relative to the much wider range of observed debris flow magnitudes suggests that additional factors influence the size of debris flow, which cannot be captured by the simplified approach applied in this thesis. The results from the Schipfenbach may further indicate a potential lower limit in catchment size below which the applied method becomes less reliable.

Table 15 Volume estimations for the Selderbach and Schipfenbach with increased sediment concentration of 60% and increased discharge coefficient to 0.7 under current climate and future climate assumptions.

| Sediment concentration = 60% and C=0.7                  |            |              | Sediment concentration = 60% and C=0.7                         |            |              |
|---------------------------------------------------------|------------|--------------|----------------------------------------------------------------|------------|--------------|
| Volume [m <sup>3</sup> ] - no climate change adjustment |            |              | Volume [m <sup>3</sup> ] - including climate change adjustment |            |              |
|                                                         | Catchment  |              |                                                                | Catchment  |              |
| Scenario                                                | Selderbach | Schipfenbach | Scenario                                                       | Selderbach | Schipfenbach |
| HQ30                                                    | 19'993.05  | 14'211.84    | HQ30                                                           | 29'969.97  | 21'303.82    |
| HQ100                                                   | 24'091.99  | 17'125.52    | HQ100                                                          | 38'644.86  | 27'470.28    |
| HQ300                                                   | 28'309.97  | 20'123.83    | HQ300                                                          | 48'280.95  | 34'319.98    |
| EHQ                                                     | 34'675.51  | 24'648.71    | EHQ                                                            | 92'927.10  | 66'056.21    |

#### 5.1.4 Uncertainty with debris flow simulations

The debris flow scenario simulations performed using RAMMS involve a number of methodological limitations and inherent uncertainties, of which only the most relevant are discussed in the following.

Among the input parameters unrelated to release characteristics, the digital elevation model (DEM) resolution and friction parameters are particularly influential for the outcome of debris-flow simulations. The spatial resolution of the DEM determines the level of topographic detail represented in the model and therefore directly affects flow routing, channel confinement, deposition patterns, and the simulated lateral extent on the fan.

Resolution can significantly alter simulated debris-flow behaviour, as variations in grid size may lead to substantial differences in flow depth, velocity and spatial extent, as coarse resolutions smooth small scale topographic features and reduce local channel confinement, whereas fine resolutions preserve micro-topographic controls that influence flow spreading and deposition (Fan & Galoie, 2025).

The SwissALTI3D dataset, which was used as the input DEM for the simulations, provides a very high spatial resolution of 0.5 m. However, due to computational constraints and the scale of relevant landforms in the depositional areas, simulations in this study were conducted using a resolution of 5 m for initial scenario simulation and 2 m for more detailed analyses. A literature summary by Mikoš & Bezak (2021) shows that the average resolution used for simulations with RAMMS is 2-5 m, which most likely stems from the trade-off between computation time and accurate representation of topography. With a resolution of 2-5 m, very small scale terrain features influencing local flow paths may not be fully represented in the simulations, but larger features like dams that are designed to influence debris flow propagation are represented.

The selection of friction coefficients represents another major source of uncertainty in the RAMMS simulations. Since friction parameters are event specific and rarely directly measured, they are typically estimated based on previous events or transferred from comparable catchments. Among the analysed torrents, the best documented case is Brienz (2024), where calibration against observed inundation patterns was conducted.  $\mu$  was varied between 0.1 and 0.4 and  $\xi$  between 200 and 800 (Figure 39), covering the typical range reported for Alpine debris flows. This calibration resulted in a best fit with  $\mu = 0.2$  and  $\xi = 200$ .

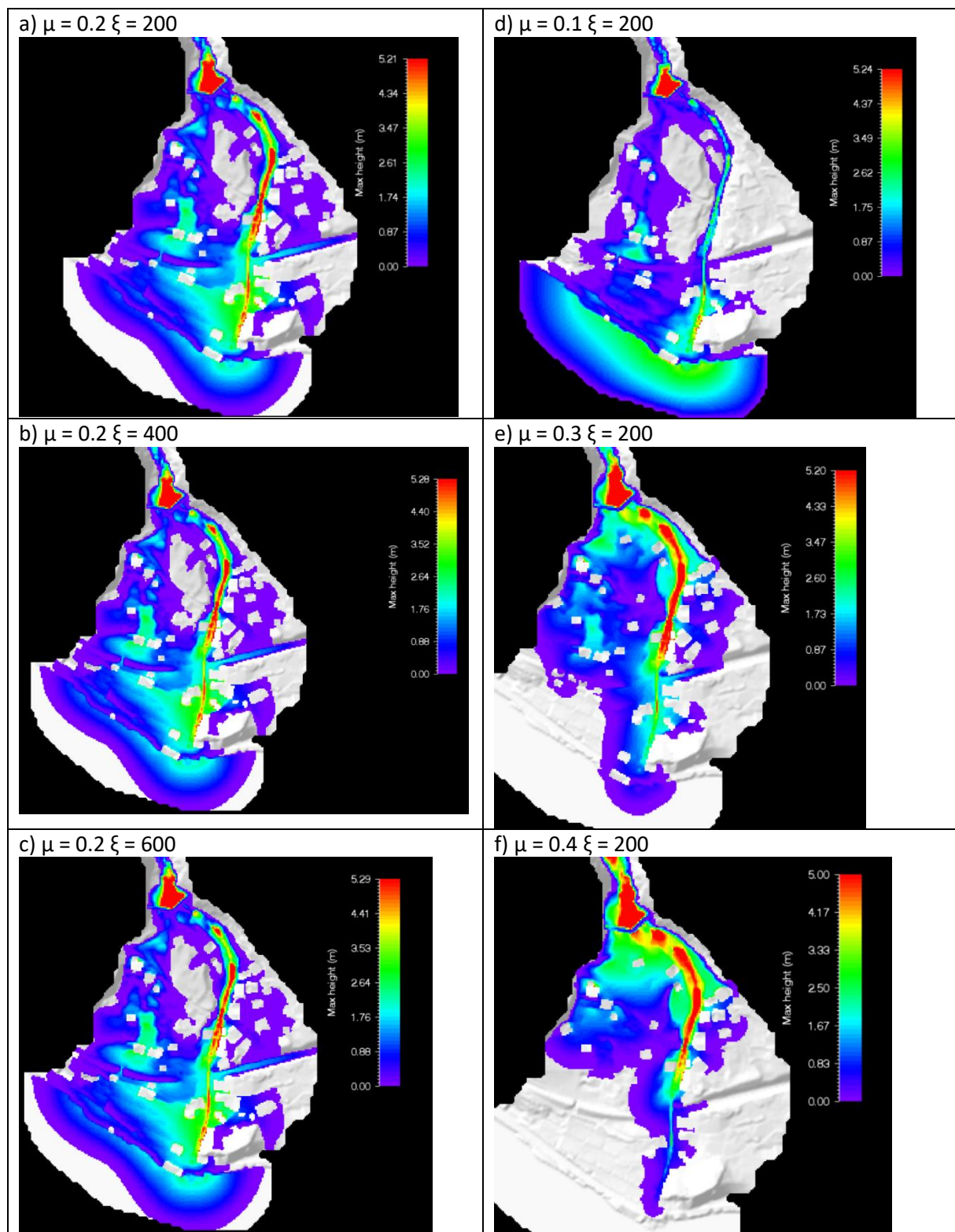


Figure 39 RAMMS Simulation results in Brienz with varying friction coefficients to calibrate best fitting friction parameters.



Due to the lack of similarly detailed documentation of events in the other catchments, all simulations were performed using  $\mu = 0.2$  and  $\xi = 200$ . These values represent intermediate conditions between granular and muddy debris flows, while slightly leaning towards muddy flow behaviour, which is consistent with recommendations for Alpine environments (Mikoš & Bezak, 2021).

It must be emphasised however, that friction parameters are not a constant material property, but vary from event to event. They strongly depend on water-sediment ratio, total flow volume, velocity and local slope conditions within the torrent (Wendeler, 2008). Because of this high variability, and lack of event and catchment specific calibrations, average friction parameters are selected, even though this introduces further uncertainty.

The representation of structural mitigation measures introduces additional uncertainty into the RAMMS simulations. Since concrete structures such as retention dams or outlet structures are not included in SwissALTI3D, they had to be manually implemented into the DEM. This was done by defining polygon shapes with assigned elevation values.

For each structure, only a single polygon with one uniform elevation value was used. To ensure that the structures were still represented in simulations with a 5 m grid resolution, the polygons were defined slightly wider in the downstream direction than the actual structures. This was necessary because narrow elements may otherwise disappear or be insufficiently resolved in coarser grids. But it is still possible that the structures were not accurately represented in the simulation because of the way RAMMS resamples raster heights that leads to smoothing of terrain (Fan & Galoie, 2025).



Figure 40 The retention wall in Brienz with a slanted and stepped crest to control the direction of overflow.

Secondly, the implementation into the DEM is simplified in regards to structure height. Only a single elevation value is assigned across the entire structure, whereas in reality many structures are slanted or stepped in order to control overflow, as illustrated in Figure 40. Such geometric details cannot be adequately captured with this simplified representation and therefore lead to inaccuracies of the simulations, especially in the case of structure overload.

Additionally, for structures that had to be added manually to the DEM, associated earthworks that were not included in the DEM were not regarded. This is particularly relevant for planned mitigation measures that have not yet been constructed. In the case of the Altdorfbach in Vitznau simulations including the new retention dam show outflow towards the orographic left (Figure 35). This behaviour is largely explained by the fact that the planned earthworks accompanying the construction of the new dam, which will increase the terrain height on that side of the torrent, are not reflected in the current DEM.

Consequently, the implemented protection structures must be understood as simplified geometric representations. Since surrounding terrain modifications, detailed crest geometries and construction-related adaptations were not incorporated, the structural mitigation measures in the simulations represent only rough approximations of the existing or planned measures.

Other factors affecting simulation accuracy include the representation of buildings within the inundation area, the interaction between debris flows and channels or retention structures under overload conditions, and the influence of forests and large wood on flow dynamics and deposition processes.

Houses could be represented in RAMMS as no flux areas or incorporated in to the DEM in the same way the missing mitigation measures were incorporated, however both approaches are not able to account for full or partial destruction. Past events showed that debris flows with medium to high intensity are capable of destroying houses or even flow through them (BAFU, 2008a; Niederer und Pozzi Umwelt AG & GEOTEST AG, 2025).

Destruction of retention dams or channelled sections of the torrent have significant effects on debris flow propagation and therefore causing hazard amplification. This process has to be considered for hazard assessment and management, but is not represented well in conventional methods (Borga et al., 2014), including RAMMS. Similarly the influence of large wood transport affects hazards as log jams could lead to overbank flow or trapped wood in retention basins contribute to faster filling of the structure (Comiti et al., 2016).

Healthy and well maintained forests in the fan area however are capable of dissipating the energy of smaller debris flows, promoting deposition, which lead to a shorter runout distance of debris flows (Michellini et al., 2017). This phenomenon is nicely illustrated in Figure 41 where debris flow deposits are contained by the surrounding forest.



Figure 41 Aerial photograph of the Buoholzbach after the debris flow in 2005, showing the effectiveness of protective forests in the fan area (BAFU, 2008a).

## 5.2 Debris flow triggers

In this thesis debris flows are associated with short duration, high intensity rainfall, yet extreme rainfall alone is rarely a sufficient explanation for their initiation. A range of additional predisposing and triggering factors control whether intense precipitation actually translates into debris flows. Key controlling variables include topography, especially channel slope, rainfall characteristics like intensity, duration, and antecedent wetness and the geological and geotechnical properties of bedrock and unconsolidated material (BAFU, 2008a). Antecedent soil moisture, snow and ice melt and shallow landslides can be more important to debris flow initiation than highly concentrated water supply (Rickenmann, 2016a). Some of the most devastating debris flows were triggered by glacial lake outburst floods (Haeberli et al., 2001).

The timing between precipitation onset and debris flow initiation varies considerably and depends on storm characteristics and antecedent moisture conditions (BAFU, 2008a; Borga et al., 2014). Observations from the Illgraben that debris flows are generated from a wide range of rainfall intensities because of antecedent wetness and snow melt (Bennett et al., 2014). In general three meteorological categories of debris flow triggering conditions can be identified, intense short duration rainfall, long duration or low intensity rainfall with antecedent wetness and rainfall coinciding with snowmelt. This variability highlights the limitations of approaches relying on a single high intensity rainfall events as debris triggers and underscores the need to consider combined hydro-meteorological and geomorphic controls when analysing debris flow triggering in Alpine catchments.



### 5.2.1 Influence of antecedent wetness

Although antecedent wetness is not accounted for in this thesis, numerous studies show that it can substantially influence debris flow initiation and magnitude. Past events in Switzerland illustrate that sufficiently wet preconditioning can lower effective triggering thresholds. During the 1987 events, debris flows developed after prolonged rainfall lasting more than 30–40 hours. Cumulative precipitation totals reached between roughly 100 and 300 mm, before debris flows were triggered. At the same time peak intensities were comparatively moderate, yet debris flows still occurred because of the combination of accumulated rainfall and small short term intensity peaks (Bundesamt für Wasserwirtschaft & Bundesamt für Umwelt Wald und Landschaft, 1991).

Process analyses from the August 2005 events show similar patterns further emphasizing the importance of antecedent wetness conditions. Even where rainfall did not generate extreme peak discharges in small catchments, under favourable preconditioning debris flows were initiated through interactions between runoff, sediment transport and landslides (BAFU, 2008a). In a study conducted in the Illgraben all 52 observed debris flows were preceded by rainfall within the two weeks prior to the triggering event. While debris flows occurred across a wide spectrum of antecedent wetness conditions, the largest events were associated with elevated pre event moisture. In some cases comparatively small rainfall amounts were sufficient to generate large debris flow volumes. Increased antecedent wetness enhances pore water pressure, promotes sediment entrainment and contributes additional pore water to the flow which increases overall event magnitude (Hirschberg et al., 2019).

These findings align with modelling approaches that highlight the need to consider both antecedent moisture and sediment availability when analysing debris flow processes (Bennett et al., 2014). Approaches based solely on rainfall intensity–duration thresholds cannot fully capture this complexity.

### 5.2.2 Influence Snow

Snow conditions can substantially influence debris flow initiation by modifying both effective water input and antecedent wetness in the catchment. During rain-on-snow events even moderate rainfall can generate disproportionately high discharge, as rainwater mixes with the snowpack and accelerates melt processes. As a result, discharge magnitudes may be significantly higher than suggested by precipitation data alone. The 1987 events July illustrate this mechanism clearly as at that time considerable snow was still present. Additionally high temperatures kept the snowline above 3000 m.a.s.l. so that precipitation fell as rain even at very high elevations, leading to abundant moisture in loose sediment and considerable contribution to discharge from melt water (Bundesamt für Wasserwirtschaft & Bundesamt für Umwelt Wald und Landschaft, 1991). These conditions demonstrate how sustained snowmelt can precondition slopes and allow debris flows to occur under rainfall intensities that might not be critical in drier settings.

Although rainfall is the primary trigger of debris flows in many mountain regions, additional water supply from snowmelt can significantly enhance triggering probability (Rickenmann, 2016a). This is also reflected in the observation that debris flows exhibit clear seasonal patterns, with very few events in winter and increased activity during snowmelt and convective storm seasons. The study by Hirschberg et al. (2019) highlights the need to explicitly quantify snowmelt effects, as they directly influence antecedent wetness and the comparability of hydrological conditions across events. Snow processes represent an additional control that can modify both preconditioning and effective discharge and therefore an important component when interpreting rainfall based debris flow triggering analyses.

However, this does not mean that the focus on high short duration high intensity precipitation as the main factor for debris flow triggering can't be valid. In areas with limited storage capacity antecedent wetness is not relevant to debris flow initiation (Stoffel et al., 2014). Evidence from the Italian Dolomites shows that debris flows in the Acquabona catchment were consistently linked to clearly defined high intensity rainfall events, often occurring after prolonged dry periods when channel bed sediments were unsaturated (Berti & Simoni, 2005). This indicates that prestorm moisture conditions and sustained multi day rainfall are not necessary to initiate debris flows. Similar findings from the Central Italian Alps emphasize the dominant role of heavy, concentrated precipitation over cumulative antecedent rainfall (Pelfini & Santilli, 2008). These observations support the focus on intense short-term rainfall as the key triggering mechanism in the investigated region.

Further, in the context of climate change focusing on short duration, high intensity precipitation as the primary trigger is not unreasonable. Future climate projections for the Alps indicate drier summers and heavy precipitation events are projected to intensify. Accompanied by a substantial reduction in snow water equivalent, with decreases of approximately 44% to 80% in a 3°C warming scenario (MeteoSwiss & ETH Zürich, 2025), effects of antecedent wetness and snow might become less relevant. These trends suggest that future debris flow activity may increasingly be driven by intense rainfall bursts supporting the emphasis on extreme short term precipitation in a warming climate.

## 6 Conclusion

The generation of debris flows and in consequence debris flows scenarios depend on many factors. Besides precipitation intensity aspects such as sediment availability, channel morphology, antecedent wetness and local slope stability influence whether debris flows are triggered and what magnitude they reach. In this thesis precipitation data was used as the basis to design debris flow scenarios. Because of the long and consistent records of precipitation amounts this approach a robust statistical basis, but does not represent all processes and triggering factors that lead to debris flow creation in a catchment. By transforming precipitation return values to discharge and then debris flow volume return values, many uncertainties are introduced and catchment specific circumstances are mostly ignored. Within these limitations, the scenarios highlight potential trends in debris flow response under intensified precipitation and provide a basis for further investigation and improvement of the method.

Even though the method is able to produce debris flow scenarios very similar to observed events for the Milibach catchment and possibly the Altdorfbach, it severely underestimates actual debris flow potential in the two smallest catchments of the Selderbach and Schipfenbach and overestimates the potential of the Buoholzbach, based on past events. These findings are also reflected in the hazard maps created for the catchments. The hazard maps for the Milibach and Altdorfbach are similar to the official maps, while the official hazard maps for the Selderbach and Schipfenbach delineate a much larger area at risk from debris flows than the maps created from the scenarios. Interestingly the hazard map for the Buoholzbach resembles the official hazard maps a lot, suggesting that the scenarios calculated for the Buoholzbach range within possible values.



When assessing the effectiveness of existing or planned mitigation measures, the accuracy of the underlying scenarios becomes particularly important. Using scenarios too small or large do not provide reliable information on the protective effect of the structure. Further, detailed representation of mitigation measures in simulations are a prerequisite to assess the effectiveness of a structure. Even though the debris flow scenarios and representation of mitigation structures in the simulations include large uncertainties, the assessment of the effectiveness of mitigation measures are overall resemble reality. In the Milibach, Altdorfbach and Buoholzbach the presented scenarios suggest a protection deficit, while the mitigation measures in the Selderbach and Schipfenbach fulfil their protection goal. This is consistent with plans or lack thereof to adjust the mitigation measures. In the Buoholzbach construction for a considerably larger retention basin started in 2024, in the Altdorfbach construction of a second larger retention basin started in 2025, in the Milibach there are currently discussions over possible improvements to the mitigation measures and for the Selderbach and Schipfenbach there are no plans to adjust the mitigation measures.

With minor adjustments the presented scenarios and analyses can serve as a basis for more detailed and catchment specific investigations. The results can also serve as an initial screening tool over a large number of catchments that supports the prioritization of more detailed, site-specific studies.

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## 9 Appendix

### 9.1 Appendix 1) Field Documentation (in German)

This part of the Appendix is written in German, as the field documentation directly reflects the thoughts and discussion held on site. German was used during the field visits, as it was the primary language spoken by all participants. The following chapters are unredacted notes from the field visits.

#### 9.1.1 Buholzbach (10.6.2025)

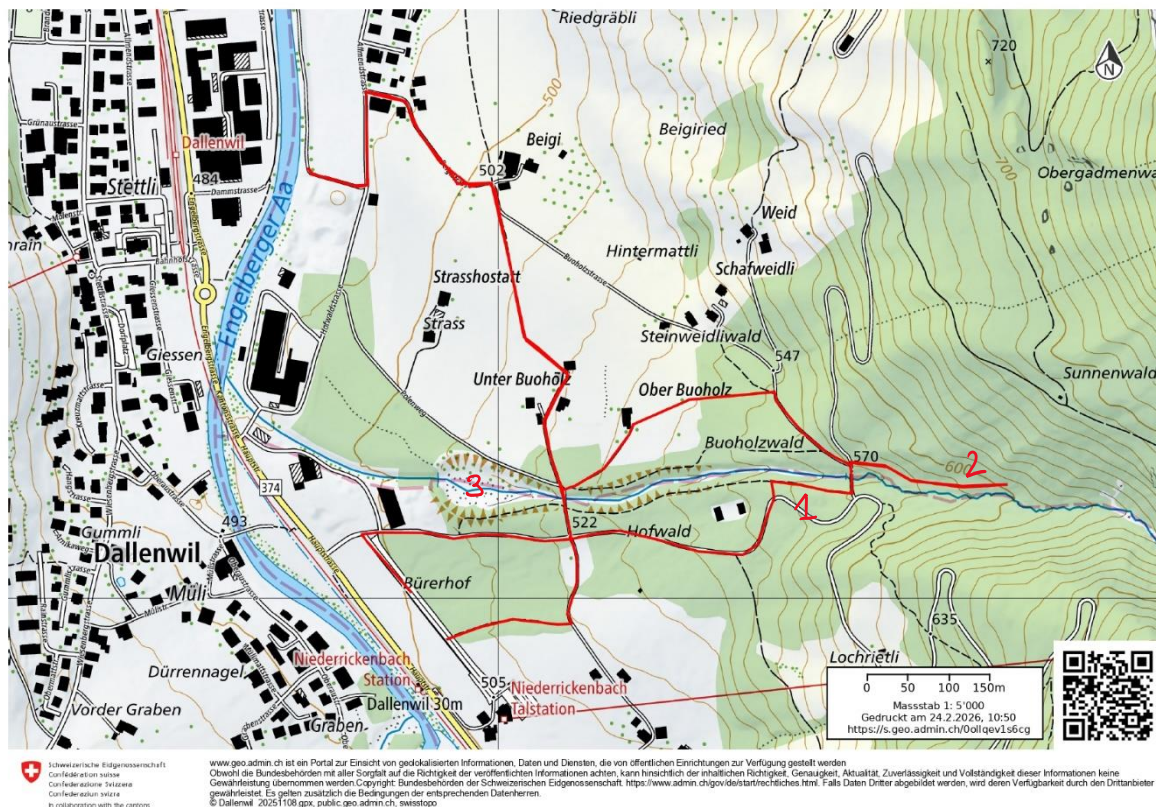


Figure A 1 Karte des unteren Buholzbachs mit der abgelaufenen Route in rot.

- 1) Im Auslaufgebiet des Bachs sind im von der Baustelle noch unberührten Gebiet typische Landschaftsformen eines Murgangkegels erkennbar, anhand der Vegetation ist anzunehmen, dass diese Ereignisse sehr lange her sind.
- 2) Etwas weiter oben hat es Ablagerungen von vermutlich 2005 mit junger Vegetation (Figure A 3).
- 3) Der alte Sammler (Figure A 2) wurde für ein Ereignis von 20'000m<sup>3</sup> designt und konnte 2005 30'000m<sup>3</sup> von 70'000m<sup>3</sup> zurückhalten, was vor dem Unwetter als sehr extrem eingestuft. Der neue Sammler inklusive Leitdämmen soll ca. 240'000m<sup>3</sup> zurückhalten, was nach heutiger Einschätzung ein 300-jährliches Ereignis wäre.

Der besuchten Bereich ist anhand des vorhandenen Sediments von kleinen bis sehr grossen Blöcken eher Ablagerungsgebiet (Figure A 4).

Hochwasserschutzprojekt (Figure A 5) ist eine Zweitvariante mit Kompromiss für die Standortbewahrung der vorhandenen Industriegebäude. Ein Hof wird aufgegeben/ersetzt. Die Kosten werden auf 50 Mio CHF geschätzt, wovon 65% vom Bund, 17.5% vom Kanton NW und 17.5% von den Gemeinden Wolfenschiessen und Dallenwil getragen wird.



Das Schadenpotential des Buoholzbachs ist sehr gross, da die Gefahr besteht, dass das abgelagerte Sediment die Engelberger Aa ausufert. In dem Fall würde die Engelberger Aa ihrem ursprünglichen Lauf folgen, von Dallenwil über Stans nach Stansstad, und im Verlauf sehr grosse Schäden verursachen

### Bilder



*Figure A 2 Der alte Geschiebesammler im Auslaufbereich des Buoholzbach. (Aufgenommen: 17.3.2025)*



*Figure A 3 Junge Ablagerungen von vermutlich 2005 entlang des Buoholzbachs mit junger Vegetation. (Aufgenommen: 17.3.2025)*



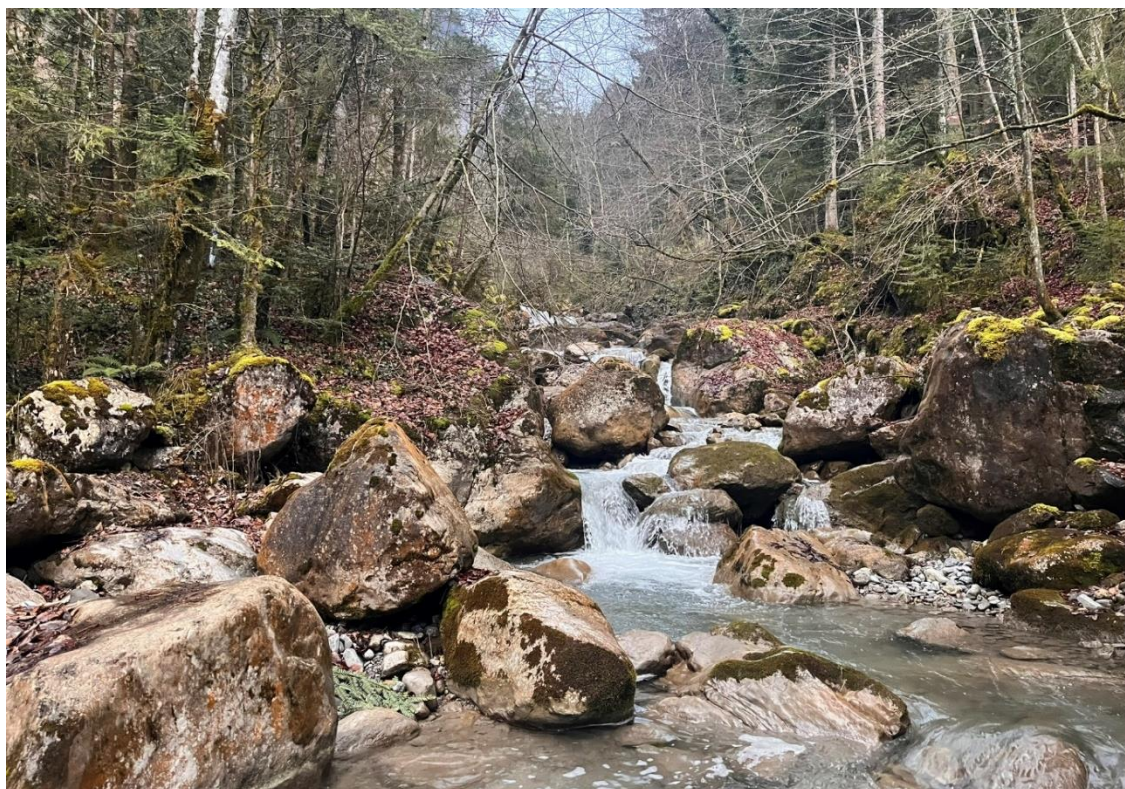


Figure A 4 Der Buoholzbach flussaufwärts mit zum Teil sehr grossen Blöcken im Bachbett.



Figure A 5 Visualisierung des Hochwasserschutzprojekts (Kanton Nidwalden, Buoholzbach.ch).



### 9.1.2 Altdorfbach (10.6.2025)

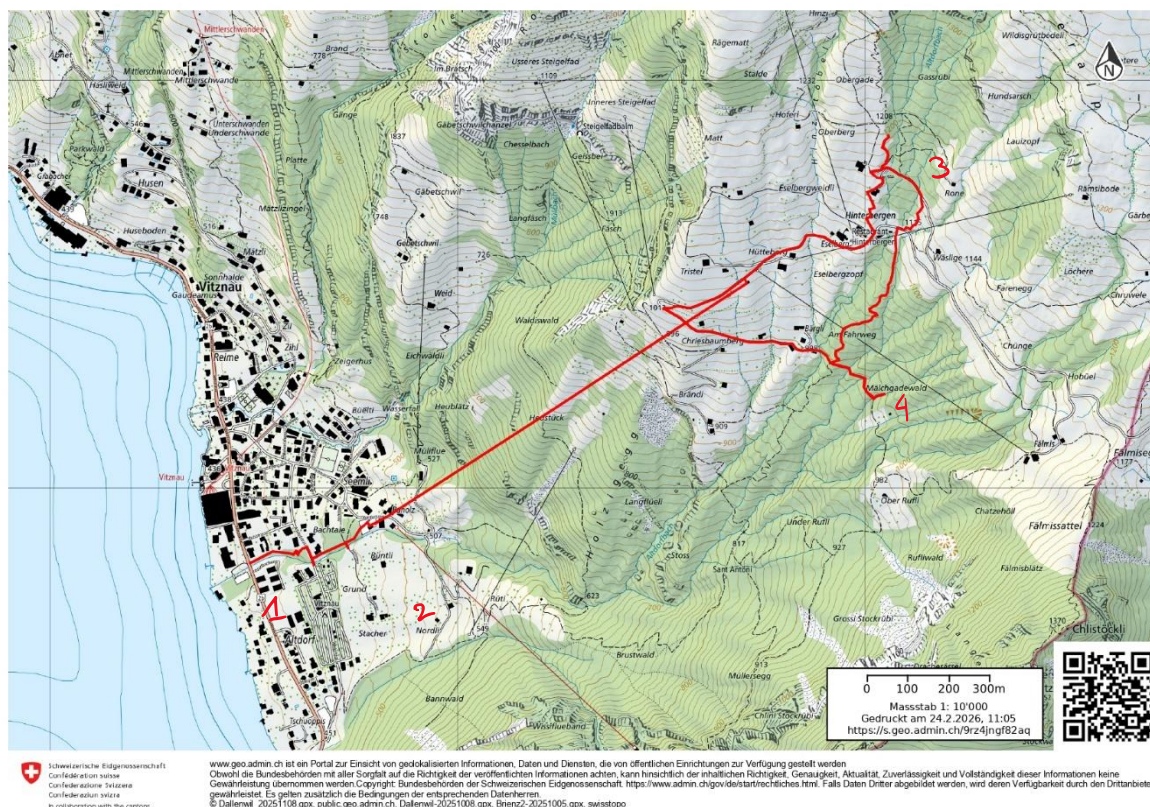


Figure A 6 Karte des Altdorfbachs mit der abgelaufenen Route in rot.

- 1) Im Dorf ist der Altdorfbach kanalisiert für den schnellen Abfluss (Figure A 7).
- 2) Von der Luftseilbahn aus ist ein Geschiebesammler oberhalb des Dorfs sichtbar (Figure A 8).
- 3) Hinterbergen: Der Altdorfbach hat viele kleine Zubringerarme. Das Einzugsgebiet bildet eine Art Kessel mit Öffnung gegen Südwesten, von wo vorherrschend Gewitterfronten ziehen. Im Einzugsgebiet ereignete sich 2024 ein grosser Erdrutsch von 400'000m<sup>3</sup> (Figure A 9). Der Hauptarm vom Altdorfbach fliesst durch diesen Rutsch und hatte 2024 bereits Murgänge geführt, welche aber nicht sehr weit kamen. Das ganze Gebiet ist überwacht mit Frühwarnsystem für Vitznau. Die Sedimentfracht bei maximaler Erosion wurde für das Bachstück, das durch den Rutsch fliesst auf 10+ m<sup>3</sup> pro Laufmeter geschätzt.
- 4) Die kleineren Nebenarme im Einzugsgebiet führen wenig Wasser und es ist wenig Sediment sichtbar (Figure A 10). Im Feld wurde für die Seitenarme die Sedimentfracht bei maximaler Erosion auf ca. 2m<sup>3</sup> pro Laufmeter geschätzt.

Vitznau liegt zu grossen Teilen in der roten und blauen Zone und die Gefahr von Murgangprozessen wird in der Gefahrenkarte ausgewiesen für den Altdorfbach. Auffällig war das dennoch rege gebaut wird. Seit dem Rutsch werden unter Notrecht Schutzmassnahmen gebaut, u.a. ist die Vergrösserung des bestehenden Sammlers und der Neubau eines zweiten Sammlers geplant mit Baustart 2025.



Bilder



*Figure A 7 Bachbett des Altdorfbachs im untersten Teil durch Vitznau.*

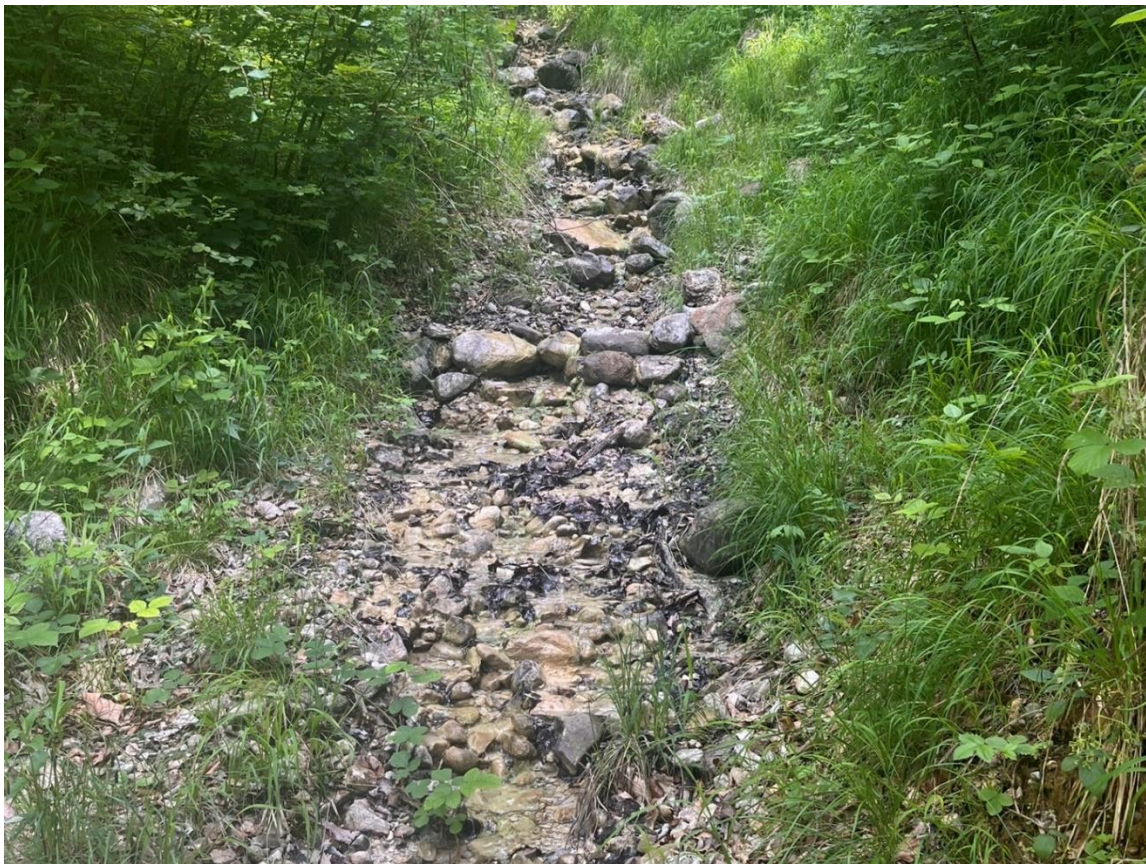


*Figure A 8 Geschiebesammler oberhalb von Vitznau, gebaut 2006.*





*Figure A 9 Der grosse Erdrutsch Gassrübi auf der Vitznaueralp.*



*Figure A 10 Kleinerer Nebenarm des Altdorfbachs.*



### 9.1.3 Milibach (7.8.2025)

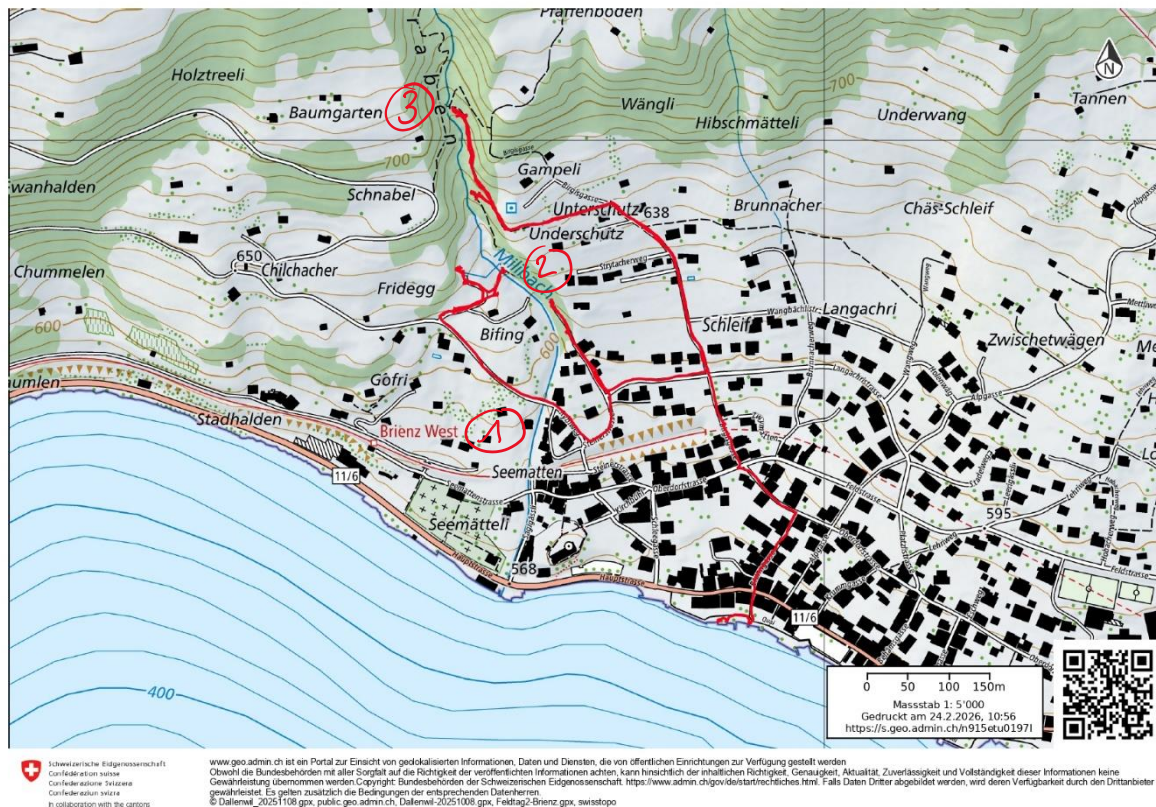


Figure A 11 Karte des unteren Milibachs in Brienz BE mit der abgelaufenen Route in rot.

- 4) Im Dorf wird der Milibach in einem engen und gut befestigten Bachbett geleitet, für einen möglichst schnellen Abfluss (Figure A 12). Die Spuren vom August 2024 sind zwischen See und Geschiebesammler noch gut sichtbar. Das Bachbett wurde wieder repariert (Figure A 13)
- 5) Der Geschiebesammler oberhalb des Dorfes, der überspült wurde, konnte ein Volumen von 18'000m<sup>3</sup> zurückhalten (Figure A 14).
- 6) Starke Erosion im Bachbett oberhalb des Geschiebesammlers zwischen 5 und 10 m tief und Ablagerung von sehr grossen Blöcken. Der Wanderweg, der entlang des Milibachs zur Planalp führt wurde zum Teil weggespült. Die Brücke bei Punkt 3 auf der Karte wurde komplett zerstört. (Figure A 15 - Figure A 17)

Aufgrund der nach dem Ereignis sofort aufgenommenen Wiederaufbauarbeiten, ist das Geschiebe rund um den Sammler und darunter nicht mehr im natürlichen Zustand und wurde meist von Maschinen verschoben oder abgetragen. Das alte Bachbett durchs Dorf wurde aber beim Ereignis zerstört und Häuser rund um den Milibach wurden beschädigt. Es sind ein Jahr nach dem Ereignis immer noch Schuttmassen und Spritzer bis unter das Dach von einzelnen Gebäude sichtbar (Figure A 18).

Es besteht einen Projektvorschlag für die Verlagerung des Milibachs gegen Westen, aus dem Dorf heraus.

Das Ereignis von August 2024 wurde von Experten als sehr selten eingestuft. Es wurden bis 100 l/m<sup>2</sup> Regen in einer Stunde und eine Abflussspitze bis 45 m<sup>3</sup>/s gemessen.



## Bilder



Figure A 12 Das Flussbett des Milibachs im Dorf kurz vor der Mündung in den See.





Figure A 13 Bachbett im oberen Teil des Dorfes, welches seit August 2024 repariert wurde.

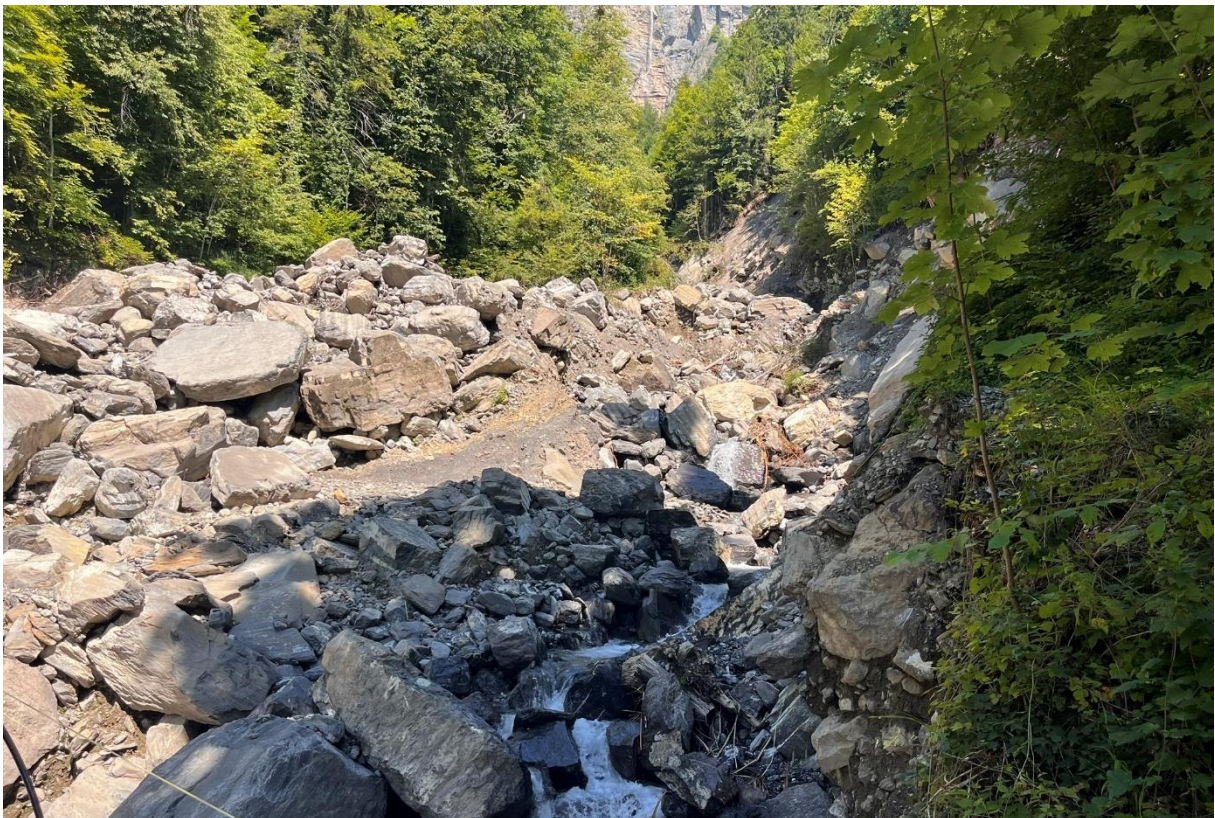


Figure A 14 Der im Jahr 2017 gebaute Geschiebesammler oberhalb von Brienz. Gut sichtbar, die Spuren der Überlastung an der Krone des Sammlers.





*Figure A 15 Unterspülter und teilweise abgestürzter Wanderweg.*



*Figure A 16 Ablagerungsgebiet von Blöcken mit zum Teil mehreren Metern Kantenlänge.*





Figure A 17 Das Bachbett des Milibachs an der Stelle wo früher eine Brücke stand. Der Bach verläuft in einer bis 8m tief erodierten Rille. An beiden Ufern sind grosse Ablagerungen zu finden.



Figure A 18 Spuren des Murgangs von August 2024 an den Gebäude nahe des Milibachs.



### 9.1.4 Milibach (5.10.2025)

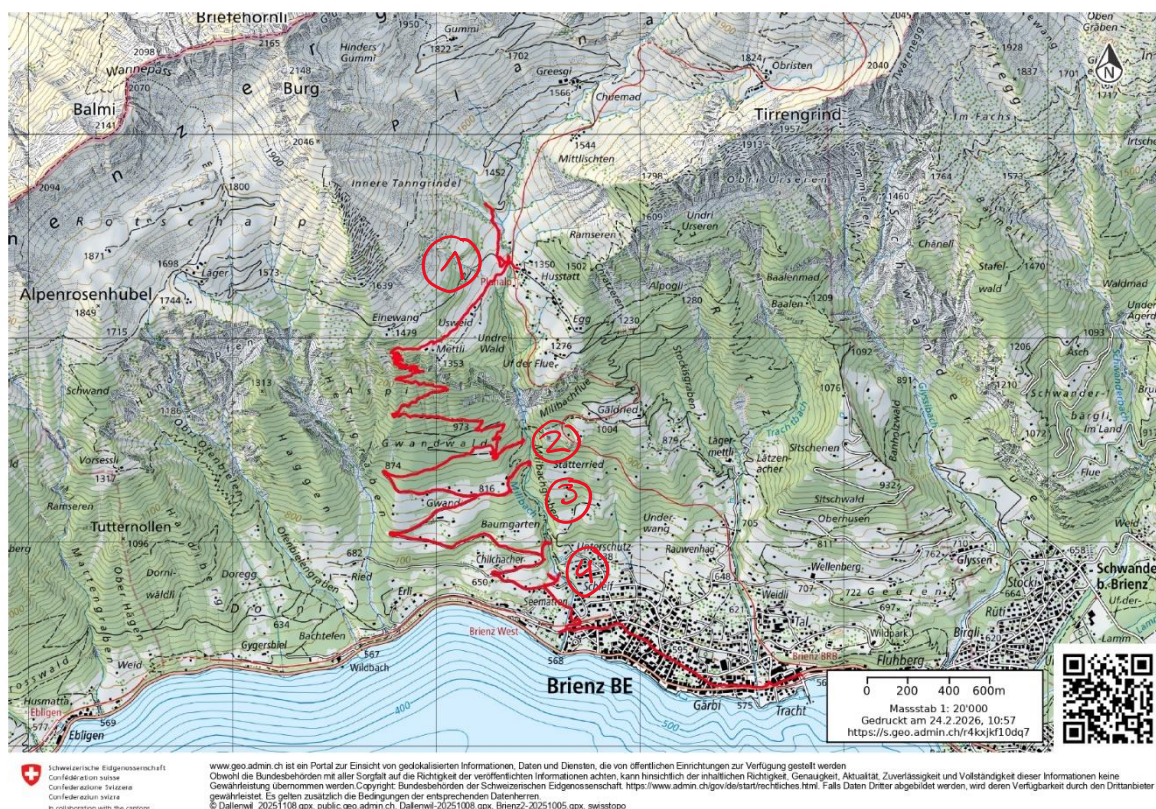


Figure A 19 Karte des Einzugsgebiets des Milibachs in Brienz BE mit der abgelaufenen Route in rot. Der obere Teil des Einzugsgebiets wurde aus zeitlichen Gründen von der BRB aus erkundet.

#### Einzugsgebiet ob Planalp

Das Einzugsgebiet ob der Planalp ist grossräumig und ähnelt in seiner Form einem Kessel (Figure A 20).

Neben den beiden wasserführenden Armen des Milibachs oberhalb der Planalp gibt es rund herum dutzende Runsen, die alle in den Milibach führen. Bei grossen Niederschlägen werden diese alle Wasser zuführen.

Wegen Schnee war es schwieriger zu sehen, aber der Grossteil der Runsen verläuft auf dem Grundgestein oder über ein paar cm Boden (Figure A 21). Lediglich die Runsen und Bächlein westlich der Planalp scheinen Sediment mitzuführen (Figure A 23).

Die beiden Arme des Milibachs führen Sediment, es lagert sich aber grösstenteils auf der Planalp ab.

Die zwei Arme des Milibachs ob der Planalp fliessen über abwechselungsweise flache Terrassen und steilere Stücke dazwischen. Die Terrassen befinden sich bei Obristen und Chuemad. Der Milibach hat sich zum Teil tief in das weiche Lockergestein (LGM Moräne) eingefressen.

### Planalp bis Brienersee

- 1) Planalp – Die Planalp ist relativ flach und Spuren von Sedimentablagerung sind vorhanden (Figure A 22), minimale Erosion. Zubringerbäche und Runsen bringen relativ wenig Sediment, Grundgestein ist meistens anstehend, ich gehen davon aus, dass hauptsächlich Wasser bis zur Planalp kam. Das Bahntrasse der Brienz-Rothorn-Bahn (BRB) wurde 2024 in der Planalp unterspült. Eine Brücke wurde beschädigt (Figure A 24).
- 2) Wasserfall – Das ganze Becken unterhalb des Wasserfalls wurde mehrere Meter tief (bis 10m) ausgewaschen, grosse Blöcke ( $d > 2.5\text{m}$ ) wurden bewegt, die Brücke und Teile des Wanderwegs wurden komplett zerstört, von der Brücke ist nichts mehr zu sehen (Figure A 25).  
Das Grundgestein ist sehr weich, das Wasser hat innerhalb eines Jahres bereits 1 m gegraben.
- 3) Obermad – starke Tiefenerosion (bis 10m), der Wanderweg ist abgerutscht
- 4) Schnabel – starke Tiefenerosion mit grossen Blöcken, klare Zeichen von Erosion

### Bilder



Figure A 20 Das Einzugsgebiet gesehen vom Briener Rothorn, gut ersichtlich ist die kesselartige Form des oberen Einzugsgebiets.





Figure A 21 Die Runsen oberhalb des Milibachs laufen grösstenteils über das anstehende Grundgestein.



Figure A 22 Sedimentablagerungen oberhalb der Planalp. Im Zentrum der Hauptarm des Milibachs und von links zwei Zubringer.





Figure A 23 Einer der beiden Zubringer (im Bild oben von links kommend) verläuft zwar übers Grundgestein, ist aber trotzdem in der Lage gewisse Mengen an Sediment mitzuführen.



Figure A 24 Brücke neben der BRB-Station Planalp frisch repariert.





*Figure A 25 Das Gebiet direkt unterhalb des Wasserfalls mit starker Tiefenerosion und Hangrutschungen.*



### 9.1.5 Buoholzbach (8.10.2025)

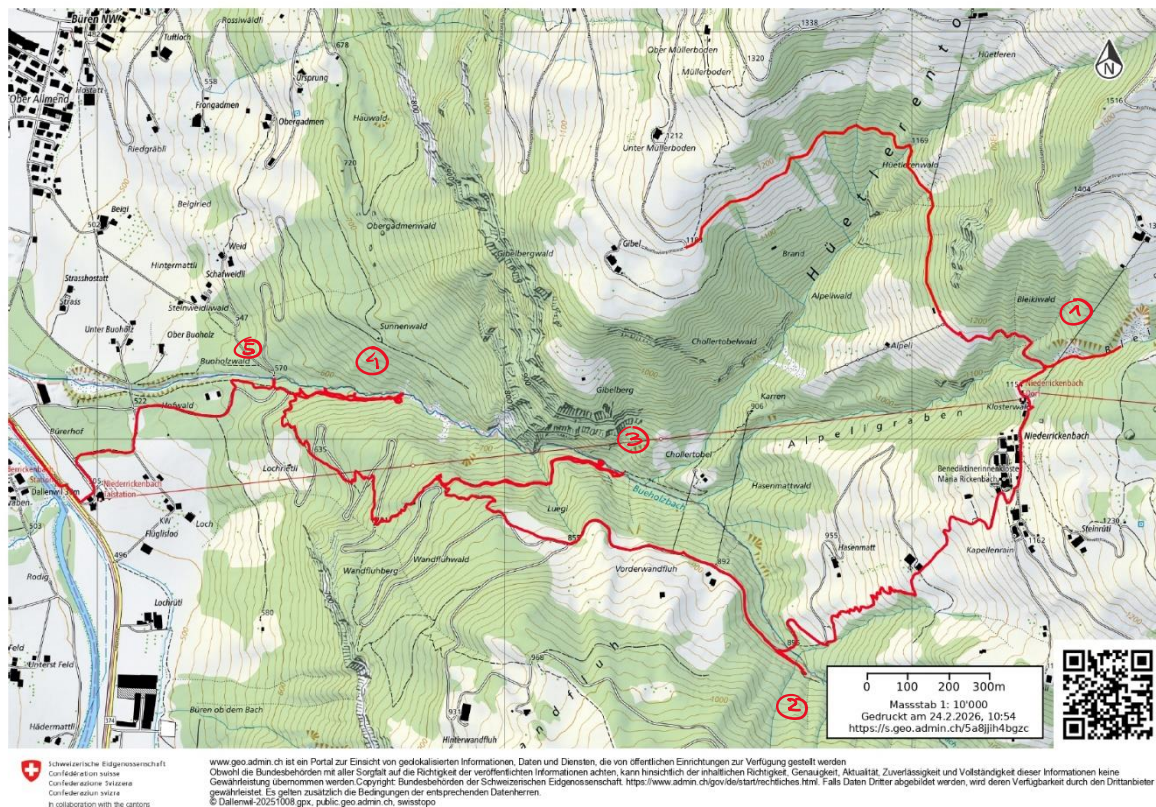


Figure A 26 Karte des Buoholzbachs zwischen Dallenwil und Niederrickenbach mit der abgelaufenen Route in rot.

- 1) Bleikigraben Geologie: entlang eines Bruchs in Hangschutt, Rutschgebiet und in Kalk der Klippendecken -> Sehr viel Material vorhanden (Figure A 27). Das Rutschmaterial ist sehr locker und durchnässt -> 2.5 – 5 m<sup>3</sup> pro Laufmeter  
Korndurchmesser grösster 20% ungefähr 20-50 cm, grösste Blöcke >1 m
- 2) Sammler von Buoholzbach vor der Einmündung von Bleikigraben- und Hütlerentobel (Figure A 28), Im Gebiet rund um den Sammler ist das Betreten verboten; der Sammler selbst, scheint voll zu sein -> Rückhaltefunktion fraglich.
- 3) Flacher Abschnitt mit sehr grossen Blöcken (>3m) und Step-pools (Figure A 29) -> Anhand der Vegetation evtl. Ablagerungsgebiet (Figure A 30)
- 4) Beginn Auslaufkegel, eher flach mit Step-pools und Schwellen für das Geschiebemanagement (Figure A 31), sehr grosse Blöcke vorhanden und Spuren von vergangenen Ereignissen im Wald um das Bachbett vorhanden -> Ablagerungsflächen, Levées, verschüttete Baumstämme und junge Vegetation
- 5) Beginn Baustelle für neues Rückhaltebecken



## Bilder



Figure A 27 Bleikigraben an einer Stelle mit sehr grossen Rutschgebieten.



Figure A 28 Sammler oberhalb von Chollertobel.



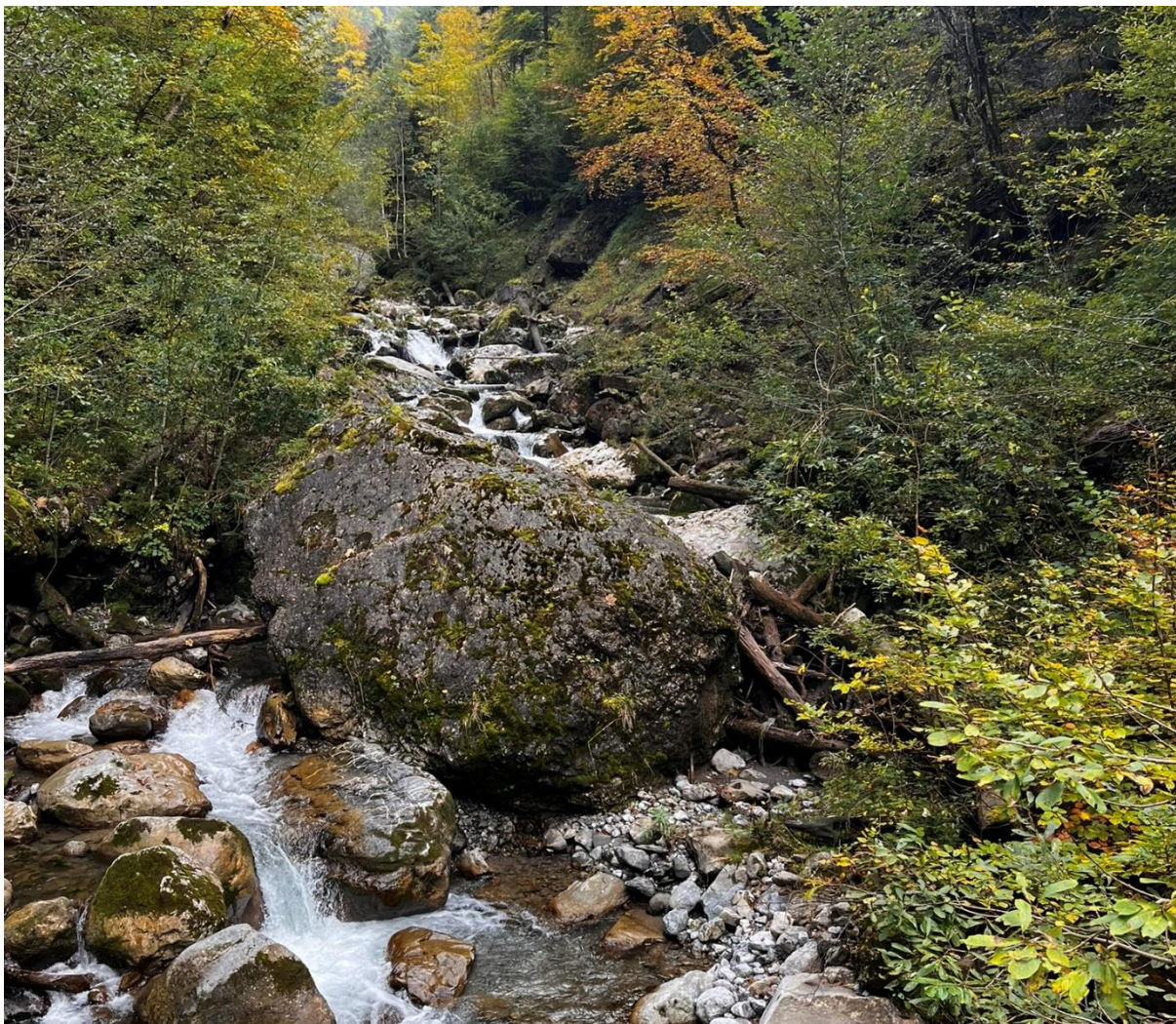


Figure A 29 Flacher Abschnitt ob Chollertobel.



Figure A 30 Flacher Abschnitt nach Chollertobel mit seitlichen Ablagerungen mit nur sehr kleiner Vegetation.





*Figure A 31 Schwelle im untersten Bereich des Buoholzbachs ob dem Ablagerungskegel.*



### 9.1.6 Buholzbach (8.11.2025)

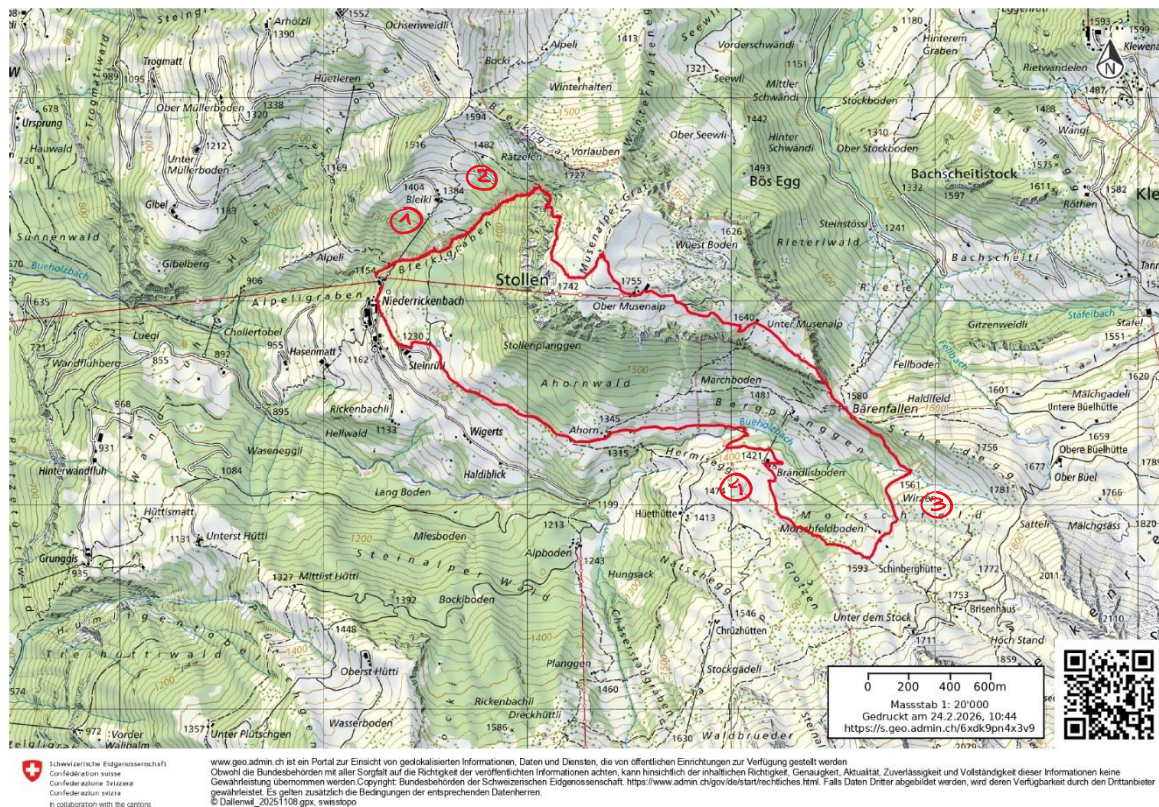


Figure A 32 Karte des oberen Einzugsgebiets des Buholzbachs mit der abgelaufenen Route in rot.

- 1) Entlang des Bleikigrabens hat es zahlreiche aktive Rutschgebiete mit viel Hangschutt von dem oberhalb liegenden Bleikigrat. Das erste Rutschgebiet von Niederrickenbach aus hat sich im letzten Monat (seit der letzten Begehung) sichtlich bewegt. Das Bachbett wurde zugeschüttet, das Wasser fliesst unterirdisch. Weiter oben im grössten Rutschgebiet sind Abflussrille und murgangähnliche Ablagerungen im Hangschutt zu sehen (Figure A 33).
- 2) Im obersten Teil des Bleikigrabens hat es weniger grosse instabile Hangschuttflächen. Der Bleikigraben läuft meist auf Grundgestein (Figure A 34)
- 3) Das Quellgebiet des Hauptarms des Buholzbachs besteht aus Alpweiden mit verteilten Baumgruppen, der Buholzbach führt relativ wenig Wasser und einigen Seitenarme sind trocken. Die Nebenarme sind im Gelände nicht erkennbar, wenn nicht darauf geachtet wird
- 4) Im Bereich Brändlisboden ist das Gefälle gering, der Buholzbach mäandriert über die Ebene, grössere Ablagerungsflächen von grobem Kies und Steinen vorhanden (Figure A 35 und Figure A 36)



## Bilder



Figure A 33 Abflusserillen und murgangähnliche Ablagerung im Rutschgebiet entlang des Bleikigrabens.



Figure A 34 Oberer Bleikigraben verläuft grösstenteils direkt auf dem Grundgestein.





*Figure A 35 Ablagerungen im Bereich Brändlisboden.*



*Figure A 36 Mäandrierender Buoholzbach unterhalb des Brändlisboden.*



### 9.1.7 Selderbach und Schipfenbach (15.11.2025)

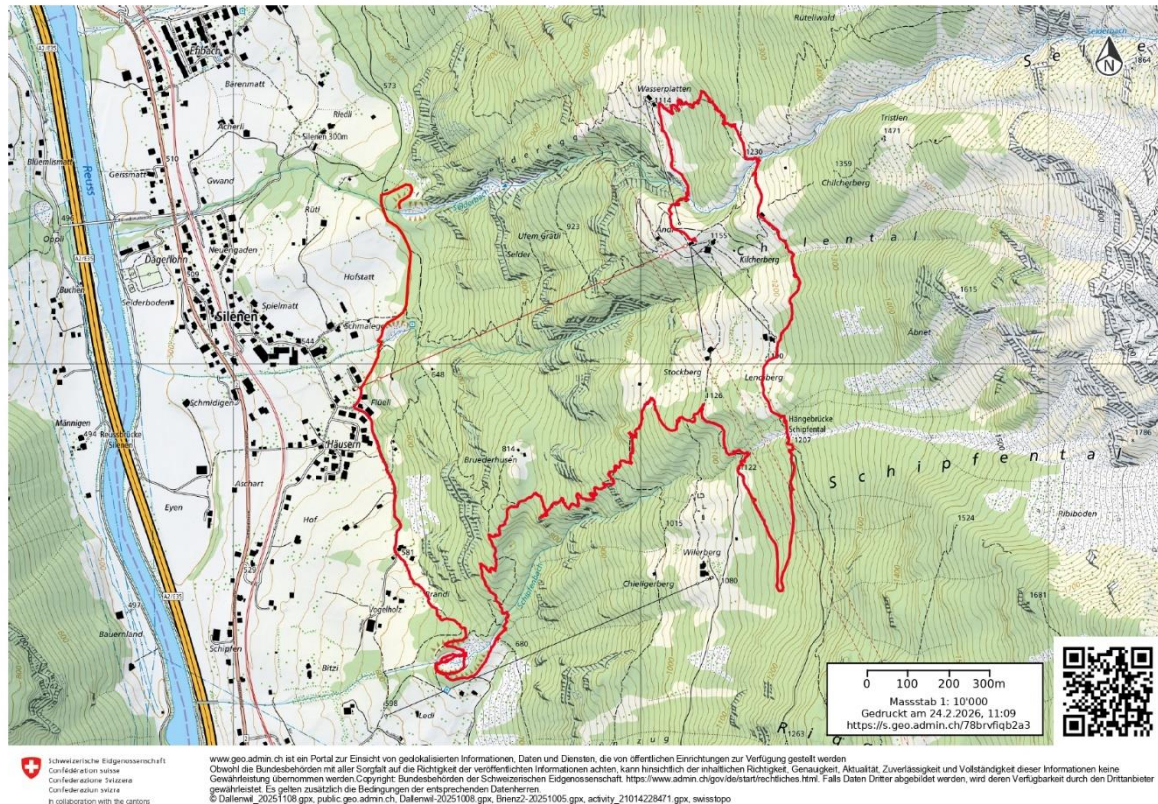


Figure A 37 Karte der abgelaufenen Route in rot im Einzugsgebiet des Selder- und Schipfenbach oberhalb von Silenen.

#### Selderbach Einzugsgebiet oben

- Sehr felsig -> anstehender Fels aber auch viel Lockermaterial vorhanden (Figure A 38)
- Bachbett trocken aber sauber (kein Laub) -> vor kurzem Wasser geführt (Figure A 39)
- Kratzspuren und frisch freigelegte (nicht verwitterte) Flächen an grossen Blöcken und Grundgestein

#### Schipfenbach ab Hängebrücke

- Stark eingeschnitten 10-15m tiefes Bachbett in Lockermaterial -> alles erodierbar, rutscht nach wenn unten weg erodiert, sehr viel Material vorhanden -> auch grosse Blöcke (Figure A 40)
- Hinweise für regelmässig bewegtes Sediment im Bachbett vorhanden -> Kratzspuren an grossen Blöcken, keine Vegetation, Wanderwege anders als auf Karte eingezeichnet und zum Teil provisorisch (keine Fixierungen, nur Trampelpfad), weggeschwemmte Weidezäune im Bachbett (Figure A 41)

#### Schipfenbach Geschiebesammler

- Relativ frische (feuchte) Ablagerungen im Geschiebesammler, ca. 1-2 m dick (Figure A 43)
- Mitteldamm im Rückhaltebecken nicht sichtbar, unter Ablagerungen begraben



Bilder



Figure A 38 Bachbett des Selderbachs oberhalb von Kilchberg, Blickrichtung Flussaufwärts.





*Figure A 39 Bachbett des Selderbachs auf Höhe Kilchberg.*





*Figure A 40 Bachbett des Schipfenbach Flussaufwärts von der Hängebrücke. Einschnitt ins Gelände ca. 10-15 m.*





*Figure A 41 Bachbett des Schipfenbachs oberhalb des Geschiebesammler mit Blick Flussaufwärts.*



*Figure A 42 Geschiebesammler und Abschlussbauwerk am Schipfenbach.*





Figure A 43 Einlauf in den Geschiebesammler des Schipfenbachs. Zum Zeitpunkt der Begehung waren Ablagerungen von ca. 1m im Sammler von einem kleinen Ereignis vorhanden.



Figure A 44 Steiler Mittellauf des Selderbach und Geschiebesammler.



## 9.2 Appendix 2) Torrent profile R-Code

```
# =====
# Longitudinal profile
# - Highlights segments steeper than 25° (in red)
# - Adds POIs with callout boxes + arrows
#
# Notes:
# * Swiss decimal notation handled via readr locale.
# * dx_min filters near-zero horizontal steps that create artefacts.
# Set dx_min to your preferred scale (e.g., 0.5, 1, 2, 5).
# =====

library(readr)

# ---- SETTINGS ----
setwd("C:/Users/mayab/OneDrive - Universität Zürich UZH/Masterthesis/Feld/Steilheitklassen/Brienz/print")
infile <- "Milibach-swisstopo.csv"
outfile <- "Milibach-profile_25deg_POI.png"

thr_deg <- 25
dx_min <- 2 # [m] try 0.5 / 1 / 2 / 5 depending on noise / desired smoothing

# ---- READ DATA ----
df <- read_csv2(
  infile,
  locale = locale(decimal_mark = ",", grouping_mark = """),
  show_col_types = FALSE
)

names(df) <- trimws(names(df))
df <- df[, c("Distance", "Altitude")]

df$Distance <- as.numeric(df$Distance)
df$Altitude <- as.numeric(df$Altitude)

df <- df[is.finite(df$Distance) & is.finite(df$Altitude), ]
df <- df[order(df$Distance), ]

# ---- COMPUTE SLOPES ----
dx <- diff(df$Distance)
dz <- diff(df$Altitude)

slope_ratio <- dz / dx
thr <- tan(thr_deg * pi/180)

steep <- is.finite(slope_ratio) & dx > dx_min & slope_ratio > thr

# ---- PLOT BASE ----
png(outfile, width = 1600, height = 900, res = 150)
par(mar = c(5, 5, 4, 2) + 0.1)

plot(
  df$Distance, df$Altitude,
  type = "l",
  col = "grey40", lwd = 2,
  xlab = "Distance along torrent profile (m)",
  ylab = "Elevation (m a.s.l.)",
  main = sprintf("Milibach profile with segments steeper >%d° and key locations", thr_deg),
  panel.first = grid(col = "grey85")
)

# ---- STEEP SEGMENTS ----
idx <- which(steep)
if (length(idx) > 0) {
  segments(
    df$Distance[idx], df$Altitude[idx],
    df$Distance[idx + 1], df$Altitude[idx + 1],
    col = "red", lwd = 5
  )
}
```

```

)
}

# ---- POIs (YOUR LIST) ----
poi <- data.frame(
  name = c("retention basin", "waterfall", "Planalp", "Obristen"),
  dist = c(460, 1400, 2040, 4250),
  col = c("orange", "dodgerblue3", "grey40", "grey40"),
  pch = c(19, 19, 19, 19),
  stringsAsFactors = FALSE
)

nearest_alt <- function(d) df$Altitude[which.min(abs(df$Distance - d))]
poi$alt <- vapply(poi$dist, nearest_alt, numeric(1))

# markers
points(poi$dist, poi$alt, pch = poi$pch, col = poi$col, cex = 1.2)

# Callout offsets (tweak if you want)
# positive offset_x moves label right, negative left
offset_x <- c(-150, 250, -150, 250)
offset_y <- c(130, -100, 130, -120)

for (i in seq_len(nrow(poi))) {
  x0 <- poi$dist[i]; y0 <- poi$alt[i]
  x1 <- x0 + offset_x[i]; y1 <- y0 + offset_y[i]

  arrows(x1, y1, x0, y0, length = 0.08, lwd = 1.5)

  lab <- poi$name[i]
  w <- strwidth(lab, cex = 0.95, units = "user") * 1.15
  h <- strheight(lab, cex = 0.95, units = "user") * 1.80

  rect(x1 - w/2, y1 - h/2, x1 + w/2, y1 + h/2,
    col = "white", border = poi$col[i], lwd = 2)
  text(x1, y1, lab, col = poi$col[i], cex = 0.95)
}

# ---- LEGEND ----
legend(
  "bottomright",
  legend = c("Profile (all slopes)", sprintf("Slope > %d°", thr_deg)),
  col = c("grey40", "red"),
  lwd = c(2, 5),
  bty = "o"
)

# Optional: POI legend (uncomment if you want it on the plot)
# legend(
#   "topleft",
#   legend = paste0(poi$name, " (", poi$dist, " m)"),
#   pch = poi$pch, col = poi$col, pt.cex = 1.1,
#   bty = "o"
# )

dev.off()

cat("Finished. Output written to:", outfile, "\n")

```

### 9.3 Appendix 3) Extreme value statistics R-Code

```
# Pakete

library(readr)

library(dplyr)

library(lubridate)

##Jahresmaxima

# 1) read data (evt. read_csv2, if ; as separator)

setwd("C:/Users/mayab/OneDrive - Universität Zürich UZH/Masterthesis/Scenarios/Brienzen/Niederschlag-Brienzen/vergleich")

d <- read_csv2("ogd-smn_brz_d_historical.csv",
               locale = locale(encoding = "UTF-8"),
               show_col_types = FALSE)

# 1.5) transform date to correct format

#d <- d %>%

# mutate(

#   date = as.Date(as.POSIXct(Datum, format = "%d.%m.%Y %H:%M", tz = "Europe/Zurich"))
# )

d <- d %>%

mutate(

  date = as.Date(Datum, format = "%d.%m.%Y %H:%M")

)

# 2) convert data with commas to points

d <- d %>%

mutate(

  prcp_mm = as.numeric(gsub(",", ".", Tagesniederschlag))

)

# 2.5) define time window (entire record period, later 1901-2024 and 1990-2024)

d <- d %>%

filter(!is.na(date)) %>%
```



```

filter(year(date) >= 1901, year(date) <= 2024)

# 3) if more than one measurement → daily sums
daily <- d %>%
group_by(date) %>%
summarise(prcp_mm = sum(prcp_mm, na.rm = TRUE), .groups = "drop")

# 3.1) save daily series and split time window
daily_all <- daily

daily_1901 <- daily_all %>%
filter(year(date) >= 1901, year(date) <= 2024)

daily_1990 <- daily_all %>%
filter(year(date) >= 1990, year(date) <= 2024)

# 4) calculate yearly maxima
jahresmaxima <- daily_all %>%
mutate(Jahr = year(date)) %>%
group_by(Jahr) %>%
summarise(
  Max_Niederschlag = max(prcp_mm, na.rm = TRUE),
  Datum_max = date[which.max(prcp_mm)],
  .groups = "drop"
) %>%
arrange(Jahr)

# 5) Check: display highest value and year
print(jahresmaxima %>% filter(Max_Niederschlag == max(Max_Niederschlag)))

# 6) Plot der Jahresmaxima (ähnlich wie dein Beispiel)

png("jahresmaxima-jahre.png", width = 1600, height = 900, res = 150)

with(jahresmaxima, {
plot(Jahr, Max_Niederschlag,
  type = "h", lwd = 2, col = "black",
  main = "Maximaler Tagesniederschlag pro Jahr",
  xlab = "Jahr", ylab = "Niederschlag [mm/d]",

```

```

    xaxt = "n")
axis(1, at = pretty(Jahr, n= 20))
box()
})

dev.off()

##Histogramme und GEV-distribution

# install.packages("extRemes")
library(extRemes)

# 1) data
x <- jahresmaxima$Max_Niederschlag

# 2) adjust GEV
fit <- fevd(x, type = "GEV", method = "MLE")

mu <- fit$results$par["location"]
sigma <- fit$results$par["scale"]
xi <- fit$results$par["shape"]

# 3) define own GEV-distribution
dgev <- function(q, loc, scale, shape) {
  z <- (q - loc) / scale
  t <- 1 + shape * z
  if (any(t <= 0)) return(rep(NA, length(q)))
  if (abs(shape) < 1e-6) {
    d <- (1/scale) * exp(-(z + exp(-z)))
  } else {
    d <- (1/scale) * (t^(-1/shape - 1)) * exp(-t^(-1/shape))
  }
  return(d)
}

# 4) create Plot
png("histogramm_gev.png", width = 1600, height = 900, res = 150)

#Histogramme and GEV-curve

```

```

hist(x,
     probability = TRUE,
     breaks = 20,
     col = "grey80", border = "grey40",
     main = "Histogramm der Extrema mit GEV-Kurve",
     xlab = "Max. Tagesniederschlag [mm]",
     ylab = "Dichte")

xx <- seq(min(x, na.rm = TRUE), max(x, na.rm = TRUE), length.out = 400)
lines(xx, dgev(xx, loc = mu, scale = sigma, shape = xi),
      col = "red", lwd = 2)

legend("topright",
      legend = c("Histogramm", "GEV-Verteilung"),
      col = c("grey40", "red"),
      lwd = c(10, 2),
      bty = "n")

dev.off()

#QQ-Plot

# QQ-Plot with extRemes
png("qqplot_gev.png", width = 1600, height = 900, res = 150)

plot(fit, type = "qq", col = "black", pch = 19)

# 1:1-Diagonale
abline(0, 1, col = "red", lwd = 2)

dev.off()

## frequency diagramme

# create Plot
png("frequenzdiagramm_gev.png", width = 1600, height = 900, res = 150)

plot(fit, type = "rl",
     main = "Frequenzdiagramm GEV",

```



```

col = "black", pch = 19,

ci = TRUE,          # Konfidenzbänder aktivieren

ci.col = "green",   # Farbe der Bänder

ci.type = "delta",  # Methode: delta = analytisch, boot = Bootstrap

log.scale = TRUE)   # x-Achse logarithmisch (wie MeteoSchweiz)

dev.off()

# define return periods
perioden <- c(10, 30, 100, 300, 1000)

# return periods
return.level(fit, return.period = perioden)

# calculate Return Levels with 95%-confidence intervals
rl <- return.level(fit, return.period = perioden, do.ci = TRUE, ci.type = "delta")

# display results
rl

write.csv(rl, "return_levels_with_ci.csv", row.names = FALSE)

# 1) find top-5-events in terms of precipitation
top5 <- jahresmaxima %>%
  arrange(desc(Max_Niederschlag)) %>%
  slice(1:5)

# 2) extract GEV-parameters
mu  <- fit$results$par["location"]
sigma <- fit$results$par["scale"]
xi  <- fit$results$par["shape"]

# 3) GEV-distribution (CDF)
pgev <- function(q, loc, scale, shape) {
  if (abs(shape) < 1e-6) {
    exp(-exp(-(q - loc) / scale))
  }
}

```

```

} else {

  t <- 1 + shape * (q - loc) / scale

  ifelse(t <= 0, NA, exp(-t^(-1 / shape)))

}

}

# 4) calculate return period (T = 1 / (1 - F(x)))
top5 <- top5 %>%

mutate(

  F = pgev(Max_Niederschlag, loc = mu, scale = sigma, shape = xi),

  Wiederkehrperiode_Jahre = 1 / (1 - F)

)

# 5) formatted table

top5 %>%

select(Jahr, Datum_max, Max_Niederschlag, Wiederkehrperiode_Jahre)

write.csv(top5, "top5_events-return_periods.csv", row.names = FALSE)

-----

## POT / GPD (Focus on extremes) + visual comparison 1901–2024 vs. 1990–2024

# helper function: POT-Events (declustert) + GP-Fit
make_pot_fit <- function(daily_df, p_u = 0.98, r = 2) {

  u <- as.numeric(quantile(daily_df$prcp_mm, probs = p_u, na.rm = TRUE))

  pot_events <- daily_df %>%

  arrange(date) %>%

  mutate(exceed = prcp_mm > u) %>%

  mutate(exceed_date = ifelse(exceed, as.numeric(date), NA_real_)) %>%

  mutate(

    last_exceed_date = lag(exceed_date),

    gap = exceed_date - last_exceed_date,

    new_cluster = ifelse(exceed & (is.na(gap) | gap > r), 1, 0),

    cluster_id = cumsum(ifelse(is.na(new_cluster), 0, new_cluster))

  ) %>%

  filter(exceed) %>%

  group_by(cluster_id) %>%

```

```

summarise(
  event_date = date[which.max(prcp_mm)],
  event_max = max(prcp_mm, na.rm = TRUE),
  .groups = "drop"
)

fit <- fevd(pot_events$event_max, threshold = u, type = "GP", method = "MLE")
list(u = u, events = pot_events, fit = fit)
}

# Parameter
p_u <- 0.98 # 98%-Schwelle (gute Balance Extrem-Fokus vs. Stabilität)
r <- 2 # Declustering-Abstand in Tagen

pot_1901 <- make_pot_fit(daily_1901, p_u = p_u, r = r)
pot_1990 <- make_pot_fit(daily_1990, p_u = p_u, r = r)

# save Diagnostics separately
png("pot_gpd_diagnostics_1901-2024.png", width = 1600, height = 900, res = 150)
plot(pot_1901$fit)
dev.off()

png("pot_gpd_diagnostics_1990-2024.png", width = 1600, height = 900, res = 150)
plot(pot_1990$fit)
dev.off()

# Return-Level comparison (on top of each other) incl. 95%-CI (dashed)
T <- seq(2, 1000, length.out = 200)

rl_1901_ci <- return.level(pot_1901$fit, return.period = T, do.ci = TRUE, ci.type = "delta")
rl_1990_ci <- return.level(pot_1990$fit, return.period = T, do.ci = TRUE, ci.type = "delta")

# extract columns (Names/order might vary depending on extRemes-version)
get_rl_cols <- function(rl_obj) {
  cn <- colnames(rl_obj)
  if (is.null(cn)) stop("'return.level()' liefert keine Spaltennamen – bitte Output prüfen.")

  est_idx <- grep("est|estimate|return\\.level|rl", cn, ignore.case = TRUE)[1]
  lo_idx <- grep("low|lower", cn, ignore.case = TRUE)[1]

```



```

hi_idx <- grep("up|upper", cn, ignore.case = TRUE)[1]

if (any(is.na(c(est_idx, lo_idx, hi_idx)))) {
  stop(paste0("Unerwartete Spaltennamen in return.level(): ", paste(cn, collapse = ", ")))
}

list(
  est = as.numeric(rl_obj[, est_idx]),
  lo = as.numeric(rl_obj[, lo_idx]),
  hi = as.numeric(rl_obj[, hi_idx])
)
}

rl_1901_cols <- get_rl_cols(rl_1901_ci)
rl_1990_cols <- get_rl_cols(rl_1990_ci)

rl_1901_est <- rl_1901_cols$est
rl_1901_lo <- rl_1901_cols$lo
rl_1901_hi <- rl_1901_cols$hi

rl_1990_est <- rl_1990_cols$est
rl_1990_lo <- rl_1990_cols$lo
rl_1990_hi <- rl_1990_cols$hi

# meaningful y-limits for all curves (incl. CI)
ylim_all <- range(c(rl_1901_lo, rl_1901_hi, rl_1990_lo, rl_1990_hi), na.rm = TRUE)

# only plot non-N/A values
ok_1901 <- is.finite(rl_1901_est) & is.finite(rl_1901_lo) & is.finite(rl_1901_hi)
ok_1990 <- is.finite(rl_1990_est) & is.finite(rl_1990_lo) & is.finite(rl_1990_hi)

png("vergleich_pot_return_levels_1901_vs_1990.png", width = 1600, height = 900, res = 150)

plot(T[ok_1901], rl_1901_est[ok_1901],
  type = "l", log = "x",
  lwd = 3, col = "black",
  xlab = "Wiederkehrperiode [Jahre]",
  ylab = "Max. Tagesniederschlag [mm]",
  ylim = ylim_all,
  main = "Vergleich POT/GPD-Return Levels (Tagesniederschlag)\n1901–2024 vs. 1990–2024")

```

```

# 95%-CI (gestrichelt)

lines(T[ok_1901], rl_1901_lo[ok_1901], col = "black", lty = 2, lwd = 2)

lines(T[ok_1901], rl_1901_hi[ok_1901], col = "black", lty = 2, lwd = 2)


lines(T[ok_1990], rl_1990_est[ok_1990], col = "red", lwd = 3)

lines(T[ok_1990], rl_1990_lo[ok_1990], col = "red", lty = 2, lwd = 2)

lines(T[ok_1990], rl_1990_hi[ok_1990], col = "red", lty = 2, lwd = 2)


legend("topleft",
      legend = c("POT/GPD 1901–2024 (Schätzung)",
                  "POT/GPD 1901–2024 (95%-CI)",
                  "POT/GPD 1990–2024 (Schätzung)",
                  "POT/GPD 1990–2024 (95%-CI)"),
      col = c("black", "black", "red", "red"),
      lwd = c(3, 2, 3, 2),
      lty = c(1, 2, 1, 2),
      bty = "n")


grid()

dev.off()


# Optional: tabular comparison of return periods

perioden <- c(10, 30, 100, 300, 1000)


rl_1901_sel <- return.level(pot_1901$fit, return.period = perioden, do.ci = TRUE, ci.type = "delta")
rl_1990_sel <- return.level(pot_1990$fit, return.period = perioden, do.ci = TRUE, ci.type = "delta")


write.csv(rl_1901_sel, "return_levels_pot_gpd_1901-2024_with_ci.csv", row.names = FALSE)
write.csv(rl_1990_sel, "return_levels_pot_gpd_1990-2024_with_ci.csv", row.names = FALSE)

```

## 9.4 Appendix 4) Detailed Results Scenario Calculations

### 9.4.1 Discharge and Volume with GEV

| municipality                           | Brienz     |            |            | Wolfenschiessen |            | Silenen    |           |         | Silenen      |           |         | Vitznau     |             |
|----------------------------------------|------------|------------|------------|-----------------|------------|------------|-----------|---------|--------------|-----------|---------|-------------|-------------|
| torrent                                | Milibach   |            |            | Bueholz         |            | Selderbach |           |         | Schipfenbach |           |         | Altdorfbach |             |
| station                                | Brienz     | Interlaken | Meiringen  | Stans           | Engelberg  | Bristen    | Göschenen | Altdorf | Bristen      | Göschenen | Altdorf | Gersau      | Luzern      |
| base data catchment - swisstopo        |            |            |            |                 |            |            |           |         |              |           |         |             |             |
| A [km <sup>2</sup> ]                   | 4.83       |            |            | 13.9            |            | 1.77       |           |         | 1.34         |           |         | 2.77        |             |
| L [m]                                  | 5300       |            |            | 6600            |            | 3235       |           |         | 2560         |           |         | 3565        |             |
| dH [m]                                 | 1682       |            |            | 1216            |            | 1472       |           |         | 1198         |           |         | 1112        |             |
| Slope                                  | 0.317      |            |            | 0.184           |            | 0.455      |           |         | 0.468        |           |         | 0.312       |             |
| tc [min]                               | 22.37      |            |            | 32.65           |            | 13.31      |           |         | 11.00        |           |         | 16.59       |             |
| tc [h]                                 | 0.37       |            |            | 0.54            |            | 0.22       |           |         | 0.18         |           |         | 0.28        |             |
| precipitation data based on MeteoSwiss |            |            |            |                 |            |            |           |         |              |           |         |             |             |
| p24h [mm/24h]                          |            |            |            |                 |            |            |           |         |              |           |         |             |             |
| 10                                     | 72.5       | 69         | 70.5       | 87.2            | 88.6       | 95.2       | 98.8      | 80.5    | 95.2         | 98.8      | 80.5    | 113.1       | 72.8        |
| 30                                     | 95.5991055 | 88.4058921 | 95.9321774 | 137.880441      | 123.184877 | 139.5      | 135.9     | 107.3   | 139.5        | 135.9     | 107.3   | 183.820646  | 97.90459935 |
| 100                                    | 118.302056 | 106.956133 | 122.007401 | 195.705111      | 161.224205 | 182.6      | 174.9     | 133.7   | 182.6        | 174.9     | 133.7   | 256.049376  | 124.2018908 |
| 300                                    | 142.216773 | 125.932098 | 150.512618 | 268.862525      | 204.388833 | 231.1      | 218.0     | 161.1   | 231.1        | 218.0     | 161.1   | 342.81517   | 153.1380472 |
| 1000                                   | 132.6      | 119.4      | 141.8      | 219.1           | 192.7      | 188.7      | 198.0     | 155.7   | 188.7        | 198.0     | 155.7   | 250.9       | 145.7       |
| rt                                     | 0.15       |            |            | 0.19            |            | 0.06       |           |         | 0.05         |           |         | 0.11        |             |
| p1h [mm/h]                             |            |            |            |                 |            |            |           |         |              |           |         |             |             |
| 10                                     | 29.17      | 27.76      | 28.37      | 30.44           | 30.93      | 25.73      | 26.71     | 21.77   | 25.95        | 26.94     | 21.96   | 44.99       | 28.96       |
| 30                                     | 38.47      | 35.57      | 38.60      | 48.14           | 43.01      | 37.71      | 36.75     | 29.01   | 38.04        | 37.07     | 29.26   | 73.12       | 38.94       |
| 100                                    | 47.60      | 43.03      | 49.09      | 68.33           | 56.29      | 49.37      | 47.30     | 36.15   | 49.80        | 47.71     | 36.46   | 101.85      | 49.40       |
| 300                                    | 57.22      | 50.67      | 60.56      | 93.87           | 71.36      | 62.49      | 58.95     | 43.57   | 63.03        | 59.46     | 43.95   | 136.36      | 60.91       |
| 1000                                   | 53.35      | 48.04      | 57.05      | 76.50           | 67.28      | 51.04      | 53.54     | 42.10   | 51.48        | 54.00     | 42.46   | 99.80       | 57.95       |
| runoff coefficient                     | 0.6        |            |            | 0.6             |            | 0.6        |           |         | 0.6          |           |         | 0.6         |             |
| Qmax [m <sup>3</sup> /s] v Wasser      |            |            |            |                 |            |            |           |         |              |           |         |             |             |
| 10                                     | 23.50      | 22.37      | 22.85      | 70.59           | 71.72      | 7.60       | 7.89      | 6.43    | 5.80         | 6.02      | 4.91    | 20.79       | 13.38       |
| 30                                     | 30.99      | 28.66      | 31.10      | 111.61          | 99.72      | 11.13      | 10.85     | 8.56    | 8.50         | 8.28      | 6.54    | 33.78       | 17.99       |
| 100                                    | 38.35      | 34.67      | 39.55      | 158.42          | 130.51     | 14.58      | 13.96     | 10.67   | 11.13        | 10.66     | 8.15    | 47.06       | 22.83       |
| 300                                    | 46.10      | 40.82      | 48.79      | 217.64          | 165.45     | 18.45      | 17.40     | 12.86   | 14.09        | 13.29     | 9.82    | 63.00       | 28.14       |
| 1000                                   | 42.98      | 38.70      | 45.97      | 177.36          | 155.99     | 15.07      | 15.81     | 12.43   | 11.51        | 12.07     | 9.49    | 46.11       | 26.78       |



| municipality                           | Brienz          |            |           | Wolfenschiessen |           | Silenen    |           |         | Silenen      |           |         | Vitznau     |          |
|----------------------------------------|-----------------|------------|-----------|-----------------|-----------|------------|-----------|---------|--------------|-----------|---------|-------------|----------|
| torrent                                | Milibach        |            |           | Bueholz         |           | Selderbach |           |         | Schipfenbach |           |         | Altdorfbach |          |
| station                                | Brienz          | Interlaken | Meiringen | Stans           | Engelberg | Bristen    | Göschenen | Altdorf | Bristen      | Göschenen | Altdorf | Gersau      | Luzern   |
| base data catchment - swisstopo        |                 |            |           |                 |           |            |           |         |              |           |         |             |          |
| A [km <sup>2</sup> ]                   | 4.83            |            |           | 13.9            |           | 1.77       |           |         | 1.34         |           |         | 2.77        |          |
| L [m]                                  | 5300            |            |           | 6600            |           | 3235       |           |         | 2560         |           |         | 3565        |          |
| dH [m]                                 | 1682            |            |           | 1216            |           | 1472       |           |         | 1198         |           |         | 1112        |          |
| Slope                                  | 0.317           |            |           | 0.184           |           | 0.455      |           |         | 0.468        |           |         | 0.312       |          |
| Qmax [m <sup>3</sup> /s] water         |                 |            |           |                 |           |            |           |         |              |           |         |             |          |
| 10                                     | 23.50           | 22.37      | 22.85     | 70.59           | 71.72     | 7.60       | 7.89      | 6.43    | 5.80         | 6.02      | 4.91    | 20.79       | 13.38    |
| 30                                     | 30.99           | 28.66      | 31.10     | 111.61          | 99.72     | 11.13      | 10.85     | 8.56    | 8.50         | 8.28      | 6.54    | 33.78       | 17.99    |
| 100                                    | 38.35           | 34.67      | 39.55     | 158.42          | 130.51    | 14.58      | 13.96     | 10.67   | 11.13        | 10.66     | 8.15    | 47.06       | 22.83    |
| 300                                    | 46.10           | 40.82      | 48.79     | 217.64          | 165.45    | 18.45      | 17.40     | 12.86   | 14.09        | 13.29     | 9.82    | 63.00       | 28.14    |
| 1000                                   | 42.98           | 38.70      | 45.97     | 177.36          | 155.99    | 15.07      | 15.81     | 12.43   | 11.51        | 12.07     | 9.49    | 46.11       | 26.78    |
| Sedimentanteil nach Bennet et al. 2014 |                 |            |           |                 |           |            |           |         |              |           |         |             |          |
| fw [%]                                 | 60              |            |           |                 |           |            |           |         |              |           |         |             |          |
| fs [%]                                 | 40              |            |           |                 |           |            |           |         |              |           |         |             |          |
| Qs [m <sup>3</sup> /s] Sediment        |                 |            |           |                 |           |            |           |         |              |           |         |             |          |
| 10                                     | 15.67           | 14.91      | 15.24     | 47.06           | 47.81     | 5.06       | 5.26      | 4.28    | 3.87         | 4.01      | 3.27    | 13.86       | 8.92     |
| 30                                     | 20.66           | 19.10      | 20.73     | 74.41           | 66.48     | 7.42       | 7.23      | 5.71    | 5.67         | 5.52      | 4.36    | 22.52       | 12.00    |
| 100                                    | 25.57           | 23.11      | 26.37     | 105.61          | 87.01     | 9.72       | 9.31      | 7.11    | 7.42         | 7.11      | 5.43    | 31.37       | 15.22    |
| 300                                    | 30.73           | 27.21      | 32.53     | 145.09          | 110.30    | 12.30      | 11.60     | 8.58    | 9.39         | 8.86      | 6.55    | 42.00       | 18.76    |
| 1000                                   | 28.66           | 25.80      | 30.64     | 118.24          | 103.99    | 10.05      | 10.54     | 8.29    | 7.67         | 8.05      | 6.33    | 30.74       | 17.85    |
| Qtot [m <sup>3</sup> /s]               |                 |            |           |                 |           |            |           |         |              |           |         |             |          |
| 10                                     | 39.17           | 37.28      | 38.09     | 117.64          | 119.53    | 12.66      | 13.14     | 10.71   | 9.67         | 10.04     | 8.18    | 34.64       | 22.30    |
| 30                                     | 51.65           | 47.76      | 51.83     | 186.02          | 166.19    | 18.56      | 18.08     | 14.27   | 14.17        | 13.81     | 10.90   | 56.31       | 29.99    |
| 100                                    | 63.91           | 57.78      | 65.92     | 264.03          | 217.51    | 24.29      | 23.27     | 17.79   | 18.55        | 17.77     | 13.58   | 78.43       | 38.04    |
| 300                                    | 76.83           | 68.04      | 81.32     | 362.73          | 275.75    | 30.75      | 29.01     | 21.44   | 23.48        | 22.15     | 16.37   | 105.01      | 46.91    |
| 1000                                   | 71.64           | 64.51      | 76.61     | 295.60          | 259.98    | 25.11      | 26.34     | 20.71   | 19.18        | 20.12     | 15.82   | 76.85       | 44.63    |
| Vtot [m <sup>3</sup> ]                 |                 |            |           |                 |           |            |           |         |              |           |         |             |          |
|                                        | Rickenmann 2016 |            |           |                 |           |            |           |         |              |           |         |             |          |
| 10                                     | 15885.21        | 14920.79   | 15332.55  | 63912.85        | 65214.50  | 3802.89    | 3986.82   | 3077.66 | 2703.24      | 2833.99   | 2187.72 | 13598.59    | 7785.79  |
| 30                                     | 22544.38        | 20419.02   | 22643.85  | 114148.29       | 98972.23  | 6170.59    | 5970.71   | 4426.41 | 4386.29      | 4244.22   | 3146.46 | 25147.57    | 11328.65 |
| 100                                    | 29524.02        | 25986.60   | 30699.39  | 177828.11       | 139140.54 | 8678.03    | 8219.32   | 5847.87 | 6168.68      | 5842.61   | 4156.89 | 38254.74    | 15309.80 |
| 300                                    | 37272.53        | 31954.73   | 40045.71  | 265823.25       | 187874.36 | 11692.19   | 10860.48  | 7407.95 | 8311.26      | 7720.06   | 5265.86 | 55349.15    | 19957.32 |
| 1000                                   | 34111.32        | 29871.29   | 37134.32  | 205152.42       | 174378.73 | 9049.89    | 9614.51   | 7091.88 | 6433.01      | 6834.37   | 5041.18 | 37283.51    | 18738.32 |

## 9.4.2 Discharge and Volume with POT

| municipality                           | Brienz   |            |           | Wolfenschiessen |           | Silenen    |         |           | Silenen      |         |           | Vitznau     |        |
|----------------------------------------|----------|------------|-----------|-----------------|-----------|------------|---------|-----------|--------------|---------|-----------|-------------|--------|
| torrent                                | Milibach |            |           | Bueholz         |           | Selderbach |         |           | Schipfenbach |         |           | Altdorfbach |        |
| station                                | Brienz   | Interlaken | Meiringen | Stans           | Engelberg | Bristen    | Altdorf | Göschenen | Bristen      | Altdorf | Göschenen | Gersau      | Luzern |
| base data catchment - swisstopo        |          |            |           |                 |           |            |         |           |              |         |           |             |        |
| A [km^2]                               | 4.83     |            |           | 13.9            |           | 1.77       |         |           | 1.34         |         |           | 2.77        |        |
| L [m]                                  | 5300     |            |           | 6600            |           | 3235       |         |           | 2560         |         |           | 3565        |        |
| dH [m]                                 | 1682     |            |           | 1216            |           | 1472       |         |           | 1198         |         |           | 1112        |        |
| Slope                                  | 0.317    |            |           | 0.184           |           | 0.455      |         |           | 0.468        |         |           | 0.312       |        |
| tc [min]                               | 22.37    | 32.37      |           | 32.65           |           | 13.31      |         |           | 11.00        |         |           | 16.59       |        |
| tc [h]                                 | 0.37     | 0.54       |           | 0.54            |           | 0.22       |         |           | 0.18         |         |           | 0.28        |        |
| precipitation data based on MeteoSwiss |          |            |           |                 |           |            |         |           |              |         |           |             |        |
| p24h [mm/24h]                          |          |            |           |                 |           |            |         |           |              |         |           |             |        |
| 10                                     | 126.3    | 105.6      | 123.3     | 176.0           | 147.4     | 190.2      | 144.6   | 188.8     | 190.2        | 144.6   | 188.8     | 180.7       | 127.7  |
| 30                                     | 142.5    | 114.7      | 139.3     | 207.8           | 168.4     | 221.7      | 166.2   | 216.0     | 221.7        | 166.2   | 216.0     | 200.1       | 144.1  |
| 100                                    | 161.0    | 124.4      | 157.8     | 247.2           | 193.2     | 259.9      | 191.9   | 248.0     | 259.9        | 191.9   | 248.0     | 221.4       | 162.9  |
| 300                                    | 178.8    | 133.0      | 175.5     | 288.0           | 217.4     | 298.4      | 217.3   | 279.1     | 298.4        | 217.3   | 279.1     | 240.8       | 180.9  |
| 1000                                   | 199.2    | 142.1      | 195.9     | 338.6           | 246.0     | 345.2      | 247.3   | 315.5     | 345.2        | 247.3   | 315.5     | 262.0       | 201.6  |
| rt                                     | 0.15     |            |           | 0.19            |           | 0.06       |         |           | 0.05         |         |           | 0.11        |        |
| p1h [mm/h]                             |          |            |           |                 |           |            |         |           |              |         |           |             |        |
| 10                                     | 50.83    | 42.48      | 34.29     | 61.46           | 51.48     | 51.43      | 39.10   | 51.04     | 51.88        | 39.44   | 51.49     | 71.89       | 50.79  |
| 30                                     | 57.32    | 46.17      | 38.74     | 72.55           | 58.81     | 59.94      | 44.95   | 58.42     | 60.46        | 45.34   | 58.93     | 79.60       | 57.32  |
| 100                                    | 64.79    | 50.07      | 43.87     | 86.32           | 67.44     | 70.27      | 51.89   | 67.05     | 70.88        | 52.34   | 67.64     | 88.05       | 64.81  |
| 300                                    | 71.94    | 53.51      | 48.79     | 100.55          | 75.91     | 80.70      | 58.75   | 75.46     | 81.40        | 59.26   | 76.12     | 95.77       | 71.96  |
| 1000                                   | 80.17    | 57.17      | 54.47     | 118.22          | 85.89     | 93.35      | 66.88   | 85.30     | 94.17        | 67.46   | 86.04     | 104.22      | 80.17  |
| runoff coefficie                       | 0.6      |            |           | 0.6             |           | 0.6        |         |           | 0.6          |         |           | 0.6         |        |
| Qmax [m^3/s] water                     |          |            |           |                 |           |            |         |           |              |         |           |             |        |
| 10                                     | 40.95    | 34.23      | 27.62     | 142.50          | 119.35    | 15.18      | 11.54   | 15.07     | 11.59        | 8.81    | 11.51     | 33.22       | 23.47  |
| 30                                     | 46.18    | 37.19      | 31.21     | 168.21          | 136.34    | 17.70      | 13.27   | 17.25     | 13.51        | 10.13   | 13.17     | 36.78       | 26.48  |
| 100                                    | 52.20    | 40.34      | 35.34     | 200.13          | 156.37    | 20.75      | 15.32   | 19.80     | 15.84        | 11.70   | 15.12     | 40.68       | 29.94  |
| 300                                    | 57.96    | 43.11      | 39.31     | 233.12          | 176.00    | 23.83      | 17.34   | 22.28     | 18.19        | 13.24   | 17.01     | 44.25       | 33.25  |
| 1000                                   | 64.59    | 46.06      | 43.88     | 274.10          | 199.13    | 27.56      | 19.74   | 25.18     | 21.05        | 15.08   | 19.23     | 48.15       | 37.04  |
| EHQ                                    | 104.39   | 80.68      | 70.68     | 400.25          | 312.73    | 41.49      | 30.64   | 39.59     | 31.69        | 23.40   | 30.24     | 81.37       | 59.89  |

| municipality                           | Brienz          |            |           | Wolfenschiessen |           | Silenen    |          |           | Silenen      |          |           | Vitznau     |          |
|----------------------------------------|-----------------|------------|-----------|-----------------|-----------|------------|----------|-----------|--------------|----------|-----------|-------------|----------|
| torrent                                | Milibach        |            |           | Bueholz         |           | Selderbach |          |           | Schipfenbach |          |           | Altdorfbach |          |
| station                                | Brienz          | Interlaken | Meiringen | Stans           | Engelberg | Bristen    | Altdorf  | Göschenen | Bristen      | Altdorf  | Göschenen | Gersau      | Luzern   |
| base data catchment - swisstopo        |                 |            |           |                 |           |            |          |           |              |          |           |             |          |
| A [km^2]                               | 4.83            |            |           | 13.9            |           | 1.77       |          |           | 1.34         |          |           | 2.77        |          |
| L [m]                                  | 5300            |            |           | 6600            |           | 3235       |          |           | 2560         |          |           | 3565        |          |
| dH [m]                                 | 1682            |            |           | 1216            |           | 1472       |          |           | 1198         |          |           | 1112        |          |
| Slope                                  | 0.317           |            |           | 0.184           |           | 0.455      |          |           | 0.468        |          |           | 0.312       |          |
| Qmax [m^3/s] water                     |                 |            |           |                 |           |            |          |           |              |          |           |             |          |
| 10                                     | 40.95           | 34.23      | 27.62     | 142.50          | 119.35    | 15.18      | 11.54    | 15.07     | 11.59        | 8.81     | 11.51     | 33.22       | 23.47    |
| 30                                     | 46.18           | 37.19      | 31.21     | 168.21          | 136.34    | 17.70      | 13.27    | 17.25     | 13.51        | 10.13    | 13.17     | 36.78       | 26.48    |
| 100                                    | 52.20           | 40.34      | 35.34     | 200.13          | 156.37    | 20.75      | 15.32    | 19.80     | 15.84        | 11.70    | 15.12     | 40.68       | 29.94    |
| 300                                    | 57.96           | 43.11      | 39.31     | 233.12          | 176.00    | 23.83      | 17.34    | 22.28     | 18.19        | 13.24    | 17.01     | 44.25       | 33.25    |
| 1000                                   | 64.59           | 46.06      | 43.88     | 274.10          | 199.13    | 27.56      | 19.74    | 25.18     | 21.05        | 15.08    | 19.23     | 48.15       | 37.04    |
| EHQ                                    | 104.39          | 80.68      | 70.68     | 400.25          | 312.73    | 41.49      | 30.64    | 39.59     | 31.69        | 23.40    | 30.24     | 81.37       | 59.89    |
| Sedimentanteil nach Bennet et al. 2014 |                 |            |           |                 |           |            |          |           |              |          |           |             |          |
| fw [%]                                 | 60              |            |           |                 |           |            |          |           |              |          |           |             |          |
| fs [%]                                 | 40              |            |           |                 |           |            |          |           |              |          |           |             |          |
| Qs [m^3/s] Sediment                    |                 |            |           |                 |           |            |          |           |              |          |           |             |          |
| 10                                     | 27.30           | 22.82      | 18.42     | 95.00           | 79.56     | 10.12      | 7.69     | 10.05     | 7.73         | 5.88     | 7.67      | 22.14       | 15.64    |
| 30                                     | 30.79           | 24.80      | 20.81     | 112.14          | 90.90     | 11.80      | 8.85     | 11.50     | 9.01         | 6.76     | 8.78      | 24.52       | 17.66    |
| 100                                    | 34.80           | 26.89      | 23.56     | 133.42          | 104.24    | 13.83      | 10.21    | 13.20     | 10.56        | 7.80     | 10.08     | 27.12       | 19.96    |
| 300                                    | 38.64           | 28.74      | 26.21     | 155.42          | 117.33    | 15.88      | 11.56    | 14.85     | 12.13        | 8.83     | 11.34     | 29.50       | 22.17    |
| 1000                                   | 43.06           | 30.70      | 29.25     | 182.73          | 132.75    | 18.37      | 13.16    | 16.79     | 14.03        | 10.05    | 12.82     | 32.10       | 24.70    |
| EHQ                                    | 69.59           | 53.78      | 47.12     | 266.83          | 208.49    | 27.66      | 20.43    | 26.39     | 21.12        | 15.60    | 20.16     | 54.25       | 39.93    |
| Qtot [m^3/s]                           |                 |            |           |                 |           |            |          |           |              |          |           |             |          |
| 10                                     | 68.25           | 57.05      | 46.04     | 237.50          | 198.91    | 25.31      | 19.24    | 25.12     | 19.32        | 14.69    | 19.18     | 55.36       | 39.11    |
| 30                                     | 76.97           | 61.99      | 52.01     | 280.34          | 227.24    | 29.50      | 22.12    | 28.75     | 22.52        | 16.89    | 21.95     | 61.30       | 44.14    |
| 100                                    | 86.99           | 67.23      | 58.90     | 333.54          | 260.61    | 34.58      | 25.53    | 32.99     | 26.41        | 19.50    | 25.20     | 67.81       | 49.91    |
| 300                                    | 96.60           | 71.86      | 65.51     | 388.54          | 293.34    | 39.71      | 28.91    | 37.13     | 30.32        | 22.07    | 28.36     | 73.75       | 55.42    |
| 1000                                   | 107.64          | 76.76      | 73.13     | 456.83          | 331.89    | 45.94      | 32.91    | 41.97     | 35.08        | 25.13    | 32.05     | 80.25       | 61.74    |
| EHQ                                    | 173.99          | 134.46     | 117.81    | 667.09          | 521.22    | 69.15      | 51.07    | 65.99     | 52.81        | 39.00    | 50.39     | 135.61      | 99.81    |
| Vtot [m^3]                             |                 |            |           |                 |           |            |          |           |              |          |           |             |          |
|                                        | Rickenmann 2016 |            |           |                 |           |            |          |           |              |          |           |             |          |
| 10                                     | 32082.31        | 25566.80   | 19490.49  | 155520.73       | 124251.87 | 9137.65    | 6458.14  | 9050.83   | 6495.40      | 4590.70  | 6433.69   | 24614.07    | 15855.31 |
| 30                                     | 37354.06        | 28402.78   | 22746.94  | 191846.06       | 147063.14 | 11093.18   | 7705.51  | 10737.68  | 7885.47      | 5477.38  | 7632.76   | 28003.06    | 18478.02 |
| 100                                    | 43617.26        | 31475.74   | 26625.42  | 239041.96       | 174915.90 | 13565.91   | 9241.77  | 12784.18  | 9643.18      | 6569.41  | 9087.50   | 31818.54    | 21586.25 |
| 300                                    | 49799.33        | 34241.94   | 30463.03  | 289984.89       | 203170.35 | 16163.27   | 10813.54 | 14846.42  | 11489.48     | 7686.69  | 10553.42  | 35386.44    | 24646.32 |
| 1000                                   | 57115.18        | 37226.71   | 35015.49  | 355953.24       | 237539.41 | 19435.35   | 12741.77 | 17337.71  | 13815.40     | 9057.35  | 12324.32  | 39385.11    | 28257.99 |
| EHQ                                    | 104883.95       | 75687.92   | 64024.64  | 574810.59       | 420610.32 | 32621.16   | 22223.17 | 30741.40  | 23188.40     | 15797.10 | 21852.19  | 76512.22    | 51907.23 |



## 9.4.3 Discharge and Volume with POT upper ci

| municipality                           | Brienz   |            |           | Wolfenschiessen |           | Silenen    |           |         | Silenen      |           |         | Vitznau     |        |
|----------------------------------------|----------|------------|-----------|-----------------|-----------|------------|-----------|---------|--------------|-----------|---------|-------------|--------|
| torrent                                | Milibach |            |           | Bueholz         |           | Selderbach |           |         | Schipfenbach |           |         | Altdorfbach |        |
| station                                | Brienz   | Interlaken | Meiringen | Stans           | Engelberg | Bristen    | Göschenen | Altdorf | Bristen      | Göschenen | Altdorf | Gersau      | Luzern |
| base data catchment - swisstopo        |          |            |           |                 |           |            |           |         |              |           |         |             |        |
| A [km^2]                               | 4.83     |            |           | 13.9            |           | 1.77       |           |         | 1.34         |           |         | 2.77        |        |
| L [m]                                  | 5300     |            |           | 6600            |           | 3235       |           |         | 2560         |           |         | 3565        |        |
| dH [m]                                 | 1682     |            |           | 1216            |           | 1472       |           |         | 1198         |           |         | 1112        |        |
| Slope                                  | 0.317    |            |           | 0.184           |           | 0.455      |           |         | 0.468        |           |         | 0.312       |        |
| tc [min]                               | 22.37    |            |           | 32.65           |           | 13.31      |           |         | 11.00        |           |         | 16.59       |        |
| tc [h]                                 | 0.37     |            |           | 0.54            |           | 0.22       |           |         | 0.18         |           |         | 0.28        |        |
| precipitation data based on MeteoSwiss |          |            |           |                 |           |            |           |         |              |           |         |             |        |
| p24h [mm/24h]                          |          |            |           |                 |           |            |           |         |              |           |         |             |        |
| 10                                     | 151.8    | 121.2      | 147.3     | 245.4           | 178.6     | 273.9      | 177.4     | 233.7   | 273.9        | 177.4     | 233.7   | 243.0       | 151.9  |
| 30                                     | 177.1    | 134.8      | 172.0     | 307.0           | 211.4     | 339.8      | 211.7     | 277.8   | 339.8        | 211.7     | 277.8   | 281.9       | 176.9  |
| 100                                    | 207.7    | 150.0      | 201.8     | 389.0           | 252.1     | 425.7      | 254.7     | 332.4   | 425.7        | 254.7     | 332.4   | 327.8       | 207.0  |
| 300                                    | 238.6    | 164.1      | 231.9     | 479.3           | 294.1     | 518.7      | 299.3     | 388.4   | 518.7        | 299.3     | 388.4   | 372.6       | 237.2  |
| 1000                                   | 275.8    | 179.7      | 268.2     | 598.4           | 345.9     | 639.1      | 354.8     | 457.3   | 639.1        | 354.8     | 457.3   | 425.0       | 273.4  |
| rt                                     | 0.15     |            |           | 0.19            |           | 0.06       |           |         | 0.05         |           |         | 0.11        |        |
| p1h [mm/h]                             |          |            |           |                 |           |            |           |         |              |           |         |             |        |
| 10                                     | 61.07    | 48.75      | 59.28     | 85.68           | 62.35     | 74.08      | 47.97     | 63.18   | 74.72        | 48.38     | 63.74   | 96.67       | 60.41  |
| 30                                     | 71.25    | 54.25      | 69.19     | 107.19          | 73.81     | 91.87      | 57.25     | 75.12   | 92.67        | 57.75     | 75.78   | 112.14      | 70.35  |
| 100                                    | 83.57    | 60.37      | 81.21     | 135.80          | 88.02     | 115.12     | 68.87     | 89.89   | 116.12       | 69.47     | 90.67   | 130.40      | 82.34  |
| 300                                    | 95.99    | 66.03      | 93.32     | 167.33          | 102.67    | 140.27     | 80.94     | 105.03  | 141.49       | 81.64     | 105.95  | 148.22      | 94.35  |
| 1000                                   | 110.95   | 72.30      | 107.92    | 208.92          | 120.75    | 172.80     | 95.95     | 123.66  | 174.31       | 96.79     | 124.73  | 169.04      | 108.76 |
| runoff coefficie                       | 0.6      |            |           | 0.6             |           | 0.6        |           |         | 0.6          |           |         | 0.6         |        |
| Qmax [m^3/s] water                     |          |            |           |                 |           |            |           |         |              |           |         |             |        |
| 10                                     | 49.20    | 39.27      | 47.76     | 198.64          | 144.55    | 21.87      | 14.16     | 18.65   | 16.70        | 10.81     | 14.25   | 44.66       | 27.91  |
| 30                                     | 57.40    | 43.70      | 55.74     | 248.51          | 171.12    | 27.12      | 16.90     | 22.18   | 20.71        | 12.91     | 16.94   | 51.81       | 32.51  |
| 100                                    | 67.33    | 48.64      | 65.43     | 314.85          | 204.09    | 33.99      | 20.33     | 26.54   | 25.95        | 15.53     | 20.27   | 60.25       | 38.04  |
| 300                                    | 77.33    | 53.20      | 75.18     | 387.95          | 238.04    | 41.41      | 23.89     | 31.01   | 31.62        | 18.25     | 23.68   | 68.48       | 43.59  |
| 1000                                   | 89.39    | 58.25      | 86.95     | 484.38          | 279.97    | 51.02      | 28.33     | 36.51   | 38.96        | 21.63     | 27.88   | 78.10       | 50.25  |

| municipality                           | Brienz    |            |           | Wolfenschiess |           | Silenen    |           |          | Silenen      |           |          | Vitznau     |          |
|----------------------------------------|-----------|------------|-----------|---------------|-----------|------------|-----------|----------|--------------|-----------|----------|-------------|----------|
| torrent                                | Milibach  |            |           | Bueholz       |           | Selderbach |           |          | Schipfenbach |           |          | Altdorfbach |          |
| station                                | Brienz    | Interlaken | Meiringen | Stans         | Engelberg | Bristen    | Göschenen | Altdorf  | Bristen      | Göschenen | Altdorf  | Gersau      | Luzern   |
| base data catchment - swisstopo        |           |            |           |               |           |            |           |          |              |           |          |             |          |
| A [km <sup>2</sup> ]                   | 4.83      |            |           | 13.9          |           | 1.77       |           |          | 1.34         |           |          | 2.77        |          |
| L [m]                                  | 5300      |            |           | 6600          |           | 3235       |           |          | 2560         |           |          | 3565        |          |
| dH [m]                                 | 1682      |            |           | 1216          |           | 1472       |           |          | 1198         |           |          | 1112        |          |
| Slope                                  | 0.317     |            |           | 0.184         |           | 0.455      |           |          | 0.468        |           |          | 0.312       |          |
| Qmax [m <sup>3</sup> /s] water         |           |            |           |               |           |            |           |          |              |           |          |             |          |
| 10                                     | 49.20     | 39.27      | 47.76     | 198.64        | 144.55    | 21.87      | 14.16     | 18.65    | 16.70        | 10.81     | 14.25    | 44.66       | 27.91    |
| 30                                     | 57.40     | 43.70      | 55.74     | 248.51        | 171.12    | 27.12      | 16.90     | 22.18    | 20.71        | 12.91     | 16.94    | 51.81       | 32.51    |
| 100                                    | 67.33     | 48.64      | 65.43     | 314.85        | 204.09    | 33.99      | 20.33     | 26.54    | 25.95        | 15.53     | 20.27    | 60.25       | 38.04    |
| 300                                    | 77.33     | 53.20      | 75.18     | 387.95        | 238.04    | 41.41      | 23.89     | 31.01    | 31.62        | 18.25     | 23.68    | 68.48       | 43.59    |
| 1000                                   | 89.39     | 58.25      | 86.95     | 484.38        | 279.97    | 51.02      | 28.33     | 36.51    | 38.96        | 21.63     | 27.88    | 78.10       | 50.25    |
| EHQ                                    | 134.66    | 97.27      | 130.86    | 629.70        | 408.17    | 67.98      | 40.67     | 53.08    | 51.91        | 31.05     | 40.53    | 120.49      | 76.09    |
| Sedimentanteil nach Bennet et al. 2014 |           |            |           |               |           |            |           |          |              |           |          |             |          |
| fw [%]                                 | 60        |            |           |               |           |            |           |          |              |           |          |             |          |
| fs [%]                                 | 40        |            |           |               |           |            |           |          |              |           |          |             |          |
| Qs [m <sup>3</sup> /s] Sediment        |           |            |           |               |           |            |           |          |              |           |          |             |          |
| 10                                     | 32.80     | 26.18      | 31.84     | 132.43        | 96.37     | 14.58      | 9.44      | 12.44    | 11.13        | 7.21      | 9.50     | 29.78       | 18.61    |
| 30                                     | 38.27     | 29.14      | 37.16     | 165.68        | 114.08    | 18.08      | 11.27     | 14.79    | 13.81        | 8.61      | 11.29    | 34.54       | 21.67    |
| 100                                    | 44.89     | 32.42      | 43.62     | 209.90        | 136.06    | 22.66      | 13.56     | 17.69    | 17.30        | 10.35     | 13.51    | 40.16       | 25.36    |
| 300                                    | 51.55     | 35.46      | 50.12     | 258.64        | 158.70    | 27.61      | 15.93     | 20.67    | 21.08        | 12.17     | 15.79    | 45.66       | 29.06    |
| 1000                                   | 59.59     | 38.83      | 57.97     | 322.92        | 186.65    | 34.01      | 18.89     | 24.34    | 25.97        | 14.42     | 18.59    | 52.07       | 33.50    |
| EHQ                                    | 89.78     | 64.85      | 87.24     | 419.80        | 272.11    | 45.32      | 27.11     | 35.38    | 34.61        | 20.70     | 27.02    | 80.33       | 50.73    |
| Qtot [m <sup>3</sup> /s]               |           |            |           |               |           |            |           |          |              |           |          |             |          |
| 10                                     | 82.01     | 65.46      | 79.60     | 331.07        | 240.92    | 36.45      | 23.60     | 31.09    | 27.84        | 18.02     | 23.74    | 74.44       | 46.52    |
| 30                                     | 95.66     | 72.84      | 92.91     | 414.19        | 285.20    | 45.21      | 28.17     | 36.97    | 34.52        | 21.51     | 28.23    | 86.36       | 54.18    |
| 100                                    | 112.22    | 81.06      | 109.05    | 524.75        | 340.14    | 56.65      | 33.89     | 44.23    | 43.26        | 25.88     | 33.78    | 100.41      | 63.41    |
| 300                                    | 128.88    | 88.66      | 125.30    | 646.59        | 396.74    | 69.02      | 39.82     | 51.68    | 52.71        | 30.41     | 39.47    | 114.14      | 72.65    |
| 1000                                   | 148.98    | 97.08      | 144.91    | 807.30        | 466.62    | 85.03      | 47.21     | 60.85    | 64.93        | 36.05     | 46.47    | 130.17      | 83.75    |
| EHQ                                    | 224.44    | 162.12     | 218.09    | 1049.50       | 680.28    | 113.29     | 67.78     | 88.46    | 86.52        | 51.76     | 67.55    | 200.82      | 126.81   |
| Vtot [m <sup>3</sup> ]                 |           |            |           |               |           |            |           |          |              |           |          |             |          |
| Rickenmann 2016                        |           |            |           |               |           |            |           |          |              |           |          |             |          |
| 10                                     | 40476.69  | 30428.68   | 38977.67  | 236801.51     | 158355.63 | 14502.45   | 8365.91   | 11858.13 | 10308.91     | 5946.81   | 8429.22  | 35807.66    | 19750.32 |
| 30                                     | 49190.99  | 34836.53   | 47403.92  | 314427.54     | 196061.99 | 19045.97   | 10466.77  | 14762.85 | 13538.62     | 7440.19   | 10494.01 | 43213.85    | 23950.23 |
| 100                                    | 60205.08  | 39885.24   | 58058.81  | 424215.60     | 245043.51 | 25340.38   | 13224.52  | 18526.39 | 18012.93     | 9400.51   | 13169.28 | 52301.81    | 29227.95 |
| 300                                    | 71737.38  | 44677.34   | 69221.66  | 552545.61     | 297756.08 | 32540.77   | 16222.69  | 22563.54 | 23131.25     | 11531.72  | 16039.05 | 61511.73    | 34723.12 |
| 1000                                   | 86180.81  | 50117.06   | 83212.64  | 731816.88     | 365629.51 | 42374.31   | 20122.11  | 27742.10 | 30121.32     | 14303.58  | 19720.16 | 72647.34    | 41567.91 |
| EHQ                                    | 144771.74 | 95909.78   | 139610.72 | 1020087.13    | 589242.18 | 60934.58   | 31800.26  | 44549.36 | 43314.68     | 22604.86  | 31667.42 | 125767.19   | 70282.80 |

## 9.5 Appendix 6) Intensity Maps R-Code

```
# =====

# Debris flow-intensity maps (weak/medium/strong) from GeoTIFFs

# - Inputs: *_MaxHeight.tif, *_MaxVelocity.tif

# - Output: intensity raster + map (PDF/PNG) per scenario

# =====

# ---- packages ----

library(terra)

library(tmap)

# ---- directories ----

in_dir <- "C:/UZH_GEO805/Master/Silenen/scenario2/Selder"

out_dir <- file.path(in_dir, "intensity_out")

dir.create(out_dir, showWarnings = FALSE, recursive = TRUE)

# swisstopo background as georeferenced raster (GeoTIFF)

# (wenn du keinen Hintergrund plotten willst: bg_path <- NULL setzen)

bg_path <- "C:/UZH_GEO805/Master/map/Silenen-map-raster-10.tif" # <- anpassen oder NULL

# map output

export_png <- TRUE

export_pdf <- TRUE

# colours for intensity and labels

int_cols <- c("#b8f28a", "#45c447", "#0b6b2b")

int_labs <- c("schwach", "mittel", "stark")

# transparency of intensity layer

int_alpha <- 0.55

# ---- intensity classification ----

# ha (MaxHeight): <=0.5 schwach, 0.5-2 mittel, >2 stark

class_ha <- function(ha) ifel(ha <= 0.5, 1, ifel(ha <= 2, 2, 3))

# v*ha: <=0.25 schwach, 0.25-1 mittel, >1 stark

class_vha <- function(vha) ifel(vha <= 0.25, 1, ifel(vha <= 1, 2, 3))
```



```

# ---- align raster to reference raster ----

read_align <- function(path, ref) {

  r <- rast(path)

  if (!compareGeom(r, ref, stopOnError = FALSE)) {

    r <- resample(r, ref, method = "bilinear")

  }

  r
}

# ---- find files ----

h_files <- list.files(in_dir, pattern = "_MaxHeight\\.tif$", full.names = TRUE, recursive = TRUE)
v_files <- list.files(in_dir, pattern = "_MaxVelocity\\.tif$", full.names = TRUE, recursive = TRUE)

if (length(h_files) == 0) stop("Keine *_MaxHeight.tif gefunden.")
if (length(v_files) == 0) stop("Keine *_MaxVelocity.tif gefunden.")

# Prefix-Matching via base name without suffix

prefix_h <- sub("_MaxHeight\\.tif$", "", basename(h_files))
prefix_v <- sub("_MaxVelocity\\.tif$", "", basename(v_files))
v_map <- setNames(v_files, prefix_v)

# ---- load background (optional) ----

bg <- NULL

if (!is.null(bg_path)) {

  if (!file.exists(bg_path)) stop("bg_path existiert nicht: ", bg_path)

  bg <- rast(bg_path)

}

# ---- tmap Modus ----

tmap_mode("plot")

# ---- processing per scenario ----

for (i in seq_along(h_files)) {

  pref <- prefix_h[i]
  h_path <- h_files[i]

  if (!pref %in% names(v_map)) {

    warning("Fehlt MaxVelocity für: ", pref, " (übersprungen)")

    next
  }
}

```

```

}

message("Verarbeite: ", pref)

# load inputs
ha <- rast(h_path)
v <- read_align(v_map[[pref]], ha)

# intensities per criterium
l_ha <- class_ha(ha)
l_vha <- class_vha(v * ha)

# total intensity = highest classification
l_total <- app(c(l_ha, l_vha), fun = max, na.rm = TRUE)

# check: only 1/2/3, otherwis NA
l_total[l_total < 1 | l_total > 3] <- NA

# save intensity raster
out_tif <- file.path(out_dir, paste0(pref, "_l_total.tif"))
writeRaster(l_total, out_tif, overwrite = TRUE)

# factors for tmap with fix levels (exactly 3 legend entries)
l_fac <- as.factor(l_total)
levels(l_fac)[[1]] <- data.frame(
  value = c(1, 2, 3),
  label = int_labs
)

# crop background (optional)
bg_crop <- NULL
if (!is.null(bg)) {
  bg_crop <- crop(bg, ext(l_total))
  # Nur fürs Plotten: gleiche Auflösung/Extent wie l_total
  if (!compareGeom(bg_crop, l_total, stopOnError = FALSE)) {
    bg_crop <- resample(bg_crop, l_total, method = "bilinear")
  }
}

# create map (tmap v4)

```

```

if (!is.null(bg_crop)) {
  m <- tm_shape(bg_crop) +
    tm_raster(
      col = names(bg_crop)[1],
      col.scale = tm_scale_continuous(values = gray.colors(256, start = 0.55, end = 0.98)),
      col.legend = tm_legend(show = FALSE)
    ) +
    tm_shape(l_total) +
    tm_raster(
      col = names(l_total)[1],
      col.scale = tm_scale_intervals(
        style = "fixed",
        breaks = c(0.5, 1.5, 2.5, 3.5), # exakt 3 Klassen für Werte 1/2/3
        values = int_cols
      ),
      col.legend = tm_legend(title = "Intensität", labels = int_labs),
      col_alpha = int_alpha
    )
} else {
  m <- tm_shape(l_total) +
    tm_raster(
      col = names(l_total)[1],
      col.scale = tm_scale_intervals(
        style = "fixed",
        breaks = c(0.5, 1.5, 2.5, 3.5),
        values = int_cols
      ),
      col.legend = tm_legend(title = "Intensität", labels = int_labs),
      col_alpha = 1
    )
}

m <- m +
  tm_title("Murgang-Intensitätskarte") +
  tm_layout(
    legend.outside = TRUE,
    frame = FALSE
  ) +
  tm_scalebar(
    breaks = c(0, 0.1, 0.2),

```



```

width = 45,      # extra Platz, damit Labels sicher reinpassen
text.size = 0.4,
lwd = 0.8,
color.dark = "black",
color.light = "white",
position = c(0.03, 0.03),
bg = FALSE,
allow_clipping = FALSE
) +
tm_compass(position = c("right", "top"))

# Export
if (export_png) {
  out_png <- file.path(out_dir, paste0(pref, "_Intensitaet.png"))
  tmap_save(m, out_png, width = 2400, height = 1600, dpi = 300)
}

if (export_pdf) {
  out_pdf <- file.path(out_dir, paste0(pref, "_Intensitaet.pdf"))
  tmap_save(m, out_pdf, width = 10, height = 7)
}
}

message("Fertig. Outputs in: ", out_dir)

```

## 9.6 Appendix 7) Hazard Maps R-Code

```
# =====

# Hazard maps (9 classes intern) + Legend with 3 levels + residual risk

# tmap 3.3.4, terra

# - Intern: classes 1–9 according to matrix (probability dominates)

# - Visualisation: 3 colouts (yellow/blue/red) + extrem as light yellow

# - Legende: only 3 levels + residual risk

# =====

library(terra)
library(tmap)

tmap_mode("plot")

# -----

# INPUTS

# -----

in_dir <- "C:/UZH_GEO805/Master/Silenen/scenario2/Selder/intensity_out"

l30_path <- file.path(in_dir, "Selderbach-dam-scenario2-f30-v1_l_total.tif")
l100_path <- file.path(in_dir, "Selderbach-dam-scenario2-f100-v1_l_total.tif")
l300_path <- file.path(in_dir, "Selderbach-dam-scenario2-f300-v1_l_total.tif")

# swisstopo Basemap (singleband gray)
bg_path <- "C:/UZH_GEO805/Master/map/Silenen-map-raster-10.tif" # <- adjust

# extreme event (seperate run) as intensity map (1..3)
# if not available: ext_path <- NULL
ext_path <- NULL
ext_path <- file.path(in_dir, "Selderbach-dam-scenario2-EHQ-v2_l_total.tif")

# Outputs
out_dir <- file.path(in_dir, "hazard_out")
dir.create(out_dir, showWarnings = FALSE, recursive = TRUE)

out_tif <- file.path(out_dir, "Gefahrenklasse_1-9_future.tif")
out_pdf <- file.path(out_dir, "Gefahrenkarte_future.pdf")
out_png <- file.path(out_dir, "Gefahrenkarte_future.png")
```

```

# -----
# Helper
# -----

stop_if_missing <- function(p) if (!file.exists(p)) stop("Datei nicht gefunden: ", p)

clean_l <- function(l) {
  l[l < 1 | l > 3] <- NA
  l
}

align_to <- function(r, ref) {
  if (!compareGeom(r, ref, stopOnError = FALSE)) {
    r <- resample(r, ref, method = "near") # Klassen -> nearest neighbour
  }
  r
}

# -----
# 1) load
# -----

stop_if_missing(l30_path); stop_if_missing(l100_path); stop_if_missing(l300_path); stop_if_missing(bg_path)

l30 <- rast(l30_path)
ref <- l30
l100 <- align_to(rast(l100_path), ref)
l300 <- align_to(rast(l300_path), ref)

l30 <- clean_l(l30)
l100 <- clean_l(l100)
l300 <- clean_l(l300)

bg <- rast(bg_path)
bgc <- crop(bg, ext(ref))
if (!compareGeom(bgc, ref, stopOnError = FALSE)) {
  bgc <- resample(bgc, ref, method = "bilinear")
}

# -----
# 2) Matrix: intensity × return period -> classes 1..9

```



```

# (weak 3/2/1, medium 6/5/4, strong 9/8/7)
# -----

haz_mat <- matrix(
  c(
    3, 2, 1, # schwach: 30,100,300
    6, 5, 4, # mittel : 30,100,300
    9, 8, 7 # stark : 30,100,300
  ),
  nrow = 3, byrow = TRUE,
  dimnames = list(c("schwach", "mittel", "stark"), c("T30", "T100", "T300"))
)

haz_from_l <- function(l, colname) {
  out <- l
  out[] <- NA_real_
  for (int in 1:3) out[l == int] <- haz_mat[int, colname]
  out
}

H30 <- haz_from_l(l30, "T30")
H100 <- haz_from_l(l100, "T100")
H300 <- haz_from_l(l300, "T300")

# Aggregation: worst class per pixel
H <- app(c(H30, H100, H300), fun = max, na.rm = TRUE)
H[H < 1 | H > 9] <- NA
names(H) <- "hazard_1_9"

writeRaster(H, out_tif, overwrite = TRUE)

# -----

# 3) Extreme event as light yellow area (residual risk)
# -----

hatch <- NULL
if (!is.null(ext_path)) {
  stop_if_missing(ext_path)
  lext <- align_to(rast(ext_path), ref)
  lext <- clean_l(lext)

  # everywhere where extreme event covers

```

```

ext_mask <- !is.na(text)

# HQ-Maske: everywhere with «normal” hazards
hq_mask <- !is.na(H) # oder !is.na(H3), spielt keine Rolle

# Residual risk only where EHQ is affects, but not HQ
rest_mask <- ext_mask & !hq_mask

# continous area (1/NA)
hatch <- ifel(rest_mask, 1, NA)
names(hatch) <- "restgefaehrdung"

}

# -----
# 4) Portray: intern H (1–9), portray extern as H3 (3 levels)
#   Legende: rot -> blau -> gelb + Restgefährdung
# -----

# 3 colours
col_yellow <- "#ffd000"
col_blue  <- "#1f78d1"
col_red   <- "#cc0000"

# Basemap gray (singleband)
bg_layer <- tm_shape(bgc) +
  tm_raster(
    col = names(bgc)[1],
    col.scale = tm_scale_continuous(values = gray.colors(256, start = 0.55, end = 0.98)),
    col.legend = tm_legend(show = FALSE)
  )

# ---- H (1–9) -> H3 (1–3) ----
# 1–2 -> 1 (schwach)
# 3–6 -> 2 (mittel)
# 7–9 -> 3 (erheblich)
H3 <- classify(
  H,
  rbind(
    c(-Inf, 2.5, 1),

```

```

c( 2.5, 6.5, 2),
c( 6.5, Inf, 3)
),
include.lowest = TRUE
)

# build factor + order of legend entries (3,2,1)
H3f <- as.factor(H3)
levels(H3f)[[1]] <- data.frame(
  value = c(3, 2, 1),
  label = c("erhebliche Gefährdung", "mittlere Gefährdung", "schwache Gefährdung")
)

# Hazard-Layer: fix colour per class
haz_layer <- tm_shape(H3f) +
  tm_raster(
    col = names(H3f)[1],
    col.scale = tm_scale_categorical(
      values = c(
        "erhebliche Gefährdung" = col_red,
        "mittlere Gefährdung" = col_blue,
        "schwache Gefährdung" = col_yellow
      )
    ),
    col.legend = tm_legend(title = ""),
    col_alpha = 0.55
  )

# Residual risk (light yellow)
ext_layer <- NULL
if (!is.null(hatch)) {
  # Restgefährdung / EHQ als sehr hellgelber Overlay
  EHQ_f <- as.factor(hatch)
  levels(EHQ_f)[[1]] <- data.frame(value = 1, label = "Restgefährdung")

  ext_layer <- tm_shape(EHQ_f) +
    tm_raster(
      col = names(EHQ_f)[1],
      col.scale = tm_scale_categorical(values = c("Restgefährdung" = "#ffe680")),

```



```

    col.legend = tm_legend(title = ""),
    col_alpha = 0.35
  )

}

m <- bg_layer + haz_layer
if (!is.null(ext_layer)) m <- m + ext_layer


# Titel + Layout + Scalebar + north arrow
m <- m +
  tm_title("Murgang-Gefahrenkarte") +
  tm_layout(
    legend.outside = TRUE,
    frame = FALSE
  ) +
  tm_scalebar(
    breaks = c(0, 0.1, 0.2),
    width = 45,
    text.size = 0.45,
    lwd = 0.8,
    color.dark = "black",
    color.light = "white",
    position = c(0.03, 0.03),
    bg = FALSE,
    allow_clipping = FALSE
  ) +
  tm_compass(position = c("right", "top"))


# Export
tmap_save(m, out_pdf, width = 10, height = 7)
tmap_save(m, out_png, width = 2400, height = 1600, dpi = 300)

message("Fertig! Outputs in: ", out_dir)

```

## 10 Declaration of AI-use

| AI-Based Tool    | Use                                                             | Scope                       | Remarks                                                      |
|------------------|-----------------------------------------------------------------|-----------------------------|--------------------------------------------------------------|
| Chat GPT         | Alternate formulation, text revision, spell check, translations | Entire document             |                                                              |
|                  | Creation of Title                                               | Title                       | Title idea and discussions of variations                     |
|                  | Programming and troubleshooting in R                            | R-code                      | initial frame work and help understanding functions from GPT |
| Scholar GPT      | Additional literature research                                  | Theory, Methods, Discussion | Citations not from GPT, only from original source            |
| DeepL Translator | Translation of single words or phrases                          | Entire document             | German <-> English                                           |

## 11 Declaration of Independence

Personal declaration: I hereby declare that the submitted thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the thesis.

A handwritten signature in black ink, appearing to read 'M. Bäurle'. The signature is fluid and cursive, with a large 'M', a dot over the 'B', and a stylized 'äurle'.

Maya Bäurle

Stans, 28. February 2026