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Process-based identification and estimation of bedload sources of the 2012 St. Lorenzen debris flow event

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Zusammenfassung

Im Rahmen dieser Studie wurde das Einzugsgebiet des Lorenzerbachs südwestlich von St. Lorenzen im Paltental (Steiermark) untersucht. Am 21. Juli 2012 bildete sich nach Starkniederschlägen ein Murgang, der die Ortschaft schwer beschädigte. Um die Gerinne und deren angrenzenden Hänge hinsichtlich ihrer Rolle im Geschiebehaushalt zu untersuchen wurden Geländestudien mit Methoden der Fernerkundung kombiniert. Mittels Felduntersuchungen konnten neben den geologischen Rahmenbedingungen die Eigenschaften der Systemelemente bestimmt- und geschiebemobilisierende Prozesse erfasst werden. Durch die Verfügbarkeit von hochauflösenden Orthofotos aus zwei Befliegungen wurden Massenbewegungen, welche mit dem Ereignis von 2012 in Verbindung stehen, kartiert und statistisch analysiert. Auf Basis der Erkenntnisse aus den GIS- und geländegestützten Untersuchungen konnten die Feststoffkubaturen mithilfe eines in der Schweiz entwickelten, prozessbasierten Geschiebeabschätzverfahrens quantifiziert werden. Dabei wurde als Szenario für die Methode der Prozessablauf des Murgangs von 2012 gewählt. Die Studie zeigt, dass das Wildbachsystem unterschiedlich stark von Hang- und Gerinneprozessen beeinflusst wird, weshalb das Einzugsgebiet in vier charakteristische Prozessgebiete unterteilt werden kann. Das Murpotential des Lorenzerbachs geht wahrscheinlich von zahlreich auftretenden Massenbewegungen aus, welche nicht nur Material vom Hang ins Gerinne liefern, sondern auch zu Verklausungen führen können. Diese Hangprozesse treten hauptsächlich im zentralen Einzugsgebiet auf, wo stark tektonisch beanspruchte- und verwitterungsanfällige Gesteine anstehen. Die durch das Geschiebeabschätzverfahren ermittelten Kubaturen zeigen eine gute Korrelation mit Werten aus der Literatur. Größere Abweichungen konnten lediglich bei längeren, flachen Gerinneabschnitten ermittelt werden. Weitere Anwendungen auf steilere Wildbachsysteme könnten die Stärken und Schwächen des Abschätzverfahrens näher beleuchten.

Abstract

In the framework of this study, the catchment of the Lorenzerbach near the village of St. Lorenzen in Styria was investigated. On the 21st of July 2012, a debris flow was triggered that severely damaged the locality situated below. In order to investigate the torrents and their adjacent slopes concerning their bedload contribution, on-site studies were combined with remote sensing. Fieldwork was conducted to determine the properties of the geologic units and system elements. Also, bedload-mobilizing processes were inventoried. As high-resolution orthophotos from two overflights are available, landslides which are related to the 2012 event could be mapped and statistically analyzed. The findings from GIS- and field-based studies were then used to apply a process-based, Swiss-developed bedload estimation procedure. The scenario for the quantification method was chosen in a way that the most critical processes of the 2012 debris flow were considered. The study shows that the torrent system is influenced to varying degrees by slope- and torrent processes, which is why the catchment can be subdivided into four characteristic process areas. The debris flow potential of the Lorenzerbach probably originates from numerous landslides, which not only transport material from the slopes into the torrents but can also block them. These slope processes mainly occur in the central parts of the catchment, where tectonically stressed rocks prone to weathering are exposed. The results from the bedload estimation procedure were compared to literature values. A good correlation could be determined for most torrent segments. Significant deviations were only evident at longer channel sections with a low gradient. Further applications of the estimation procedure on steeper mountain torrent systems could contribute to highlight the strengths and weaknesses of the quantification method.

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1 Introduction

Natural hazards such as floods, avalanches and debris flows are very common in areas, where steep relief and precipitation are present. Because nearly two-thirds of Austria is covered by the Alps, large parts of the country are located in the catchments of avalanche- and torrent systems (Rudolf-Miklau et al. 2009), which is impressively shown in Figure 1-1. It is evident that states with high relief such as Tyrol, Salzburg, Carinthia, and Styria are more affected than states at the border of the Alps such as Lower Austria or the Burgenland.

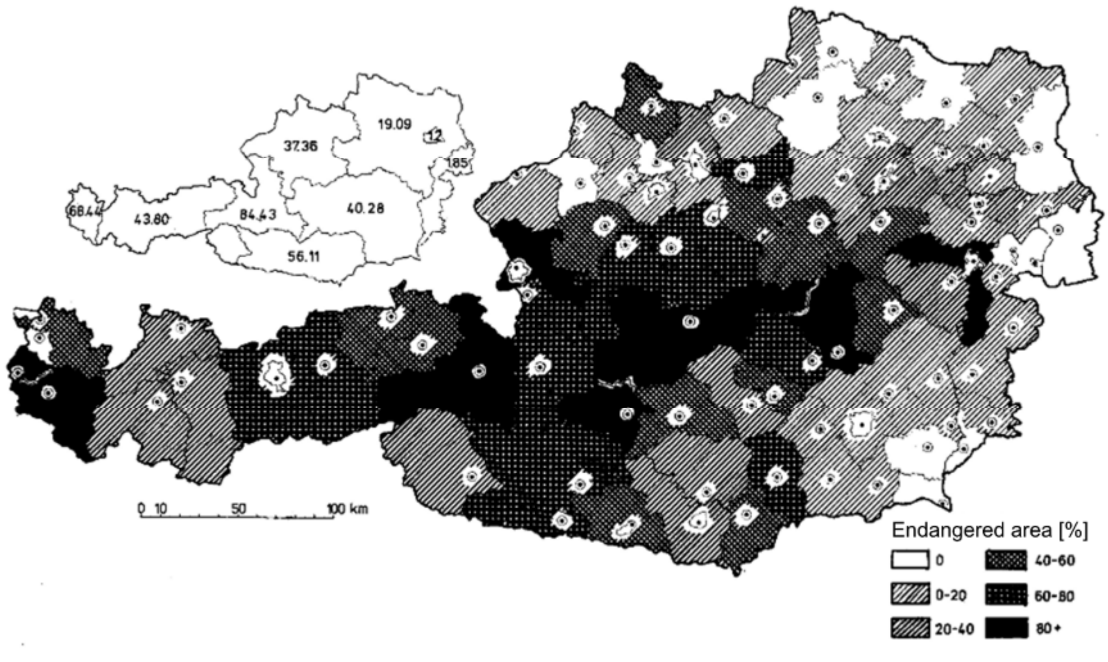


Figure 1-1: Austria's states (top left) and political districts and their percental area which is endangered by alpine mountain torrent systems (bottom right). Modified after Aulitzky (1986).

Thus, it is no surprise that over Austria's populating history many catastrophic events took place. A prominent example for a destructive debris flow event that received large media attention is the debris flow that struck "St. Lorenzen im Paltental" in Styria. After a long period of intense rainfall, on the 21st of July 2012, a debris flow was triggered in the catchment of the Lorenzerbach. St. Lorenzen, the village situated directly next to the Lorenzerbach, was struck by the landslide. Sixty-seven buildings were damaged, seven of them were utterly destroyed.

Aside from the deposition of thousands of cubic meters of bed load, over 4,000 stêre of wood had to be removed from the affected areas. Fortunately, no people were killed during the event.

The past activity of the Lorenzerbach concerning debris flow and flooding processes is well known. Since 1852, nine events were documented. From 1921 on, several structures were built in order to prevent or minimize damages in the event-case (Hübl et al. 2012). After the event of 2012, additional retaining structures were built, and remediation measures were conducted on damaged safety construction. Detailed event documentation was carried out by the University of Natural Resources and Life Sciences Vienna (BOKU Wien), in which the magnitude and the repercussions of the processes were mapped at the village, and parts of the torrent system. Additionally, hydraulic simulations were performed by Janu and Mehlhorn (2013) to reconstruct the event.

As engineers and earth scientists are confronted with alpine mountain torrent systems in daily practice, the question arises, whether crucial torrent- and slope process constellations can be identified prior to an event and whether the amount of material involved can be quantified. In the framework of the present study high-resolution airborne laser scan and orthophoto data are analyzed with modern GIS applications. Additionally, field studies were carried out to evaluate the crucial slope and torrent processes as well as the geologic properties to determine their repercussions on the bedload household of the Lorenzerbach. Important questions that are tackled in this study are: What are the most important torrent- and slope properties and processes constellations that are responsible for the debris flow threat in the catchment of the Lorenzerbach? In which way does the geologic framework impact the torrent geometry and the process outcome? The obtained results shall then be utilized to apply the Swiss-developed, process-based assessment method after Gertsch (2009), which is capable of quantifying the bedload cubature that could be delivered during a significant debris flow event. The scenario for the estimation procedure should thereby be adjusted to the event of 2012 in order to test the applicability of the Swiss-developed method for Austrian mountain torrent systems.

2 Study area and geological context

The investigations were carried out in the catchment of the Lorenzerbach, which is situated southwesterly of the village “St. Lorenzen im Paltental” in Styria, Austria. The village belongs to the borough Liezen, beholds 374 inhabitants and is a cadastral community of the city Trieben.

The study area is extending from St. Lorenzen towards the southwest and measures appr. 5 km^2 (Figure 2-1). The western boundary proceeds from the Pettaler Alm (1075 m) over the Kirchbacheralm (1402 m) towards the summit of the 2188 m high Almspitz mountain, which represents the highest elevation in the examined region. The study area proceeds along the southeastern ridge (Schafriedel) of the Almspitz towards the summit of the Lugstein, over the 1275 m high Hohenbühl towards St. Lorenzen, which acts as the northern border.

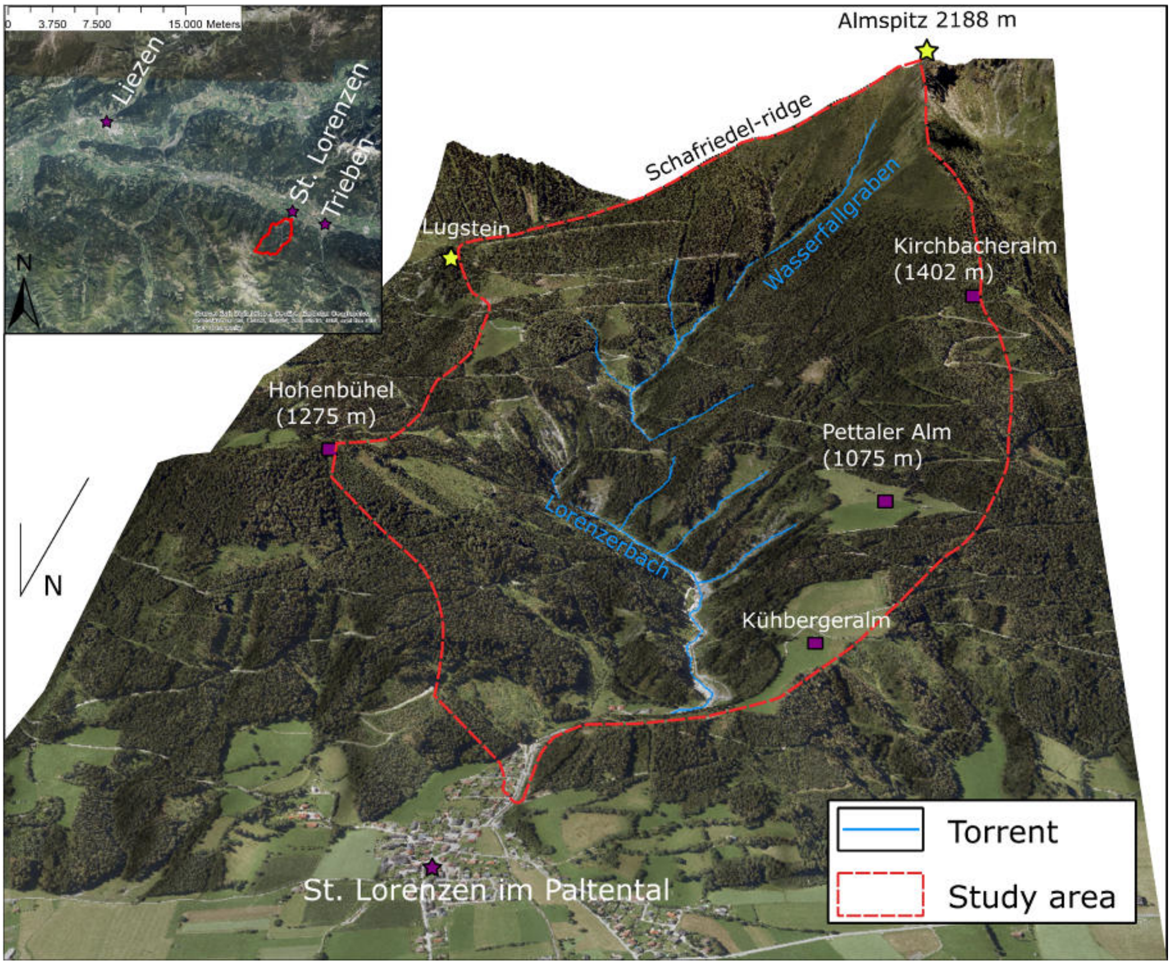


Figure 2-1: Location (upper left map) and extent of the study area (right map). The study area is situated southwesterly of the village St- Lorenzen im Paltental and stretches along the surroundings of the Lorenzerbach.

The morphology of the study area is characterized by the depression carved through fluvial erosion of the Lorenzerbach, forming the Lorenzergraben. This irregularly-shaped, incised feature connects to the “Wasserfallgraben” at an altitude of around 1460 m, which is situated at the northeastern flank of the Almspitz Mountain. The Lorenzerbach flows from the southwest towards the northeast and is fed by several tributaries throughout its flow path. It exits the study area at St. Lorenzen and mounds into the Palten river.

The geologic units surrounding St. Lorenzen belong to the Austroalpine nappe, which represents fragments of the former continental shelf/slope of the Adriatic plate. To the north of St. Lorenzen, Upper Austroalpine carbonate rocks of the Northern Calcareous Alps form the sharp and steep relief of the Gesäuse national park. Towards the south, these sharp morphologies get replaced by a rather smooth morphologic expression, being built up by the rocks of the Greywacke zone. The units of the greywacke zone cover a large part of the study site, being preserved as tectonically stressed greywacke schists, greenschists, and carbonates (Figure 2-2 after Metz (1967)). From a tectonic point of view, they are related to the Upper Austroalpine nappe. In the southeastern part of the mapping area, granites, gneisses, and biotite-schists of the Silvretta-Seckau nappe system are exposed. They represent parts of the Upper Austroalpine basement nappes (Middle-Austroalpine nappe in former classification after Tollmann (1977)) and form the summits of the southwards of St. Lorenzen situated Rottenmanner Tauern and the Almspitz mountain (Schmid et al. 2004). They are accounted to the Bösenstein Crystalline, which represents a tectonically separated part of the Seckauer Tauern. These units were thrusted upon the units of the Greywacke zone (Ratschbacher 1986). Quaternary deposits cover large parts of the study area. In the uppermost parts, talus deposits cover the northeastern flank of the Almspitz. Besides that, glacial deposits cover the most part of the distant slopes, surrounding the Lorenzerbach. In the proximity of the torrent itself, colluvial sediments and fluvial deposits can be found.

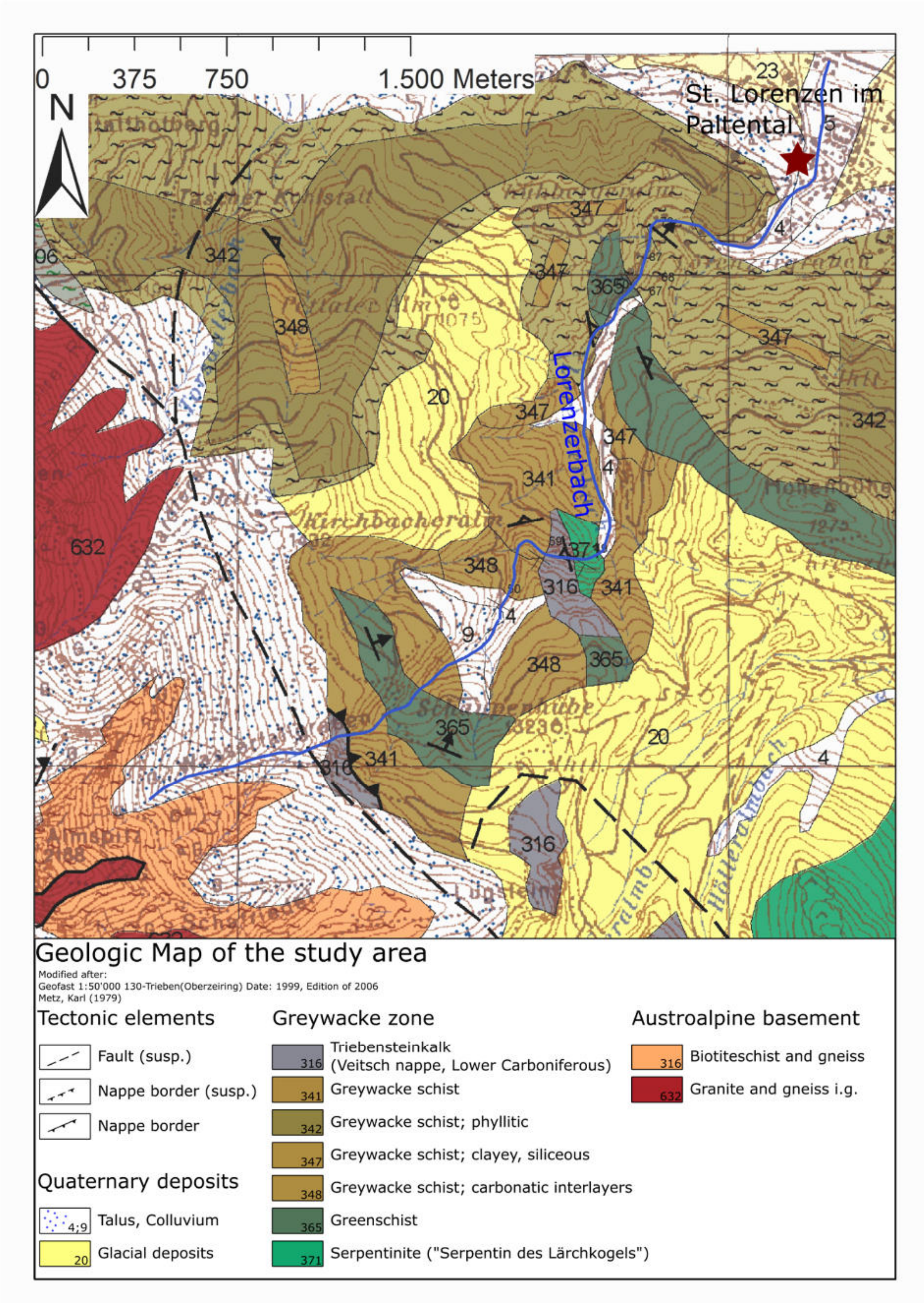


Figure 2-2: Geologic map of the study area and its surroundings: Most parts of the study area consists of rocks of the Greywacke zone. In the upper parts, Austroalpine basement units area exposed (Geofast map 130-Trieben(Oberzeiring) (1999) & Metz K. (1979), modified).

3 Mountain torrent systems

To determine the hazardousness of an alpine mountain torrent system, its structure and the accompanying processes and process interactions must be understood prior to the investigations. Therefore, this chapter provides a brief overview of the most relevant slope and torrent processes and their influence on the bedload household according to the findings of basic research.

3.1 Terminology and definition

Alpine mountain torrent (Ger.: Wildbach*)*:

According to §99(1) of the Austrian Forest Guideline, an alpine mountain torrent (*Wildbach*) is a permanently- or episodically fluid bearing torrent that transports dangerous amounts of bedload during short-lasting periods of increased flow rates. It erodes the material in its catchment and deposits that mass inside or outside its creek bed. It is part of the alpine mountain torrent system, which is subdivided in the catchment and the alluvial fan deposits, resulting from debris flows and periods of increased bedload transportation (Kienholz et al. 1998).

Bedload (Ger.: Geschiebe):

Bedload is defined by solid particles that are transported along the torrent bed. It derives from erosional and geomorphologic processes in the catchment, where weathering mechanisms or landslides eventually lead to the input of debris into a torrent, which is then transported as bedload.

Catchment (Ger.: Einzugsgebiet):

The catchment is the area in a hydrologic system, where the collected precipitation drains off into a common outlet, such as torrents or rivers in the lowermost point of the catchment. In this feature, the most important processes take place, which ultimately define the hazardousness of an alpine mountain torrent system.

3.2 Structure of an Alpine mountain torrent system

Alpine mountain torrent systems comprise of the catchment, the fan apex and the alluvial fan (Figure 3-1).

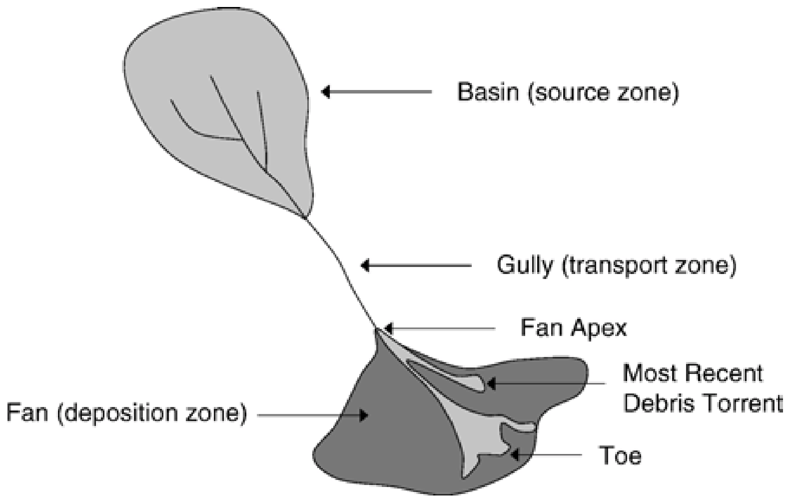


Figure 3-1:Simplified, schematic sketch of a mountain torrent system. The basin or catchment contains all relevant processes of bedload production and mobilization. The fan marks the deposition zone (Sterling and Slaymaker 2006).

The source zone thereby equals the catchment, which is bordered by the watershed. Its fundament is built up by geologic units with specific properties. It contains the torrent system and its adjacent slopes and receives precipitation through rain and snow and is consequently accountable for the surface and subsurface runoff processes. Apart from that, material supply is produced in the catchment due to erosion- and weathering processes. The fan apex marks the exit point for all transported material, which then accumulates at the alluvial fan.

In Alpine mountain torrent systems, besides the initial geologic/tectonic/climatic or hydrologic situation, a complex interaction between slopes and torrents determines the capability of bedload delivery and flooding potential. This interaction is visualized in a schematic sketch by Hegg (1996) (Figure 3-2).

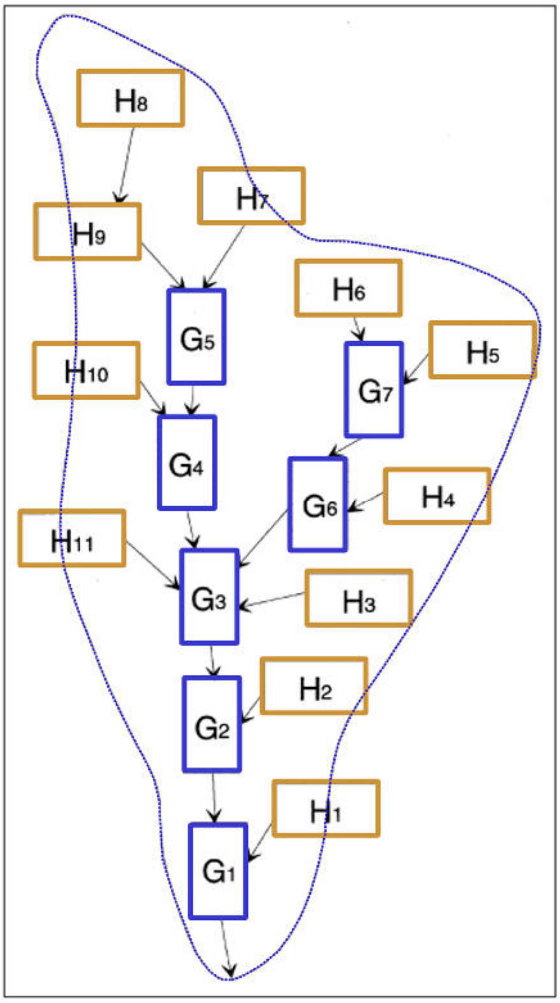


Figure 3-2: The components in the basin of an alpine mountain torrent system comprise of slope- and torrent subsystems (H and G respectively). The interaction between these elements leads to mass transfer (surface- and subsurface waters, organic and inorganic material) and ultimately controls the bedload household. Modified after Hegg (1996).

All subsystems are connected through water and sediment transfers. H_n thereby describes the subsystem "Slope" and G_n describes the subsystem "Torrent". In each subsystem, H or G respectively, bedload delivering or mobilizing processes play a role.

In general, it can be distinguished between processes concerning the water budget and processes related to the bedload household (Hegg et al. 2001). The latter can again be subdivided in bedload production, which comprises processes that are responsible for the production of loose material, bedload mobilization, which includes processes that transport loose material towards the next discharge element, and ultimately the transfer mechanism, which defines the type of material transport in the discharge element towards the exit point of the alpine mountain torrent system (Hegg et al. 2001). The interactions between the subsystems and accompanied mechanisms respectively are consolidated in Figure 3-3 in a simplified way.

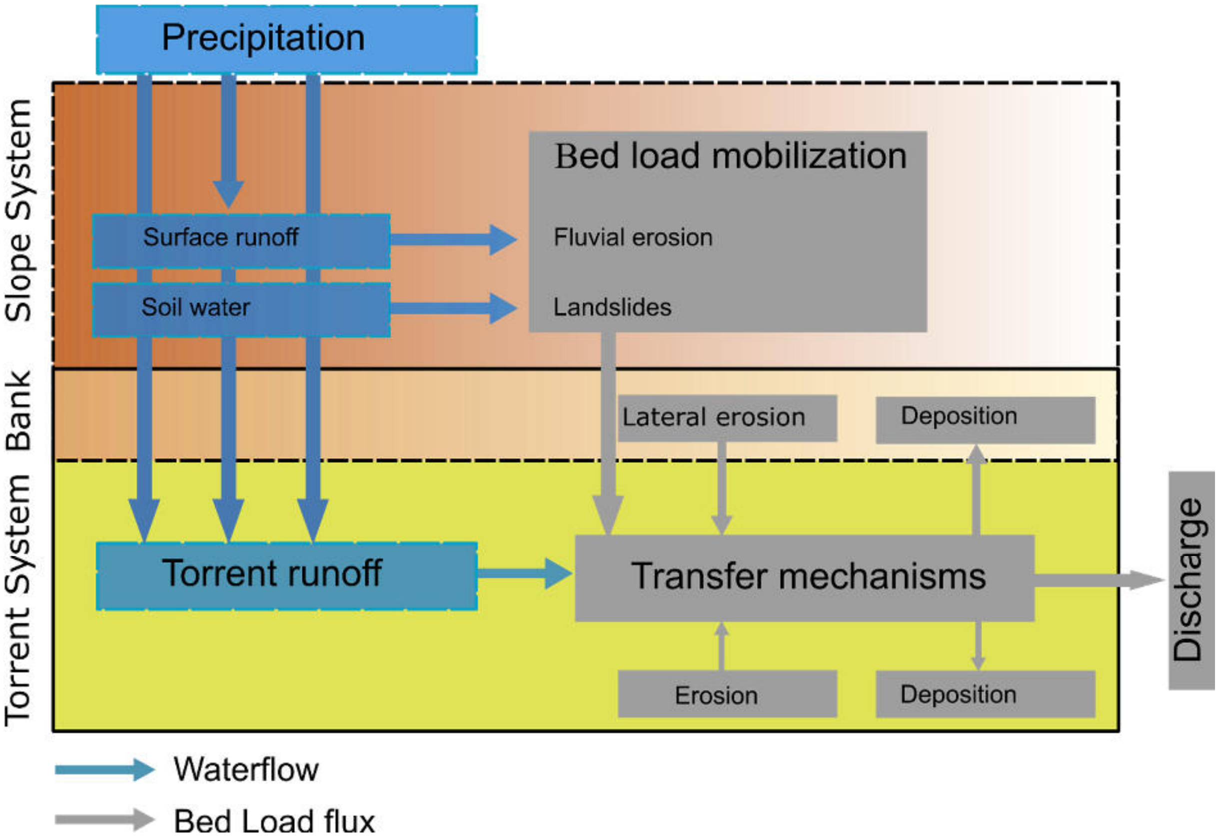


Figure 3-3:Simplified process system in an Alpine mountain torrent system. Subsystem "slope" is dashed, subsystem "torrent" is drawn through. The subsystem "bank" beholds an exceptional position: It is influenced both by the torrent system and the slope system. Modified after Gertsch (2009)& Liener (2000).

In the following subchapters, the most relevant processes in the respective subsystems are introduced, as their identification is necessary to assess the potential of the torrent system to deliver solid particles.

3.2.1 Water budget and water supply

Processes concerning the water budget in an alpine mountain torrent system comprise the development of runoff at the slopes and the further water flux in the torrents. Apart from climatic aspects that have a significant impact on the water budget and further the debris flow potential (Wieczorek and Glade 2005), vegetation and the soil properties in the catchment play an important role. A critical point for the flooding potential is to determine how fast precipitation can reach the next torrent. The fastest way for water to travel from slope to torrent is via surface runoff, which occurs in cases of a fully saturated subsoil. Thereby the flooding potential is drastically increased. Vegetation and unsaturated soil bodies can retain a certain amount of water due to infiltration and evapotranspiration (Hegg et al. 2001). However, longer periods of rainfall, heavy rain events and snowmelt in spring can yield an exceeding of the storage capacity of the soil body (Luzian et al. 2002) and ultimately produce flooding.

Interflow, in contrast, is defined as a near surface, lateral type of water flow with lower travel speed (compared to surface runoff) in unsaturated soils. Some parts of interflow can be stored in groundwater bodies, other parts reach the next torrent element and consequently become operative concerning the drainage and overall runoff behavior.

3.2.2 Bedload production

In an alpine mountain torrent system, loose material supply is produced due to the physical and chemical weathering processes that act on the geologic units in the catchment. Weathering rates are dependent on the altitude range of the catchment, the lithologic properties and the exposition of the slopes (Gertsch 2009). It is a rather continuous process that does not change much over time.

Concerning the loose material available in the catchment, Stiny (1931) discerns between "Jungschutt", which represents young, unvegetated deposits that derive from weathering- or landslide processes and "Altschutt", which represents older sediment deposits that were generated e.g. through glacial or fluvial processes. The name "Jungschutt" or "young debris" and "Altschutt" or "old debris" is thereby directly linked with the time, as they are generated in the present- or bygone time respectively (Luzian et al. 2002). Both sediment types vary in their composition and grain size distribution but are essential for the bedload household of an alpine mountain torrent system, as they can be eroded much easier than bedrock. Apart from the material generation through weathering, erosion of the soil bodies itself can result in triggering further slope instabilities which ultimately leads to a large input of sediments (and perhaps vegetation) into the torrent.

3.2.3 Bedload mobilization

In an Alpine mountain torrent system, the material is mobilized by either fluvial erosion or by slope processes such as landslides. Fluvial erosion can lead to the development of gullies, which typically occurs in mountainous regions with steeply inclined slopes where high runoff velocities are reached. The development of gullies can be favored due to tectonic processes that weaken the exposed bedrock or can proceed out of old landslide scars (Valentin et al. 2005). Fluvial erosion acting in gullies is capable of eroding through loose/solid material and transport the mass to the next torrent. Thereby, the accumulated and the eroded material in the gully itself is mobilized. Erosional processes that result from the increased water energy due to often steep slopes in Alpine mountain torrent systems can also erode through the underlying rock or soil body and thus increase the total displaced material. The development of debris flow phenomena can also often be observed in gullies.

Landslides can mobilize small to large compartments of rock and soil bodies. Varnes (1978) thereby distinguishes between**:**

- **Falls:** Rapid shift of fragments out of a steep slope with little to no shear displacement descending mostly through the air by free fall, leaping bounding or rolling
- **Slides:** Sliding of soil/rock along an either planar (*rotational slides*) or concave sliding plane (*translational slides*)
- **Lateral spreads:** Movement through lateral extension accommodated by shear or tensile fractures
- **Flows:** Flowing of material which behaves similar to a viscous liquid. Very slow flowing rates of mm to meters per year are called *creeping*.
- **Complex:** Combination of one or more previously described landslide mechanism

Apart from the mobilized cubature and consequently the delivering of the material to the torrent, landslides can also block a torrent segment. Thereby material accumulates behind the newly developed barrier, which gets remobilized when the barrier breaches, often triggering a debris flow (Hegg et al. 2001). The barrier itself can develop out of the mobilized soils, or the vegetation cover ("log jams" through the input of tree stems)).

3.2.4 Bedload transfer mechanisms in the torrent

Sediment transfer mechanisms involve those that are required to relocate solid particles, which were mobilized out of slope- and torrent processes (Chapter 3.2.3) and ultimately deposit them at the debris cone. The amount of solid particles that can be transferred by torrents is dependent on the transport process and is limited by runoff or sediment supply (Gertsch 2009). Under runoff-limited conditions, the present amount of bedload can't be mobilized due to a lack of transport capability. When the sediment supply is the limiting factor, the torrent bed and its surroundings do not offer a high enough replenishment of sediments.

After Hegg et al. (2001), three bedload transfer mechanisms can be distinguished:

- **Transport of suspended load** (*ger. "Schwebstofftransport"*)
- **Fluvial debris transport** (*ger. "Geschiebetransport"*)
- **Debris flow transport** (*ger. "Murgang"*).

Transport of suspended load and Fluvial debris transport

Transport of suspended matter is defined when the grains in the fluid stream are transported entirely as suspended load by the turbulence. Fluvial debris transport, in contrast, involves the solid particles to get transported along the immobile torrent bed by saltation, rolling and sliding (Bridge and Dominic 1984).

Debris flow transport

For debris flow transport, several definitions and classifications exist. After Varnes (1978), debris flows account to the "flow" landslide category. In the proposed classification, the respective term is dependent on the rate of movement, and the composition of the transported material (Table 3-1):

Table 3-1: Terms for mass movements of the flow category according to Varnes (1978).

Rate of movement	Bedrock	Debris (<80% sand and finer)	Earth (>80% sand and finer)
Rapid and higher (>1.5 m/day)	Rock flow (creep, slope sagging)	Debris flow Debris avalanche	Wet sand and silt flow Rapid earth flow Loess flow Dry sand flow
Less than rapid (<1.5 m/day)		Solifluction Soil creep Block stream	Earth flow

By following this definition, a landslide is a debris flow, if less than 80% of the components comprise of the sand fraction and finer particles, and if the rate of movement exceeds 1.5 meters per day.

Hungr et al. (2001) classify flow type landslides based on the grain size of the transported particles, the water content, the velocity and "special conditions" (pore pressure, liquefaction potential, etc.). According to the publication, a debris flow is defined as a "…very rapid to extremely rapid flow of saturated, non-plastic debris in a steep channel. (Plasticity Index < 5 percent in sand and finer fractions)” (Hungr et al. 2001). Furthermore, a mud flow is a “very rapid to extremely rapid flow of saturated plastic debris in a channel, involving significantly greater water content relative to the source material (Plasticity Index > 5 percent)” (Hungr et al. 2001).

Debris flow initiation through landslides

The initiation of a debris flow is mostly starting with slope failure. Landslide bodies, which can originate from several landslide mechanisms such as sliding, toppling and slumping, are thereby transformed into debris flows through effects of dilatancy and liquefaction during their way downslopes. These processes are prone to occur at slope angles greater than 15° - 20° and under the presence of a significant flux of water (Costa 1984). As not all landslides might be transformed to debris flows during their movement, they still can yield the formation of landslide dams by blocking the flow passage of an adjacent torrent. A subsequent breaching of the dam can then result in a debris flow surge (Costa 1984).

Debris flow initiation in channels/torrents

Debris flows may also develop out of steep channel beds if it becomes unstable under the effects of extreme discharge (Hungr 2005). Thereby, the channel deposits or the channel bed itself acts as the material source for the debris flow (Costa 1984).

Debris flow surge

Debris flow events are often characterized by the occurrence of one or more debris flow surges (Figure 3-4). These debris flow surges can, in an idealized way, be differenced in the precursory surge with a variable solids concentration, a boulder front with the debris flow head, and the fully developed debris flow body which is followed by an hyperconcentrated streamflow (Pierson 1988).

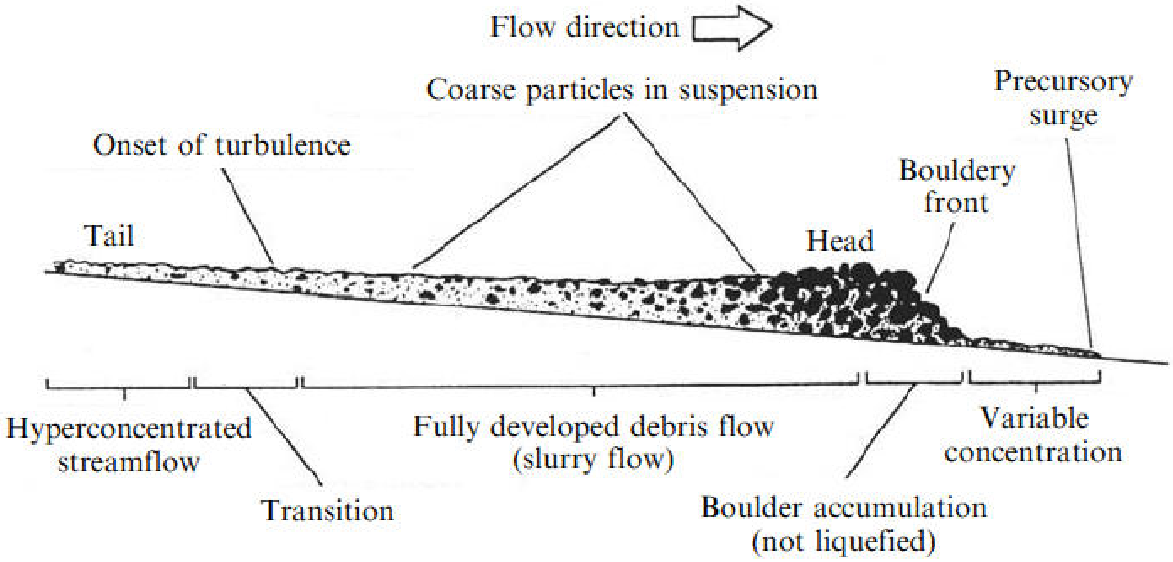


Figure 3-4: Idealized sketch of a debris-flow surge with a boulder front. From Pierson (1988).

However, this idealized sketch for most cases does not necessarily reflect the actual geometry of a debris flow, as it is dependent on a variety of factors.

Fingerprints of debris flows in the field

The impacts of debris flows compared to fluvial debris transport or transport of suspended load concerning the change in channel geometry and erosion effect are significant. Debris flows can relocate several cubic meters measuring boulders and yield massive destruction to anything that is in its path. Because of the striking impact of debris flows on the alpine mountain system's morphology, fingerprints that give hints for a bygone event can be recognized:

- *U-Shaped torrent profile*
- *Levêe deposits (ridge-shaped deposits along a channel deriving from debris flows)*
- *Large rounded boulders*
- *Unsorted deposits at the fan*

3.3 Implications for this study

Scientific studies show the complexity and interdisciplinarity (Geology, Pedology, Hydrology, Geomorphology and Rock/Soil Mechanics) of the process interactions that influence the hazard potential of mountain torrent systems. As not all aspects are possible to be considered when conducting a hazard assessment, a reasonable approach would be to determine the geological boundary conditions (rock properties, susceptibility to weathering etc.) to cover their impacts on the torrent and slope geometry and bedload household (bedload production), and to evaluate the torrent and slope properties. Thereby, indicators for mobilizing processes (especially in the subsystem “slope”) and transfer mechanisms (most particularly in the subsystem “torrent”) have to be recognized and transferred into a big picture.

Bedload production:

- *Geological boundary conditions and rock properties*

Mobilizing processes:

- *Investigation of the slopes surrounding the torrent system*
    - *Landslides*
    - *Fluvial erosion*

Transfer mechanisms:

- *Field evidence from bedload mobilizing processes*
    - *Debris Flow transport (Levêe deposits, Large boulders, etc.)*

Big Picture: Which interactions and constellations are responsible for the debris flow susceptibility?

4 Bedload estimation for Alpine mountain torrent systems

Apart from the process constellation which might be responsible for debris flow development, obviously the question arises, how the process outcome can be quantified.

For this purpose, empirical approaches and process-oriented approaches were developed over the past decades. Strictly empirical approaches are often expressed by simple equations, which cannot be adapted to the in-situ process paths that might take place in a specific mountain torrent system. Process-based approaches are mostly established on findings from empirical evaluations, but in contrast, consider a detailed resolution of the actual processes in the studied system. Prominent examples of a process-based approach are (Rimböck et al. 2013):

- SEDEX (SEDiments and EXperts): Developed in the framework of the dissertation of Eva Frick under cooperation with the civil engineering department of the Canton Bern and the Institute of Geography, Bern
- Geschiebepotenzialband GPB: Developed in the framework of the ETAlp Project report
- Bedload estimation procedure after Gertsch, 2009: Developed in the framework of the dissertation of Eva Gertsch, 2009 at the Institute of Geography, Bern under supervision of Prof. Dr. Hans Kienholz and Prof. Dr. Manfred Spreafico

These estimation procedures have in common that "homogenous areas" in the torrent and slope system have to be defined. A general outline of the development and application of the bedload estimation procedure after Gertsch (2009) is presented in this chapter, as this method was applied in the framework of this study. Besides the process-based approaches, estimation procedures exist, where the focus is set on the drainage behavior of the catchment (e.g. as conducted by Pavlidis et al. (2006) for the Hortiatis mountain massive in Greece). These approaches are not discussed in the framework of this thesis.

4.1 Examples for simple empirical approaches

Kronfellner-Kraus (1982) developed a simple equation to determine the bedload volume based on empirical relations between a location factor K, the average graben inclination J, and the catchment area E (Equation 4-1):

$$GS = K \cdot E \cdot J; \qquad \text{(eq. 4-1)}$$

with	GS [m^3]	bedload cubature at extreme events
	K [-]	location factor
	J [%]	graben inclination
	E [km^2]	catchment area

The graben inclination J is measured as the average inclination of the channel close to the exit point (fan apex). The location factor K is determined dependent on the location of the torrent system. Kronfellner-Kraus has defined four zones with respective equations to evaluate the K-factor:

I: Tauernhauptkamm

$$K = \frac{1750}{e^{0.018E}}; \qquad \text{(eq. 4-2)}$$

II: Northern and southern calcareous alps, Greywacke zone and the Niederen Tauern

II/1: With a high bedload potential

$$K = \frac{1150}{e^{0.014E}}; \qquad \text{(eq. 4-3)}$$

II/2: With a low bedload potential

$$K = \frac{540}{e^{0.008E}}; \qquad \text{(eq. 4-4)}$$

III: For torrent systems in the Alpine foreland

$$K = \frac{254}{e^{0.0016E}}; \qquad \text{(eq. 4-5)}$$

A similar approach was developed by D'Agostino et al. (1996), with the difference that a geology factor- and a process factor must be implemented. Thus, at least on a large scale, characteristics of the catchment can be adjusted to ensure a better representation of the situation.

$$V = 39 \cdot E \cdot Jc^{1.5} \cdot IG \cdot IT^{-0.3}; \qquad \text{(eq. 4-6)}$$

with	V [m^3]	Volume of transported sediments
	E [km^2]	Catchment area
	Jc [%]	Inclination of the main torrent
	IG [-]	Geology factor
	IT [-]	Process factor

Compared to the approach of Kronfellner-Kraus (1982), D'Agostino et al. (1996) offer the opportunity to define scenarios based on the determined process and includes the prevailing geologic situation in the equation. Therefore, understanding the ongoing processes in the studied torrent system at least on a large scale is mandatory and allows a better representation and comprehensiveness of the calculated cubatures. However, studies of Bertschli et al. (2008) showed that strong generalization is required if strictly empirical bedload estimation procedures (including the above-mentioned) are applied, leading to significant deviations in cubature outcome when compared to field estimations. Because of that drawback, these methods can only be used for rough approximations, but are not reliable when it comes to questions such as for retaining structure dimensioning. Given that, strictly empirical bedload estimation procedures were neglected in this thesis.

4.2 GIS- and/or field-based bedload estimation after Gertsch, 2009

This subchapter outlines the features of the bedload estimation procedure after Gertsch (2009). In order to give an appropriate insight into the method, this chapter summarizes the data pool for model development, the considerations made concerning the process systems with its negative factors, and the application. All subchapters of 4.2 are based on the dissertation of Eva Gertsch of 2009. As not all aspects can be covered, for a detailed insight, the author recommends the original dissertation.

The GIS and/or field-based bedload estimation procedure proposed by Gertsch (2009) was developed in the framework of the research project "Geschiebelieferung alpiner Wildbachsysteme bei Grossereignissen", financed by the Swiss Bundesamt für Umwelt (Federal agency for the environment) and the University of Bern. More than 100 mountain torrent systems and 80 flood- and debris flow events in Switzerland were analyzed in terms of their processes and the related bedload contribution, 58 of which had a recurrence interval of > 100 years. The empirical relations obtained by the evaluation of the study areas were implemented in a process-based bedload estimation procedure. This procedure and consequently the calculation of the bedload volume can be applied by only using GIS-Data without field observations, so with information that can be extracted from digital elevation models and open source GIS-Applications such as swisstopo, or by conducting a field and GIS-based approach. In this chapter, only the GIS- and field-based approach is summarized as it allows a more detailed bedload estimation compared to the solely GIS-based approach.

4.2.1 Data pool for model development

For the development of the estimation method, Gertsch (2009) analyzed 58 catchments of mountain torrent systems. After the development, the estimation method was tested in 43 study areas to validate the approach, 20 of which were validated based on actual events (mega-events with annuities > 100 years) and 23 were validated based on conducted hazard assessments. The study areas that were used to develop the estimation methods can be separated into two groups:

- **Analysis areas:**
    - 58 catchments of mountain torrent systems where mega-events took place
    - Used to obtain an understanding of ongoing processes in the catchments and to develop the bedload estimation method.

- **Validation areas:**
  - In total 43 catchments of mountain torrent systems used for validation of the developed bedload estimation method.
  - 20 catchments of which were validated based on actual events (**Event-validation areas)**
  - 23 catchments of which were validated in the framework of hazard assessments conducted with the developed estimation method.

For each event, precipitation analysis was performed in order to obtain a return period (of the studied event) by using governmental measuring networks. As the maximum flow rate during flood events was not evident for each dataset, it was neglected for further processing. Quantitative and qualitative data about processes concerning bedload mobilization or deposition was gathered at a torrent-segment-scale, meaning that information was collected for each individual segment (torrent-segment). The information was subdivided into qualitative and quantitive parameters for the slope and the torrent for each respective segment. Qualitative parameters for the slope in a segment comprise the bedload-mobilizing processes such as landslides or gully erosion that were quantified by calculating the actual cubature that was mobilized by multiplying the length, width and the thickness of the mobilized body. For the torrents, the decisive transport process was determined (debris flow transport or simple fluvial debris transport). It was evaluated if erosion, deposition or transit took place in the torrent segment. Erosion was calculated by multiplying the yield rate [m^3/m] with the torrent segment length. The cubature of the deposited material was quantified by multiplying the length, width, and thickness of the deposited soil body. At the lowest point of each torrent system (fan apex), the gathered information about erosion/deposition in each segment was summed up to obtain the total cubature that was delivered towards the valley. In order to describe the topographic situation in the studied torrent systems, a digital surface model with a resolution of 25 m (25mx25m raster) was used by Gertsch. As the resolution is too low to calculate an adequate flow direction raster or to specify the catchment, Gertsch used the “Basishöhenmodell” or base elevation model that derives from photogrammetric processing. The resolution was improved under the creation of a TIN (Triangular Irregular Network) in different steps to obtain a final resolution of 5 m (5mx5m per raster cell). As high-resolution LiDar data was not comprehensively available for all study areas, it was neglected. Geologic information was extracted from the digital Atlas of Switzerland and from up to 100-year-old geologic maps that were digitized. This resulted in a digital geologic dataset with information about the lithology and soils in the respective catchments.

4.2.2 Structure elements of an Alpine mountain torrent system acc. to Gertsch

Similar to the approach presented in Chapter 3, Gertsch states that an Alpine mountain torrent system can be understood as a system that contains several system elements. The system border can be defined as the basin because it comprises all processes that are relevant for the bedload supply. A system contains a number of system elements. System elements are homogenous torrent segments and their adjacent slopes that are under constant interaction. System Elements that are situated above others have direct repercussions on elements below them. Only in rare cases, given for example if retrogressive erosion takes place, elements from below have influences on elements above. Consequently, the only system elements that are unaffected by others are the first or the uppermost defined segments. Figure 4-1 provides a schematic sketch of a System with its system elements.

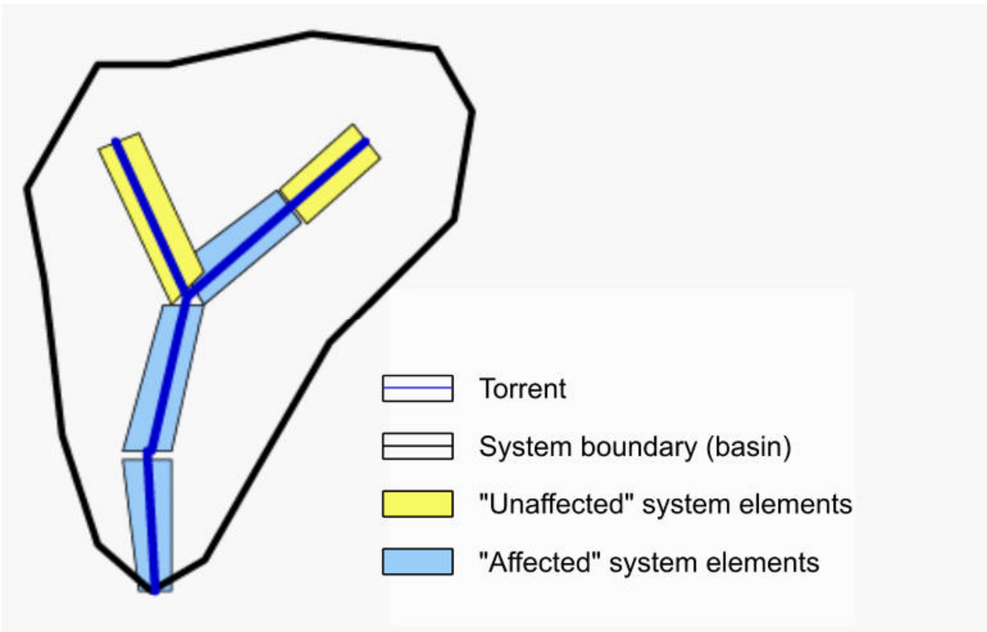


Figure 4-1: Elements of an alpine mountain torrent system: The black line indicates the basin which represents the system boundary, as all bedload-relevant processes occur in the catchment. The yellow sections indicate system elements, which are unaffected by other system elements, so for example uppermost torrent segments. Blue System elements are influenced by system elements which are situated above (Gertsch 2009).

With this approach, it is necessary to determine the **"local factors"** of each system element, as well as the **"conditions above"** to make predictions about the system behavior in an event scenario. Additionally, Gertsch defines **"threshold processes"** denoted as **"negative factors"** that overreach the defined barriers and thus have to be considered. The local factors of a system element can be separated into slope-factors and torrent factors. They are made up of different parameters as stated in Table 4-1.

Table 4-1: Local factors for slopes and torrents after Gertsch (2009)

Local factors per segment: Slope	**Local factors per segment: Torrent**
- Slope angle - Composition and material properties - Coverage - Landslide distance to the torrent - Angle towards torrent	- Loose material supply - Drainage area above (A_{EG} [km^2]) - Torrent inclination

4.2.2.1 Local factors: Slope

Slope angle

The slope angle is a driving factor to estimate the mobilization potential through landslides. As slope angles below 20° tend to inhibit slope movements due to a lack of relief energy, steeper gradients of above 45° are considered less prone for landslides due to steady denudation processes that lead to a constant restabilization of the slope.

Composition and material properties

The composition, the thickness and the stratification of a slope material have strong influences on the behavior of the system element. If a thin soil body lies upon an intact rock, the probability of mobilizing it through shallow landslides is high. This effect is amplified if the hydraulic conductivity of the loose material is low, thus allowing a rise in pore pressure that can ultimately reduce the shear resistance of the specimen.

Coverage

If the slope is covered with trees, branches, etc., it can have stabilizing effects on the underlying soil body, as roots tend to reduce pore pressure via water extraction. On the other hand, vegetation can deliver the kinetic energy of wind into the ground, leading to additional loosening effects.

Landslide distance to the torrent

The distance of the trigger point of a landslide to the torrent is important for its potential bedload contribution. The greater the distance, the lower is the probability that the landslide delivers material to the torrent. It is coupled with the slope angle in a way that a deeply incised torrent can trigger landslides even at a greater distance.

Angle of a landslide towards the torrent

The angle, with which a landslide meets the torrent, is very important for the jamming potential. If the landslide is oriented normal to the torrent, the jamming potential is much higher as if the angle differs only slightly from the streaming direction. Because of that, Gertsch defined three classes for mounding angles as follows:

- *Class "0":* mounding angle 0-20°
- *Class "45":* mounding angle 20-70°
- *Class "90":* mounding angle 70-110°

From class 0 to class 90, the potential jamming increases

4.2.2.2 Local factors: torrent

Material supply

The supply of loose material in a torrent segment determines whether erosion is possible or not. Gertsch defines three classes:

- **Lockermaterial unlimitiert** *(material, unlimited)*:
  - Often formed by thick soil body (e.g., moraine deposits) that provide large amounts of material for further transportation.
- **Lockermaterial limitiert** *(material, limited)*:
  - Rather thin soil body lying on the in-situ rock. Often fed by physical or chemical weathering processes.
  - Material limited conditions are also present in obstructed torrents (check dams etc.)
- **Fels** (*rock*):
  - Intact rock, does not contain material for further mobilization.

Drainage area above

The drainage area above a torrent segment is used as a measure for the area that received precipitation and consequently a strongly generalized parameter to represent the flow rate. It is defined as $\mathbf{A_{EG}}$ **[km²]**.

Torrent inclination

The torrent inclination indicates the potential relief energy that can be provided in a regarded torrent segment. It is an indirect measure for the erosion force that can be brought up by the stream based on its inclination. The parameter is defined as the average torrent inclination $\mathbf{J_{GA}}$ **[%]** in the segment.

4.2.2.3 Conditions above

Conditions above have a direct impact on the behavior/process outcome of underlying system elements. Gertsch considers five factors of conditions or processes above that are explained in this subchapter.

Transport process above

The transport process that is present in a torrent segment above plays a significant role when it comes to the potential for material mobilization in a torrent segment situated below. A distinction is made between fluvial debris transport (*ger.* Geschiebetrieb) and debris flow transport (*ger. Murgangtransport*). Debris flows are more prone to mobilize larger amounts of loose material, delivered by the erosion of the torrent-bed and/or the surrounding slope material.

Changes in torrent inclination

Changes in the torrent inclination from an upper to a lower segment may indicate if erosion or deposition of material takes place in a lower segment. As a measure for the changing torrent inclination, the inclination of the lower segment $\mathbf{J_{GA}}$**[%]** is divided by the inclination of the segment above $\mathbf{J_{GAob}}$**[%]**. If the outcome is below 1, the torrent profile from segment 1(upper segment) to segment 2 (lower segment) is concave, if it above 1, the geometry is convex. Values below 0.3 can be observed below waterfalls.

Local and accumulated Energy index

To obtain a measure for the kinetic energy in a torrent system, the Energy-Index was introduced by Gertsch. It is calculated for each of the defined loose material classes (Chapter 4.2.2.2) individually.

In steep torrent segments where "rock" and "material-limited" are the governing material classes at the torrent-bed and where high flow velocities are reached, the local energy Index **E-I$_{GA}$** is positive. In torrent segments with an unlimited supply of loose material ("material-unlimited"), this index is negative due to a significant loss of kinetic energy that occurs because of friction- and thermal losses. All the indexes get determined for each channel segment and have to be summed up to obtain the accumulated Energy Index **E-I$_{akk}$**. In contrast to the local energy index, the accumulated index must not be below 0 but is always 0 for the uppermost torrent segments in a system. If for example two negative local energy indexes are summed up, the resulting accumulated energy index would be 0. If the calculation shows positive values, the positive values are added to the next segment situated below. If two torrent segments mound into another segment below, the positive local energy indexes of the upper segments get summed up and are added to the lower segment. Negative local energy indexes are set to zero before further calculations are conducted. An example of the calculation is visualized in Figure 4-2.

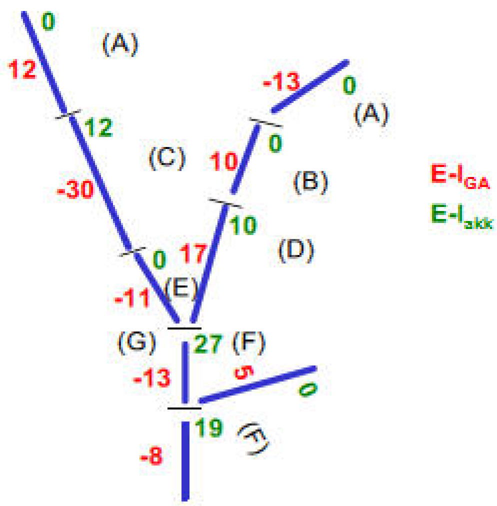


Figure 4-2: Example for the calculation of the accumulated Energy Index (E-Iakk) out of the local Energy Index (E-Iga) (Gertsch 2009).

If high **E-I$_{akk}$** values are present, an increased erosive force driven by higher relief energy can be expected. This can occur if an array of steep torrent segments are situated in succession, or if a segment with high **E-I$_{GA}$** mounds into another segment. Thus, increased water energy is provided at the contact area that can lead to further mobilization of material at the mounding point.

Material input until and within a torrent segment

The amount of sediment that can be mobilized is capped by either the sediment supply itself or the available relief energy or transport capability that can be brought up in a torrent segment. The material input above and within a torrent segment, provided e.g. by landslides, can have influences on the sediment availability and thus change the governing mechanism from **sediment-limited** to **flow-rate-limited**, meaning that due to the input of material in an upper segment, the lower segment is not capable of transporting the now available material amounts, leading to sedimentation processes. In the framework of the bedload-estimation method, this has been considered by introducing the "**Hanginput oberhalb [m^3]**" or the **slope-input above**, stated as the cumulative volume of each above lying segment that was transported from the slopes to the segments.

Discharge of multiple torrents into a torrent segment

If one torrent segment discharges into another, this may lead to the increased availability of water. Thus, more erosion can be expected in such areas. According to Gertsch, this effect can especially be observed in lower parts of a basin, because the maximum flow rates are then reached nearly at the same time.

4.2.3 Negative factors

According to Gertsch, negative factors are a constellation of processes that are prone to yield the triggering of debris flows. They can have influences on one or more torrent segments, and affect either the availability of debris/bedload or the water-energy/ runoff-behavior. Gertsch outlines eight processes that are considered as negative factors but does raise a claim to integrity, as various negative factors exist. Table 4-2 shows a list of negative factors.

Table 4-2: Bedload- and runoff-influencing negative factors after Gertsch (2009)

Influences on debris/bedload availability	**Influences on water availability/runoff behavior**
Mobilization of moraine deposits (*ger. Anriss in Bastionsmoräne*)	Flood waves (*ger. Ausbruch von Flutwellen*)
Mobilization of thawing permafrost deposits (*ger. Anriss im auftauenden Permafrost*)	Drainage of fissure/joint water (*ger. Konzentrierter Austritt von Kluftwasser*)
Erosion of with loose material-filled sealed layers (*ger. Ausräumung auf steilem, resistenteren Stauhorizont im Gerinne*)	Mounding of more than one torrent into another (*ger. Mündung mehrerer Gerinne an einem Ort*)
Spontanous triggering of large Landslides (*ger. Spontaner Abgang von Grossrutschungen*)	Failure of a jammed torrent segment (*ger. Durchbruch einer Verklausung*)

If investigations are carried out in a catchment, the probability and the accompanied repercussions of negative factors has to be considered/estimated. They are imperative for the development of event-scenarios, that could take place in an Alpine mountain torrent system.

4.2.4 Application

As already mentioned, the bedload estimation procedure after Gertsch (2009) can be applied by using a GIS-based approach only or complemented with field observations. As the solely GIS-based procedure is charged with additional uncertainties, it is neglected in the framework of this thesis. The work stages that are required to apply the assessment method of Gertsch are depicted in Figure 4-3.

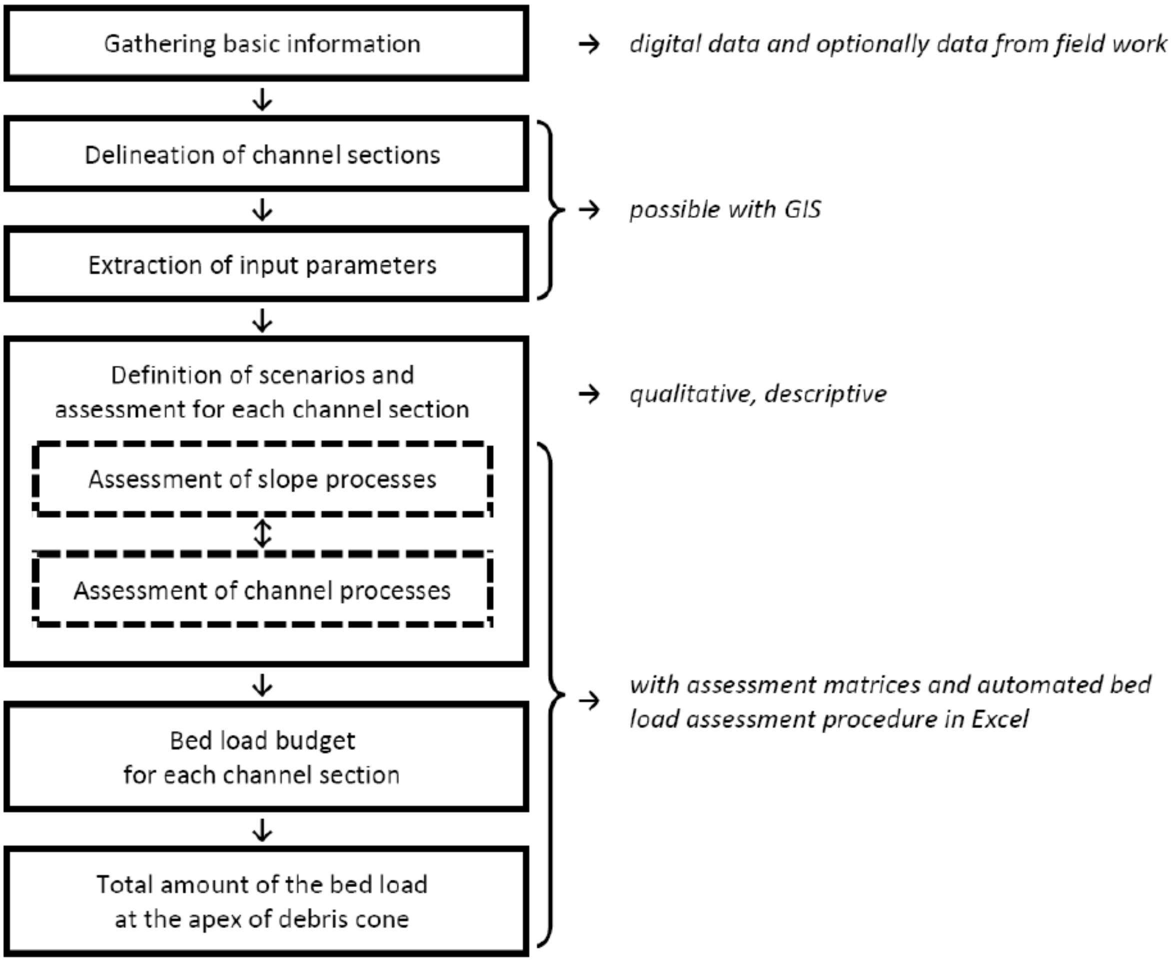


Figure 4-3: Work stages for the application of the Gertsch method. In the first step, basic information about the study area has to be gathered by conducting field studies and literature research. Then, the channel network has to be delineated into homogenous torrent segments. Based on the findings from field studies, a scenario has to be developed for each torrent segment concerning its process constellations related to the debris flow potential. This scenario and the field-determined torrent properties are implemented in the automated bedload assessment procedure to quantify the bedload output (Kienholz et al. 2010).

Gathering basic information, channel delineation, and extraction of input parameters

For the application of the field supplemented approach, a GIS-dataset with a satisfactory resolution (at least 5x5m cell size) is required. Homogenous channel sections are delineated under certain criteria as stated by Gertsch (2009). With the raster dataset, the torrent segment length, the catchment area above the starting point of a segment ($\mathbf{A_{EG}}$), and the altitude of the uppermost point of the torrent segment have to be extracted. The output data is then implemented in the provided excel file for the automated bedload estimation procedure. Automatically, the altitude difference of a defined torrent segment, the average torrent inclination **J**, the lean length, and the change of inclination expressed by $\mathbf{J_{Ga}/J_{Gaob}}$ is calculated. In the next step, the slope- and torrent processes for each defined segment have to be assigned.

Assessment of slope processes

For the slope processes, an estimated through slope processes delivered cubature to the torrent has to be determined from field observations. It has to be chosen, whether negative factors are present (joint water, flood wave, torrent blocking, etc.), and if they might result in fluvial debris transport or debris flow transport. Also, the number of input positions of landslides has to be entered. The bedload estimation procedure then automatically delivers the mobilized cubature from slope processes. With the excel sheet, it gets evaluated whether the slope input gets fully mobilized or only partly mobilized (if partly mobilized, also a mobilization factor is given), based on empirical relations. This procedure is conducted for each segment.

Assessment of channel processes

For each torrent segment, the type of material supply (Chapter 4.2.2.2) has to be assigned (**local factors**). Therefore, field studies are required. In the next step, it is asked whether and how a debris flow already developed from segments situated above, and if the mechanism remains as debris flow after the regarded segment (**conditions above**). It also has to be determined, whether a debris flow is generated in the torrent segment through negative factors, or from slope processes. Dependent on whether fluvial debris transport or debris flow transport is present in the regarded torrent segment, further cells have to be filled, which relate to the function of the torrent segment and quantify the eroded/deposited cubature. Output values for the torrent assessment represent the function of the torrent segment (erosion, deposition or transit), respectively a deposited/eroded cubature with an accompanied yield rate or deposition factor. This output is generated for each torrent segment.

Results-sheet

In the result sheet, the torrent and slope segment properties are visualized. It automatically calculates the bedload balance in the respective torrent segments and sums it up to an accumulated bedload cubature after each torrent segment. In the lowermost field, the total amount of bedload at the fan apex is displayed. Gertsch recommends representing the total delivered cubature in a range, as the bedload estimation procedure is not intended to calculate an exact cubature.

5 Methodology

The methods presented in Chapter 5.1 and 5.2 were used to characterize the catchment of the Lorenzerbach. The results are presented in Chapters 6.1 to 6.4. The methods elucidated in Chapter 5.3 were necessary for the assessment method after Gertsch (2009), the derived results are presented in Chapter 6.5.

5.1 Field studies

To obtain an overview and to validate the observations made by digital data evaluation, field studies were carried out.

Geological survey

A geological survey was conducted mainly along the Lorenzerbach to evaluate basic rock properties qualitatively and to verify/falsify the existing geologic map for the area. For each lithologic unit, if possible, a representative description of the degree of decomposition, strike, and dip of the foliation planes, the degree of jointing and description of the rock's mineralogy and texture was performed. As this study does not focus on an in-depth geologic/structural geologic investigation, mapping efforts were focused along the torrents and mainly serve as additional information used for further interpretation. Therefore, an exact stratigraphic classification and geological genesis were neglected. Field- and literature information concerning the spatial distribution of the geologic units were transferred to ArcGIS and are provided as simplified overview maps in chapter 6.1 to 6.4.

Torrent- and slope process mapping

A process-oriented investigation was conducted, mainly focusing on the channel geometry, channel processes (such as transport mechanisms), and slope processes (landslides). Additionally, torrent and slope properties were qualitatively described. The derived information was related to the findings from GIS-based studies to determine the most striking factors that control the debris flow potential in the study area. Furthermore, the field data was required for the bedload assessment method after Gertsch (2009).

5.2 GIS-based studies

An airborne laserscan (ALS) dataset with a resolution of 1 m of 2011 and orthophotos from three dates (09.07.2010, 03.08.2013 and 08.08.2016) were provided by the State of Styria. These datasets, combined with the field observations, were processed with ArcGIS 10.5 to characterize the processes in the catchment of the Lorenzerbach. This chapter describes the conducted GIS-based studies.

5.2.1 ALS-dataset processing

The provided ALS-dataset was used to generate the following output:

- A *Digital Terrain Model* was calculated to add altitude information to spatial data. This dataset was used for simple data extraction (altitude information) and to create channel- and slope profiles to identify anomalies for further interpretation.
- Based on the *Digital Terrain Model*, *Hillshade* or *shaded relief* maps were created, which convert elevation data to brightness values under a defined virtual height and azimuth of a light source. In combination with the conducted field studies, these datasets allow a robust identification of slope processes and pronounce expressions of geomorphologic features. Landslides scarps were mapped based on shaded relief maps, some of which were verified in the field. They act as an indicator for slope instabilities in the present study.
- *Slope maps* were compiled to obtain an overview of the torrent- and slope inclinations. They transfer elevation data into inclination values.
- To calculate the *channel network*, the Digital Terrain Model was “filled”, in order to eliminate errors related to sinks. Then the flow direction and flow accumulation were calculated (D8 algorithm). Based on the field studies, the starting points for overland flow were determined and used to compute the path for each channel by using the inverted flow accumulation raster to calculate the least-cost path. In channels, where the starting point of overland flow was not evident from field studies, starting points were extracted from the digital water network provided by Digitaler Atlas Steiermark (by the province of Styria).

This digital data in comparison with the conducted field studies formed the basis for characterizing the catchment with its system elements and for identifying ongoing processes.

5.2.2 Orthophoto mapping

Orthophotos with a pixel size of 0,2 m x 0,2 m from 09.07.2010 and 03.08.2013 were chosen to be compared with each other as the debris flow event of 2012 occurred in between the datasets. Changes in vegetation and/or morphology were used as a marker for slope processes. These areas were mapped under the creation of polygons in ArcGIS 10.5. The polygons were then overlaid with a 3m x 3m measuring point net which was sampled to extract information about the affected geologic units, the average slope inclinations, and the planar distance of the points towards the next torrent feature (channel network as calculated in 5.2.1). The channel network was added (Chapter 5.2.1) to visualize the potential impacts of the processes on the torrents (Figure 5-1).

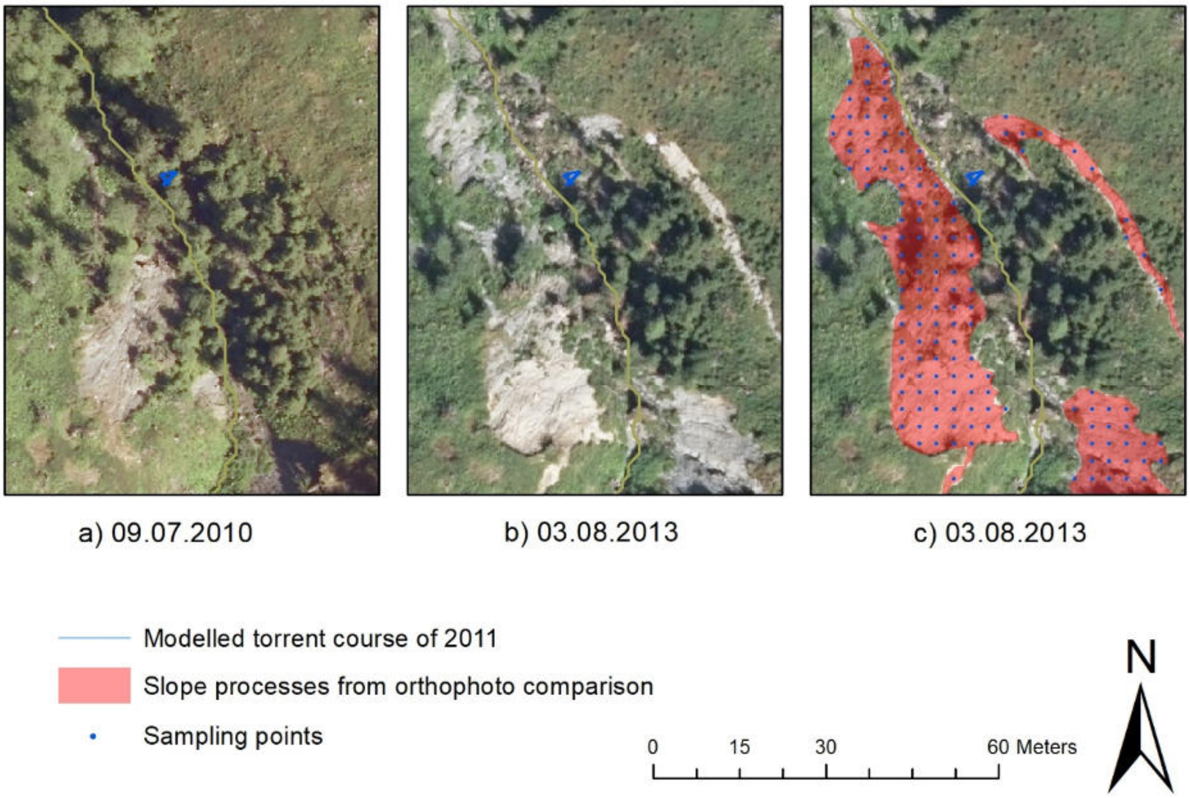


Figure 5-1: Orthophoto comparison between two epochs. a) Orthophoto from 09.07.2010 b) Orthophoto from 03.08.2013 c) Orthophoto from 03.08.2013 with the highlighted active area and the 3m x3m sampling net.

A large disadvantage of this method is that largely vegetated areas can produce shadows ultimately obscuring active areas. Additionally, torrent control structures were built and forest works were conducted in between the orthophoto epochs. These effects had to be considered. The polygons were only drawn along areas, where a clear impact of landslides was evident.

5.3 Field supplemented bedload estimation procedure after Gertsch 2009

Based on the results from field- and desk studies, the field supplemented bedload estimation procedure proposed by Gertsch (2009) was applied in the study area. For that purpose, the excel file for the automated usage of the bedload estimation procedure was provided by Gertsch herself for the present study. Data preparation and extraction was conducted with ArcGIS 10.5. The ALS dataset with a resolution of 1 m was resampled to a resolution of 5 m and filled in order to counteract problems related to sinks when calculating the catchment area. On the other hand, a raster resolution of 5 m was also used by Gertsch herself during her investigations in other torrent systems.

5.3.1 Torrent segment delineation and data extraction

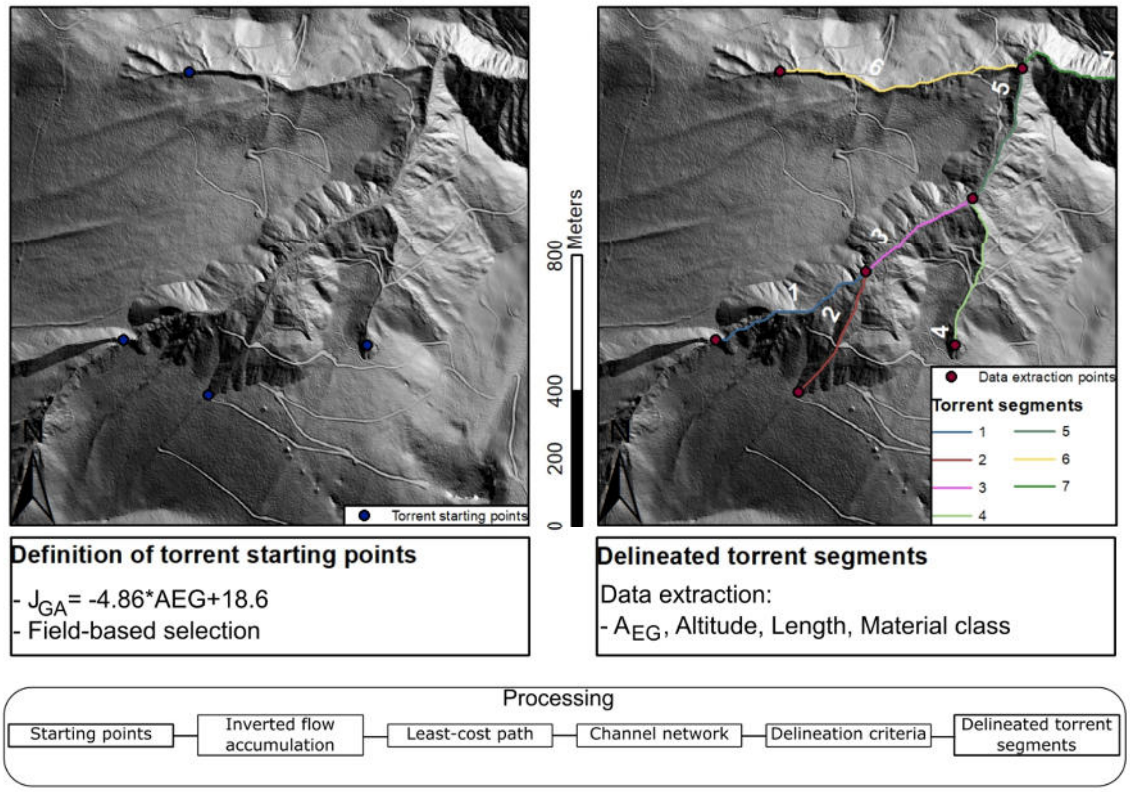


Figure 5-2: Delineation of the torrent segments. After the definition of the starting points (left map), the considered channel network is calculated. With the channel network, the torrent segments are delineated based on gradient-, material-, and mounding criteria (right map). For each uppermost point of a respective torrent segment, A_{EG}, altitude information, torrent segment length, and its material class has to be extracted (data extraction points).

To delineate the channel network for the application of the assessment method (Figure 5-2), in a first step, the starting points of the torrent segments had to be defined. The starting points were determined by using the results from field studies. According to Gertsch (2009), a starting point has to fulfill the empirically developed condition:

$$J_{start} = -4.86 * A_{EG} + 18.6 \qquad \text{(eq. 5-1)}$$

J_{start} Threshold inclination for bedload mobilization [%]

A_{EG} Catchment area above a point [km^2]

To verify this condition, a slope map and the A_{EG} raster were calculated. The A_{EG} raster file was determined by calculating a flow direction raster and consequently a flow accumulation raster, which was multiplied with the raster cell area (= 25 m^2) to obtain the catchment area above an arbitrary point (A_{EG}). By subtracting J_{start} from the slope map, all possible cells for starting points show up with a value of at least 0. The starting points were then marked with a point shapefile, and the channel network was determined by calculating a least-cost path raster based on an inverted flow accumulation raster file (same approach as stated in Chapter 5.2.1). The least-cost path raster was then converted to a polyline shapefile and torrent segments were delineated based on the following criteria:

- If the material class changes (material unlimited, material limited, rock)
- If the torrent gradient changes its class over a significant length interval (predefined classes after Gertsch (2009): 0-10%, 10-20%, 20-40 and >40%)
- If a torrent enters another torrent

The material classes were thereby determined using the findings from field studies. Torrent gradient classes were defined based on GIS-derived slope maps. The delineated segments were then numbered in a way, that a torrent segment with a lower number always enters a segment with a higher number, starting with the uppermost segment as segment number 1. For the assessment method after Gertsch (2009), a maximum amount of 12 segments can be considered. As the studied torrent system contains more channel elements, not all of them could be implemented. Delineation criteria were consequently gathered based on orthophoto evaluation and field studies, to only regard the most critical channel sections and tributaries concerning bedload mobilization.

In order to extract the determined data, a point shapefile was generated (data extraction points) which was used to mark the uppermost points of each defined torrent segment and the lowermost point of the last torrent segment (fan apex). With this feature, A_{EG}, the altitude information from the DTM, the segment length and the material class were extracted into a table.

The table received from data sampling was then entered in the excel file for the automated bedload estimation.

5.3.2 Landslide cubature estimation

To apply the assessment method after Gertsch (2009), for each delineated torrent segment the input of material through landslides has to be estimated. Therefore, the sum of the areas of the mapped landslide polygons in the proximity of a torrent segment (Chapter 5.2.2), which are connected with the adjacent torrent, were multiplied with an estimated average landslide thickness for all landslides occurring around a torrent segment (Figure 5-3).

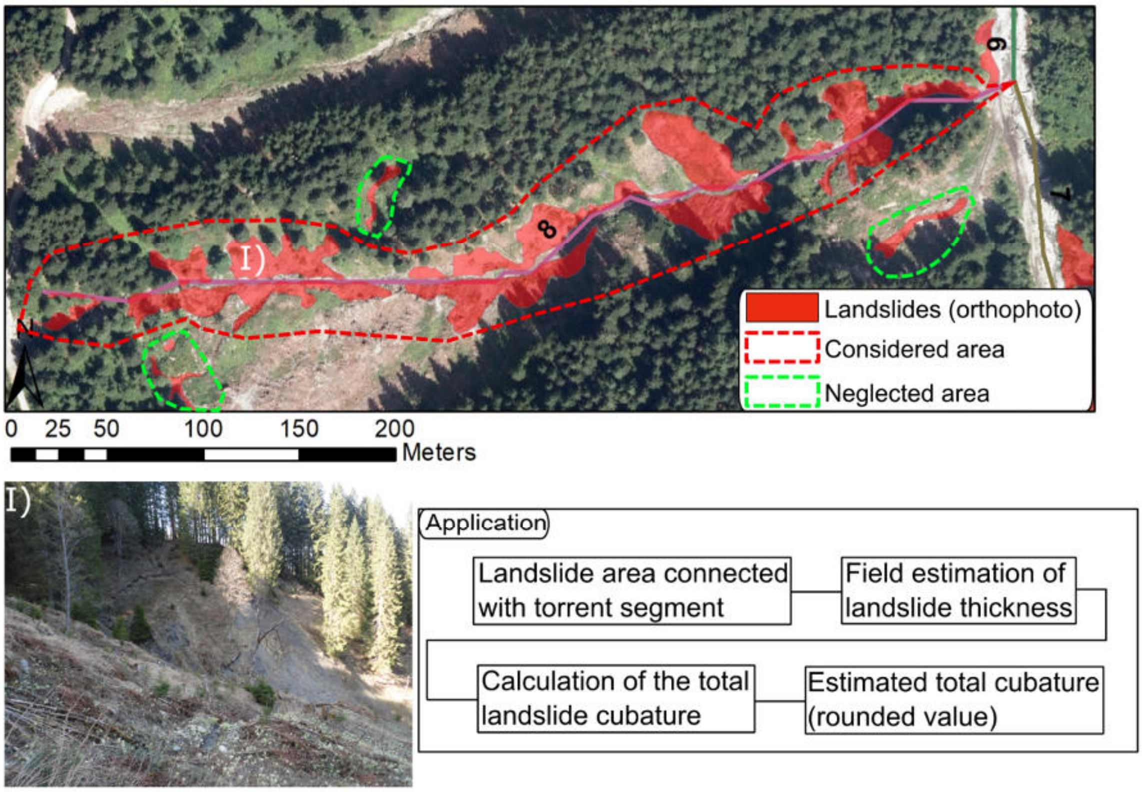


Figure 5-3: Estimation of the material input through landslides for a torrent segment. Dashed-red areas indicate considered polygons, which are directly connected to the torrent segment. Green areas are neglected as the landslide mechanism does not deliver material into the regarded torrent segment. The total cubature is calculated by multiplying the landslide area (sum of all relevant landslide polygons) in considered areas with an estimation of the average landslide thickness (from field studies). The outcome is rounded and represents the estimated total delivered landslide cubature for a torrent segment.

As it is not possible to determine the actual landslide thickness for each polygon as the time between the initiation of the slides, and the field studies was over 6 years, a rough approximation was made. As most of the landslides were identified as shallow landslides in the course of the field studies, the multiplication factor for the landslide thickness was mostly around 1. However, only the landslide cubature that reaches the torrent must be considered.

This led to a multiplication factor often lying below 1. The derived values were then rounded, representing the estimated input of material to the torrent segment through landslides.

5.3.3 Scenario

To apply the assessment method after Gertsch (2009), for each torrent segment, a scenario regarding the transport mechanism and process sequence has to be defined. In order to achieve a comparable scenario which is based on the events that took place during the debris flow event of 2012, the scenario was adjusted by using the results of the conducted event-documentation. The parameters that were assigned in the bedload estimation procedure can be found in the appendix.

Uncertainties occurred, as the studies from the event documentation differentiated three transport mechanisms (debris flow, debris transport, and fluvial debris transport), and the method after Gertsch only distinguishes between two mechanisms (debris flow transport and fluvial debris transport). As some sections were assigned with debris transport, it had to be estimated whether fluvial debris transport or debris flow transport was the decisive process mechanism in the respective torrent segment. These estimations were then based on the findings from the field studies conducted in the framework of this thesis.

6 Results and Interpretation

The first subchapter describes the geologic units, their spatial distribution, and properties. In the second subchapter, the Lorenzerbach with its channel network is visualized. In the third subchapter, the study area is subdivided into three sub-areas. For each sub-area, the results from field- and desk studies concerning the torrent- and slope properties and processes are presented. The obtained landslide statistics through orthophoto evaluation are plotted in subchapter four. The fifth subchapter explains the input generation and lists the results from the bedload estimation procedure after Gertsch, 2009.

6.1 Geological survey

This chapter summarizes the encountered lithologies in the mapping area. It gives a brief description of the geologic units and outlines the rock properties that were mapped in several outcrops. Mapping efforts were focused in the proximity of the torrent systems as their properties directly influence the bedload supply. As not all parts of the torrent system were accessible without taking significant risks, additional information was taken from the geologic map on the scale of 1:50,000 after Metz (1967).

Greywacke zone: Greywacke schist

The greywacke schist is the most dominant lithologic unit in the study area, covering the most part of the mapping area at an altitude range from ~800 m to ~1400 m above sea level. It is preserved along outcrops near the Lorenzerbach and exposed along several forest roads.

On fresh fracture surfaces, it has light- to dark- greyish color, often ranging from light brown to reddish when weathered. Its texture is characterized by thin, partly phyllitic foliation planes, which sometimes are intercepted by mm- thick quartz veins (Figure 6-1).

Figure 6-1: Folded greywacke schist with an ~80 cm thick, northwards dipping fault at an outcrop along a forest road to the E of the Lorenzerbach in the lower study area.

In the central part of the study area, close to the contact with the Triebensteinkalk, the greywacke schists are interstratified with several cm-thick carbonatic interlayers. Here, foliation moderately dips towards the southwest at angles of around 40° to 60°. Locally, graphitic entries were observed in the lower and upper parts of the study area, recognizable through black-grey colors and graphitic interlayers. In the lower parts of the mapping area (areas below the transition from greywacke schist to serpentinite), the foliation dips towards the southeast or north at steep angles, ranging from 60° to 85°. At an outcrop along a forest way, southeast of the Lorenzerbach at an altitude of around 900 m, these greywacke schists are disrupted by an approximately 80 cm thick, steeply north-dipping fault. In the proximity of the torrents, the greywacke schists are often strongly weathered (Figure 6-2).

Figure 6-2: Strongly weathered, folded greywacke schist in the lower parts of the study area ~50 m westwards of the Lorenzerbach.

Greywacke zone: Greenschist

Two of greenschist bodies traverse the lower and upper part of the study area. They have a greenish to a grey-greenish color and possess unctuous discontinuity gouges (Figure 6-3). Foliation planes dip toward NNE with angles of about 50° to 60°. Two dominant, orthogonal joint sets are developed at the lower band, dipping towards SSW- and WNW at angles of 50° to 80°.

Figure 6-3: A) Lower greenschist body at an outcrop 30 m to the west of the Lorenzerbach in the lower catchment area. B) Decomposed upper greenschist body at the Lorenzerbach.

Significant impacts of weathering could not be observed at the lower outcrop since it was not exposed proximal to the torrent. However, the upper greenschist body shows a high degree of decomposition to disintegration at the side slopes of the Lorenzerbach. Weathered compartments form fine-grained, partly cohesive soil bodies. Here, competent sections of greenschists were not observed proximal to the torrent.

Greywacke zone: Serpentinite

In the central part of the study area, where the river course shifts from originally SW-NO to WNW-ESE, serpentinite is exposed along the Lorenzerbach at a length of ~150 m. It has a dark greenish to a grey-greenish color and displays a compact habit but strongly cut by joints (Figure 6-4). Dip direction and dip angle of the serpentinite could not be detected because of the rock properties. In general, this metabasite unit is accounted to the “Serpentin des Lärchkogels”. As its colors and habit differ profoundly compared to its surrounding units (greywacke schist, Triebensteinkalk), it can clearly be identified in the field.

Figure 6-4:Strongly jointed, dark-greenish to grey greenish serpentinite in the central part of the study area.

Greywacke zone: Triebensteinkalk

The so-called "Triebensteinkalk" can be found adjoining to the serpentinite. In the central part of the study area, the transition from these carbonates to the serpentinite is exposed. The Triebensteinkalk has light greyish- to beige colors and shows decimeter thick layers heavily cut by joints. In the field, the carbonates form rock towers, reaching around ten meters of height (Figure 6-5). Apart from the towers, a transition from greywacke schist to the more compact carbonates is exposed in an SSE to NNW-running gully in the central part of the torrent system.

Figure 6-5: Rock tower consisting of Triebensteinkalk in the central part of the study area near the Lorenzerbach.

Austroalpine basement: Crystalline of the Bösenstein

The crystalline Austroalpine basement units can be found at altitudes above appr. 1400 m, being exposed directly in the torrents. In the uppermost parts of the study area, they form the ridges that lead to the summit of the 2188 m high Almspitz. They consist of biotite-schists, granites, and gneisses, partly with feldspar porphyroclasts (Figure 6-6). The degree of fragmentation of these units ranges from compact to strongly jointed. Compared to the units of the Greywacke zone, decomposition through weathering mechanisms is significantly less pronounced.

Figure 6-6: Gneiss of the Austroalpine basement in the upper parts of the study area: In this case with up to 1 cm measuring feldspar porphyroclasts.

Quaternary deposits

Large parts of the study area are covered with quaternary sediments. In the lower part of the catchment of the Lorenzerbach, nearly all smooth and hilly morphologies are covered with moraine deposits. These deposits contain a mixture of all the encountered lithologies, being embedded in a fine-grained matrix as angular to edge-rounded components (Figure 6-7). They can be identified especially in cases where crystalline rocks of the Austroalpine basement units occur at the slopes in the lower parts of the study area.

Figure 6-7: Moraine deposits at an outcrop along the forest way in the upper eastern part of the study area.

In the uppermost parts of the study area, the Austroalpine basement units and basically the whole NE-face of the Almspitz is covered by fine-grained sediments with brownish to reddish-brown colors (Figure 6-8). It can be often observed that these sediments act as an impermeable layer to surface waters due to their high fines content, resulting in wet patches. They are not perceived in the torrents themselves.

Figure 6-8: Fine-grained, brownish to reddish-brownish sediment covering most parts of the Austroalpine basement units.

Comparison of the mapping results with the geologic map on the scale of 1:50,000

The mapped geologic features and borders largely correspond to the Geofast-map 130-Trieben (Oberzeiring) of 1999, edition of March 2006, provided by the Geological Survey of Austria. Dip directions and dip angles for the foliation planes in the lower parts of the mapping area mostly conform to the literature values. In the central part, however, the spatial distribution of the Triebensteinkalk was less traceable as proposed. In contrast, serpentinite displays a larger extent proximal to the Lorenzerbach. Consequently, these differences were complemented in the geologic overview map, provided in Chapter 6.3. The nappe border, which is proposed to be located in the upper parts of the study area could not be mapped due to the inaccessibility of that area.

6.2 Channel network: Lorenzerbach and its tributaries

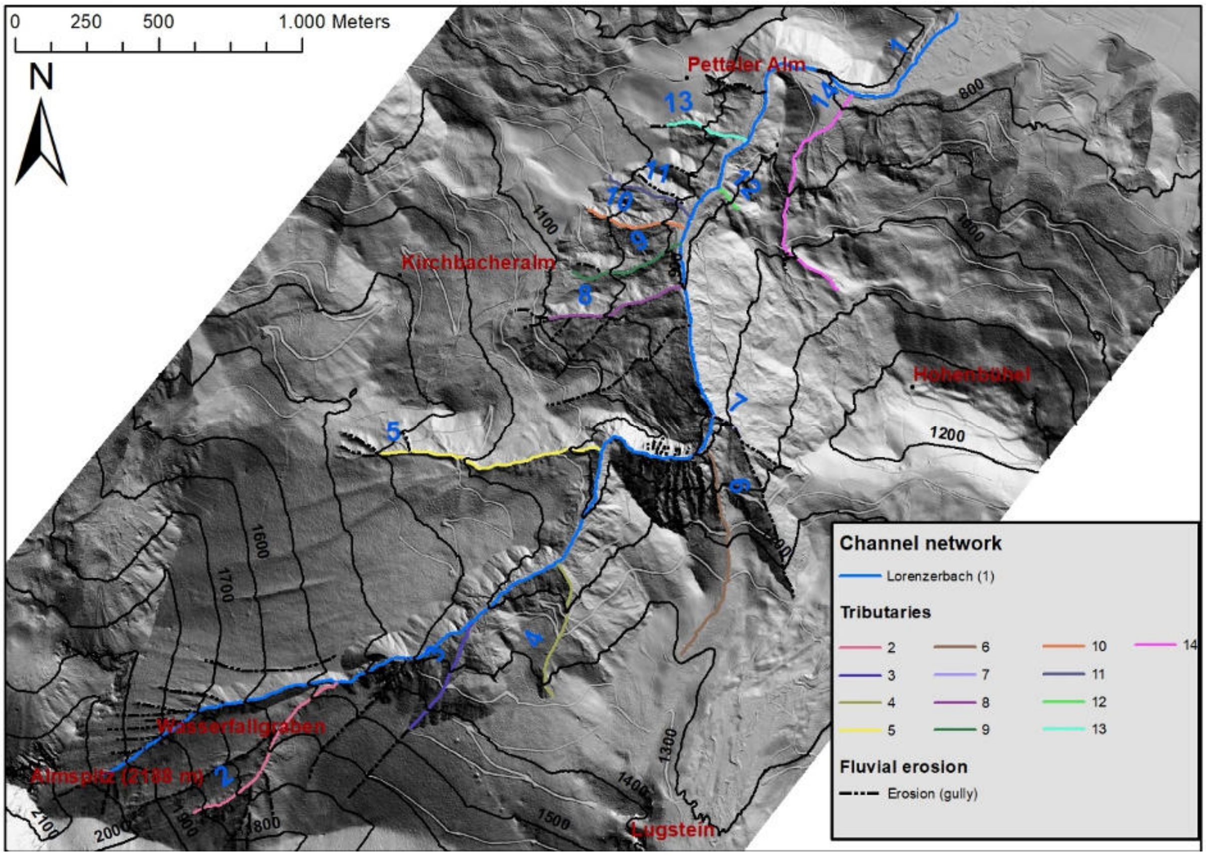


Figure 6-9: Channel network of the Alpine mountain torrent system in the catchment of the Lorenzerbach.

The channel network in the study area comprises the ~5.5 km long Lorenzerbach, which emanates easterly of the Almspitz summit (Figure 6-9). In the upper part of the catchment, it flows towards the NE, passing the Wasserfallgraben. In the central part, it describes a 90° turn towards E, being fed by tributary 5, before again turning back in a 90° angle towards N, when entering the Lorenzergraben. Just to the S of the village of St. Lorenzen, it again turns towards the E before exiting the study area. Over its course, several tributaries enter the element. According to the governmental hydrologic map, which is proposed in the GIS-Steiermark, 12 tributaries act as perennial torrents. However, tributary 7 is not considered in the proposed governmental map and was added as clear evidence of overland flow was provided through the field studies. The angle of the tributaries, relative to the Lorenzerbach, ranges from acute-angled to orthogonal. Apart from the Lorenzerbach and its tributaries, several episodically water-bearing channels or relicts of them could be identified in the field. Most of them flow along the gullies, which developed out of fluvial erosion.

The longitudinal channel profile of the Lorenzerbach is depicted in Figure 6-10.

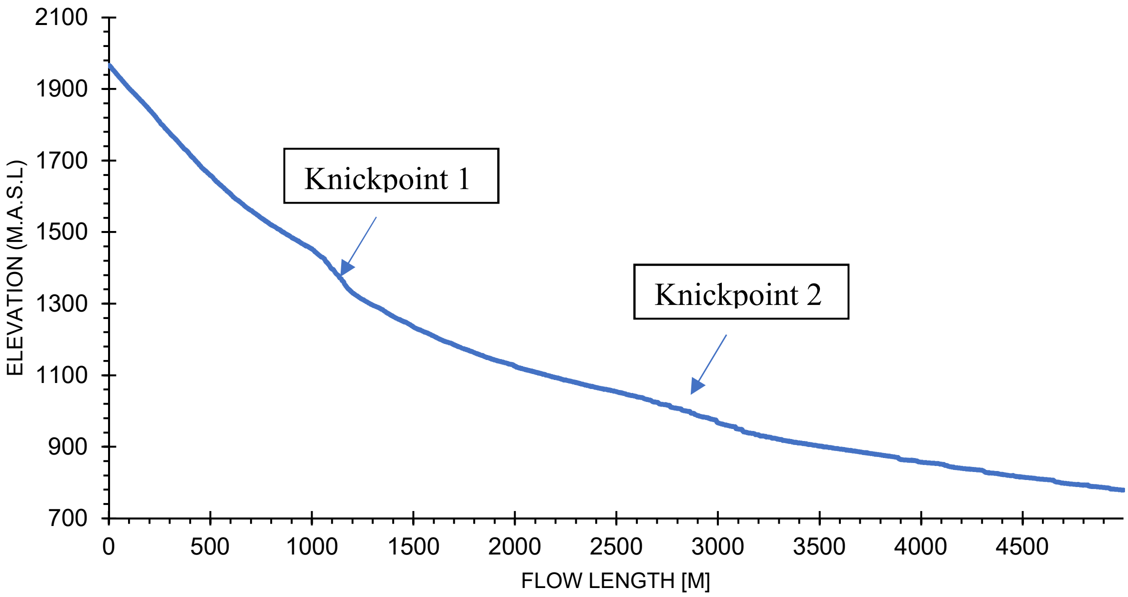


Figure 6-10: Longitudinal channel profile of the Lorenzerbach: In general, the channel describes a concave upward shaped profile. However, two distinct knickpoints are present, partitioning the channel in three well-defined segments.

The Lorenzerbach originates just below 2000 m.a.s.l. and flows at steep angles of 25° to 40°. After a flow length of ~1000 m, the channel gradient significantly increases up to values of 40° to 60°. This knickpoint represents a remarkable perturbation within the channel thalweg. A second knickpoint is visible after a distance of ~2900 m, although it is far less pronounced.

In general, gradients of the Lorenzerbach can be identified as decreasing, yielding a concave longitudinal channel profile towards the exit point of the study area.

6.3 Properties and processes of the slope- and torrent elements in the study area

In the following chapter, the obtained results from field- and GIS-based studies are presented by subdividing the study area into three subareas. The provided geological background map represents the proposed map by Metz K. (1979), which was modified based on the findings from the geological survey (Chapter 6.1).

6.3.1 Upper study area

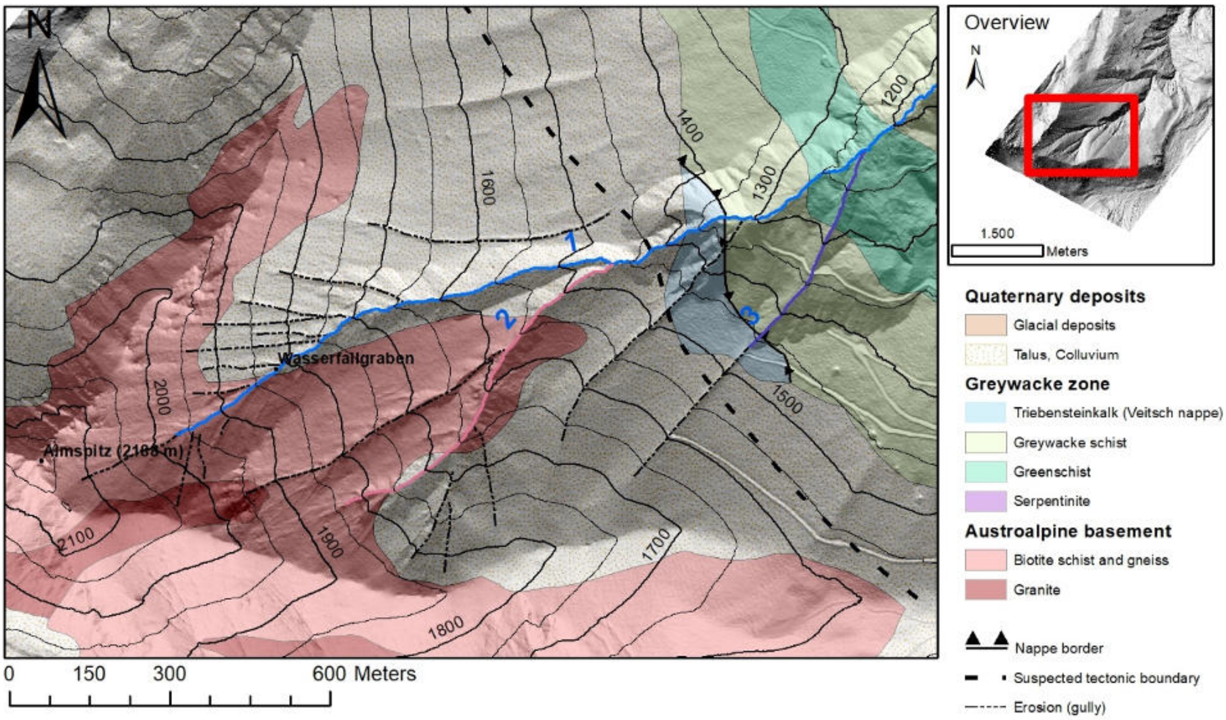


Figure 6-11: Geologic and hydrologic components of the upper study area: In this section of the study area, tributary 2 and 3 mound into the Lorenzerbach. From a geological perspective, the crystalline of the Bösenstein is exposed in the upper parts of the subarea but is often covered by Quaternary deposits. At ~1500 m, the occurrence of the Triebensteinkalk heralds the transition to the units of the Greywacke zone.

The uppermost part of the study area stretches over an altitude range from 2188 m to 1200 m and beholds the starting point of the Lorenzerbach, which emanates in the upper part of the Wasserfallgraben (Figure 6-11). In this section of the catchment, tributaries 2 and 3 enter the main torrent at altitudes of 1460 m and 1220 m respectively. In the uppermost part of the catchment section, granites, biotite schists, and gneisses of the Austroalpine basement are well exposed along the Schafriedel ridge, as well as on the summit of the Almspitz. Towards the lower parts of the subarea, exclusively from the torrents, these units are covered with quaternary sediments. At appr. 1900 m, the occurrence of limestones of the Triebensteinkalk (Veitsch Nappe) marks the nappe border from the Austroalpine basement units to the Greywacke zone which is represented by greywacke schist and greenschist following the carbonatic rocks.

Torrent properties

Figure 6-12: View from the Almspitz towards the Lorenzergraben in the uppermost part of the catchment: The Lorenzerbach develops out of a small gully. Also, its surrounding slopes are only sparsely vegetated and covered by fine-grained quaternary deposits.

In this uppermost, slightly vegetated section of the catchment, the Lorenzerbach is characterized by an initially shallowly incised gully, which develops in deepness and broadness on its thalweg (Figure 6-12). To its north and south, several small gullies mound into the torrent at acute angles. The channel bed in the uppermost section comprises out of slightly rounded to rounded blocks and gravely to sandy components, but also often exposes bedrock with a thin to nonexistent sediment cover. The channel profile sometimes is developed in a stepped-shape.

Tributary 2 shows similar channel properties: The channel bed is mainly covered by a thin accumulation of blocky to gravely rock fragments but often exposes bedrock (Figure 6-13). Torrent inclinations for both the Lorenzerbach and the tributary 2 barely deceed 40 %.

Figure 6-13 Sediment-starved conditions in tributary 2: Bedrock is exposed at the channel bed, the torrent course is controlled by discontinuities of the rock mass.

At the mounding point where tributary 2 enters the Lorenzerbach at appr. 1460 m, the torrent incision depth and torrent inclination increase. Below the mounding point, the channel bed can again be described as sediment-starved. The input of material predominately originates from slope processes or discontinuity-induced failure of the (only in the channel bed and its proximal slopes) exposed, often strongly jointed rock mass. Locally, larger boulders were observed in the channel bed (Figure 6-14).

Figure 6-14: Lorenzerbach at appr. 1450 m, shortly below the mounding point of tributary 2. A) Strongly jointed Austroalpine basement units. B) Large boulder (entry through discontinuity-controlled slope failure). C) Sediment-starved channel bed which exposes bedrock.

The course of the Lorenzerbach could not be followed from appr. 1440 m to appr. 1300 m due to a significant risk of falling on the steep and slippery channel proceedings. However, orthophoto and DTM evaluation showed that the channel geometry broadens after the steeply incised section from 1430 m to 1330 m, and more sediment seems to be covering the channel bed below the "bottleneck" at appr. 1330 m. The torrent inclination of the Lorenzerbach drops from originally > 40 % to 40 – 20% at an altitude of appr. 1300 meters. From then on, the channel bed comprises of deposited bedload, mostly covering the underlying rock bodies.

At around 1220 m above sea level, tributary 3 mounds into the Lorenzerbach. It emanates at appr. 1465 m from a small incised gully. This rather narrow developed tributary flows through two, in the shaded relief map well recognizable "Feilenblaiken", a typical erosional morphology that develops through fluvial erosion when easily erodible material (such as glacial deposits) is provided around a torrent feature. Its torrent inclination is rather steep, exceeding 40 % before mounding into the Lorenzerbach.

Slope processes in the upper study area

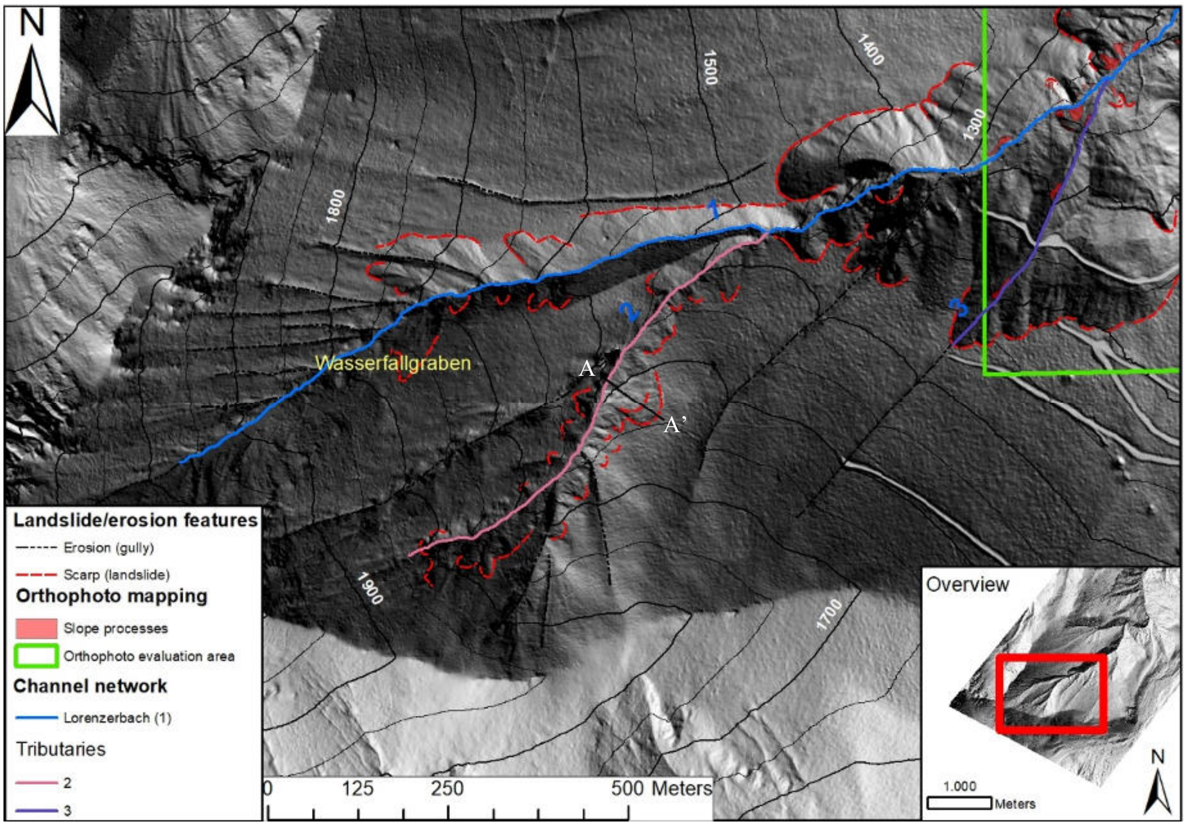


Figure 6-15: Slope processes in the uppermost study area: Landslides scarps are typically oriented towards the next channel element. Cross section A-A' is drawn through a landslide which features the main head scarp and a clearly developed subordinate scarp. Orthophoto data was not comprehensively available for this section of the study area. Only the lower parts are covered.

In the uppermost catchment, numerous scarps of (predominantly) small landslides and erosion gullies could be mapped with the provided digital surface model. It is evident that the landslides are mostly developed proximal to the torrent elements, especially if the incision depth of the hydrologic components increases. In the uppermost parts (right below the Almspitz) no significant morphologic features which provide hints for landslides were found.

Shallow landslides and bank erosion

In the uppermost part of the catchment, mostly shallow landslides or relicts of shallow landslides and fluvial erosion could be identified (Figure 6-16). Shallow landslides are suspected to be triggered mostly by the erosion of the side slopes, thus yielding slope instability. Respective landslide cubatures tend to be rather small. As the channel bed was mostly determined to be sediment starved, a high flux of the material input can be assumed, probably induced by the transport capability of the torrents during times of increased flow rates due to high torrent inclinations.

Figure 6-16: Shallow landslide induced by subsequent erosion of the adjacent slope material. The depicted feature represents the toe of the landslide of cross section A-A'.

Larger landslide features

Cross section A shows a longitudinal section through a landslide situated SE of tributary 2 appr. 1600 m above sea level (Figure 6-17).

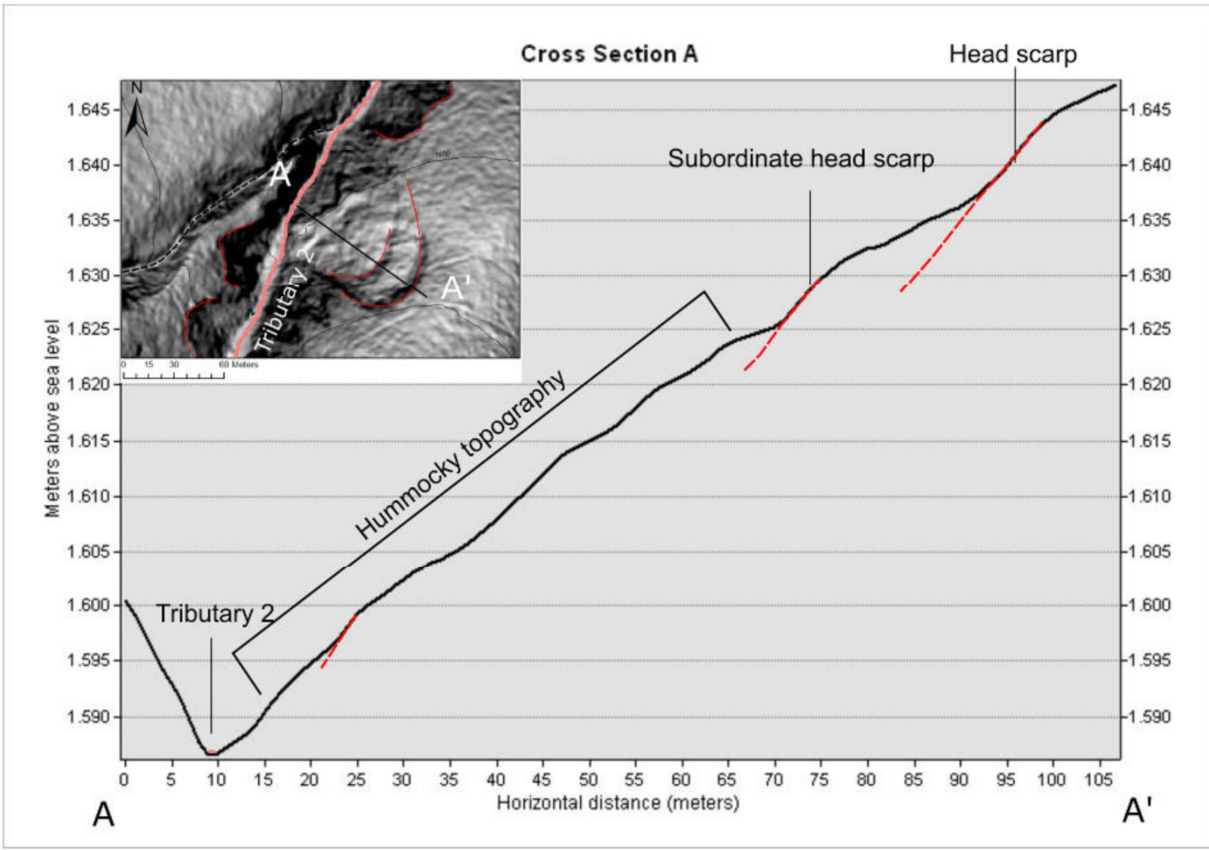


Figure 6-17: Cross section through a landslide situated to the east of tributary 2. The figure indicates the main head scarp, which is followed by a subordinate scarp. Towards the torrent, the slope surface is developed in a hummocky topography, which indicates landslide activity. The toe of the landslide is subsequently eroded by its underlying fluvial element.

The cross-section indicates a concave sliding plane at the uppermost headscarp and subordinate head scarp, both being expressed by clear perturbations in the profile. The section is followed by a hummocky topography, which provides a hint landslide activity. The toe of the landslide is subsequently eroded by tributary 2. A shallow landslide which developed out of the toe could be mapped in the field. A suggestion for the location and subterranean progression of the sliding plane is denoted in red.

Discontinuity-controlled landslides

Below the mounding point of tributary 2 into the Lorenzerbach at appr. 1450 m above sea level, a discontinuity-controlled failure mechanism is exposed on the southern side of the torrent element. There, a sliding plane along a steeply northwest dipping discontinuity plane is exposed. Below the sliding plane, fragmented rock material accumulates towards the Lorenzerbach (Figure 6-18).

Figure 6-18: Discontinuity-controlled failure mechanism exposed on the southern slope of the Lorenzerbach at appr. 1450 m above sea level. Fragmented material accumulates towards underlying torrent. Trees can also be found in the landslide deposits.

In this case, at least one discontinuity plane might be responsible for the destabilization of the adjacent slopes. Kinematically this failure mechanism is admissible if the discontinuity plane “daylights”, for example through erosion of the slope toe because of the incision of the Lorenzerbach. As the underlying torrent is quite narrow at this section, landslides like this can block the underlying torrent, which generates a natural dam. If this dam breaches, the risk of triggering a debris flow or a flood wave is high. Landslides of that manner contribute to an increased hazard potential, especially if the mounding angle is close to 90° degrees to the below-flowing torrent. This example clearly shows the weakness of orthophoto evaluation: This landslide is not recognizable in orthophoto pictures due to shadows produced by the forest. Thus, it can only be recognized in the field or with high-resolution ALS-Data.

Orthophoto evaluation for the upper study area

For the uppermost study area, orthophotos were not provided comprehensively. Solely the lower parts of the subarea could be investigated.

Figure 6-19 shows an orthophoto comparison between 09.07.2010 and 03.08.2013 in the area, where tributary 3 enters the Lorenzerbach (1) at around 1350 m.

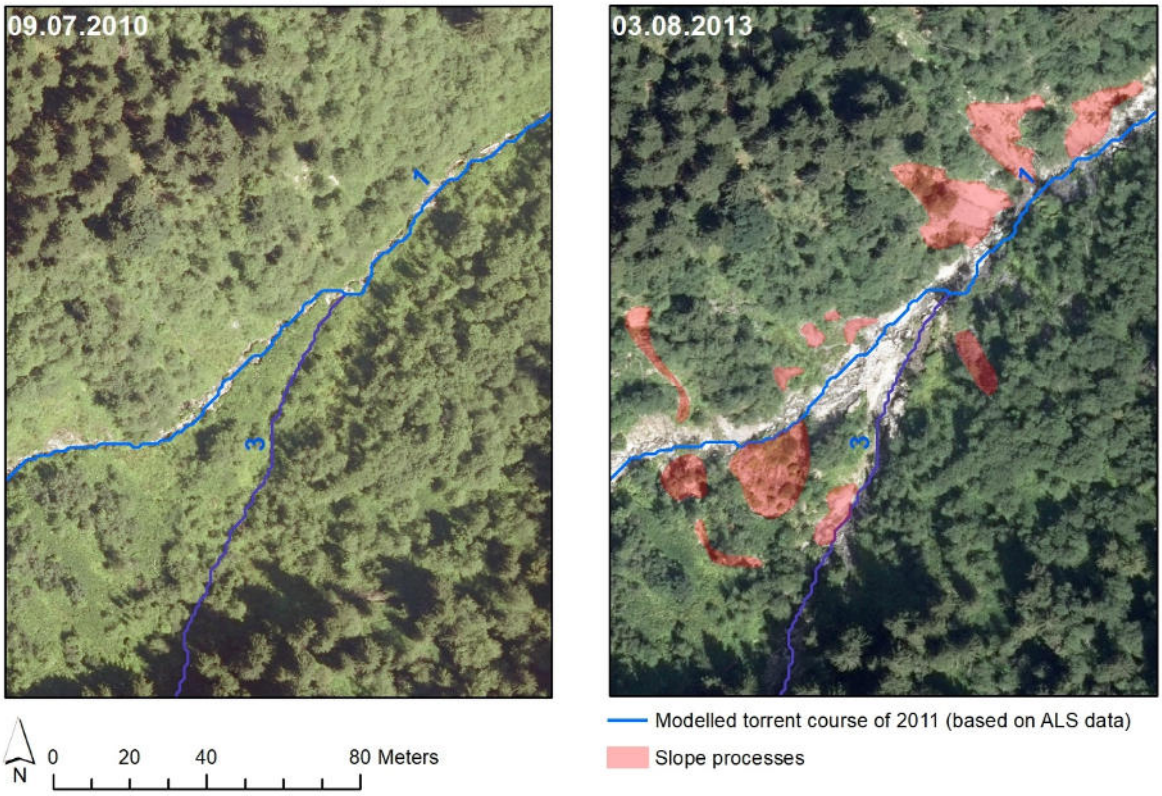


Figure 6-19: Orthophoto comparison in the lower parts of the uppermost catchment: Several landslides were triggered along the torrent segments. Erosion led to the degradation of vegetation between the Lorenzerbach (1) and tributary 3.

Between those epochs, several small- to medium sized landslides were triggered, especially at the southeastern slopes. It is clearly visible that the landslides mound quasi orthogonally to the torrent features. These slope processes also mobilized vegetation towards the discharge elements. Apart from the landslides, strong erosion of the vegetated side slopes and a broadening of the channel bed can be observed, which might result from higher water flow. Also, the course of the Lorenzerbach slightly shifts towards the southeast because of the material entry.

6.3.2 Central study area

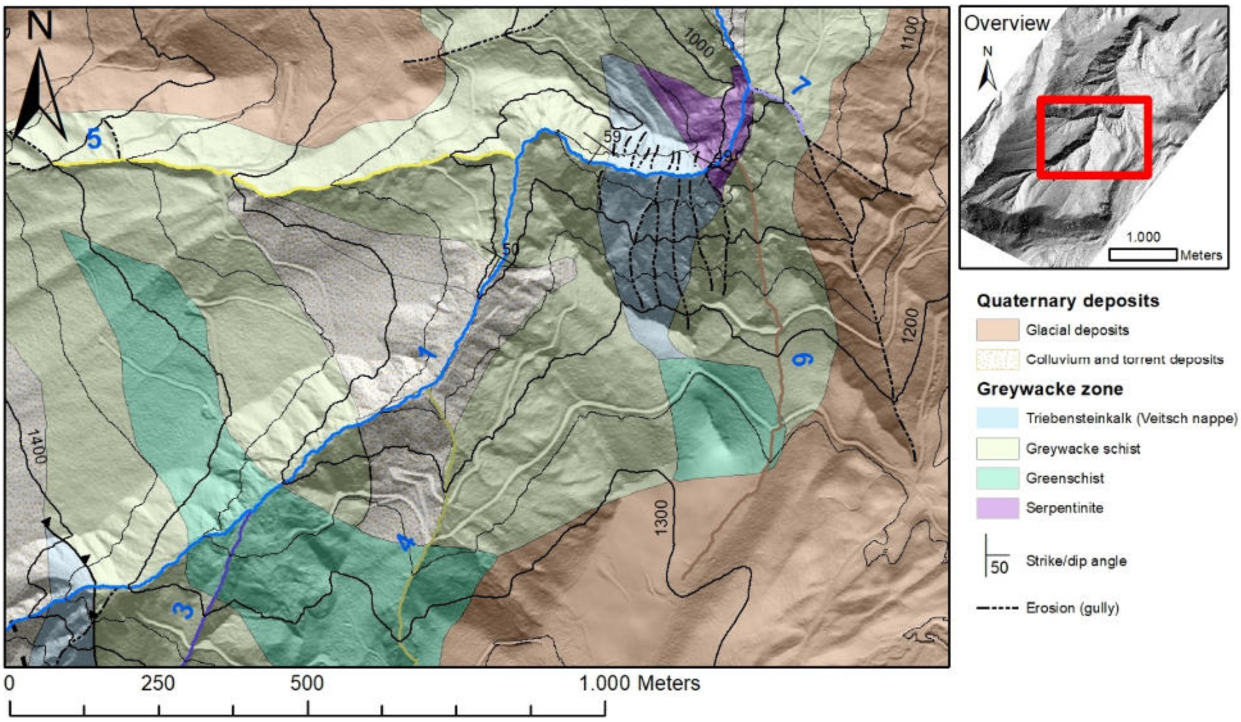


Figure 6-20: Geologic and hydrologic features of the central study area: In this section, tributaries 4, 5, 6 and 7 enter the Lorenzerbach. Also, the course of the Lorenzerbach turns towards E at appr. 1160 m. From a geologic point of view, units of the Greywacke zone are exposed. Quarternary deposits are represented by glacial- and torrent deposits and colluvium.

The central study area (Figure 6-20) covers an altitude range from 1350 m to 1000 m. In this section, tributaries 4, 5, 6 and 7 mound into the Lorenzerbach. From a geologic point of view, quaternary glacial- and colluvial deposits cover the surrounding flanks of the incised torrent system. In the proximity of the torrents, but also along various outcrops on the adjacent slopes, units of the greywacke zone are exposed, mainly featuring greywacke schists, greenschists and the carbonatic rocks (Triebensteinkalk). At appr. 1000 m above sea level (measured at the niveau of the Lorenzerbach), also serpentinite is exposed.

Torrent properties

In this section, the Lorenzerbach flows towards the northeast at moderate inclinations of mostly 20 – 40 %, sometimes deceeding 20 %. At appr. 1160 m, it makes a sharp turn towards E-SE over a length of ~370 m, before turning northwards again. The channel bed of the Lorenzerbach predominantly comprises of coarse gravels and cobbles, locally with boulders (Figure 6-21).

The underlying lithologic units are mainly perceived along the torrent slopes but rarely exposed in the torrent bed.

Figure 6-21: Lorenzerbach at appr. 1100m. Viewing direction in the flow direction. Meandering segment of the main torrent. The channel bed predominantly comprises of coarse gravels and cobbles, locally with boulders. In the background, a shallow landslide is recognizable.

At appr. 1130 m, tributary 4 enters the Lorenzerbach. It originates at appr. 1330 m above sea level and is steeply inclined (> 40 %). Its channel bed is predominantly composed of coarse gravels, while being relatively narrowly developed, rarely exceeding 2 m in channel broadness.

The mounding point of tributary 5 into the main torrent is situated at appr. 1060 m. It emanates at 1300 m and mostly flows through a forest section. It is narrowly developed with the channel bed mostly measuring < 2 m in broadness. Its inclination mostly lies between 20 % and 40 %. Appr. 20 m before the mounding point to the Lorenzerbach, the torrent inclination drastically increases to values above 40 % before entering the Lorenzerbach.

Tributary 6 mounds into the Lorenzerbach at appr. 990 m. It is steeply inclined measuring over >40 % in torrent inclination. Riverbed conditions proximal to the main torrent (100 m) can be described as sediment starved. Here, torrent inclinations of >80% could be detected. In most parts from main torrent niveau to appr. 1100 m, bedrock material is exposed. Tributary 7 shows similar properties.

Slope processes in the central study area

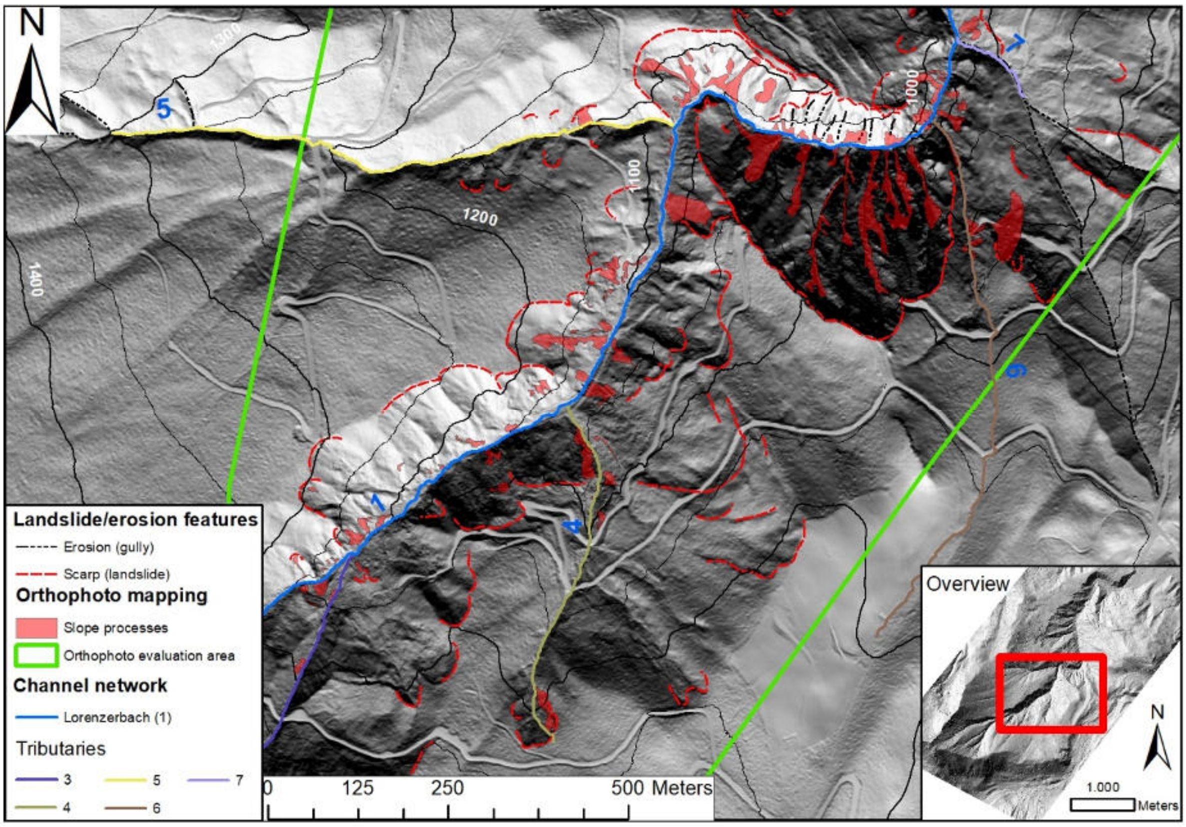


Figure 6-22: Slope processes in the central study area: Through conducting field studies and analyzing the ALS dataset, a large number of landslide scarps could be mapped. Orthophoto evaluation revealed the initiation of numerous landslides between the period under review. It is striking that the landslide density is the highest in the section, where the Lorenzerbach describes an E-W directed course. In this section of the study area, also numerous gullies could be mapped.

Along the flanks around the torrents, numerous landslide scarps could be mapped by analyzing the laserscan data (Figure 6-22). Most of the scarps are oriented towards the adjacent torrents. Apart from suspected landslide headscarps, several erosional features could be mapped, especially in the NE part of the study area section. Orthophoto evaluation revealed the initiation of numerous landslides along the torrent elements. The highest landslide density can be observed at the gully flanks, where the Lorenzerbach describes an E-W directed course.

Shallow landslides and bank erosion

Several shallow landslides could be identified. They mostly occur along the adjacent slopes of the Lorenzerbach but were also observed alongside tributaries 4 and 6. Figure 6-23 depicts a shallow landslide on the right embankment of the Lorenzerbach at 1125 m. The landslide developed out of colluvium. The landslide mechanism tends to be a mixture between flowing and sliding. Bushes and small trees also got transported into the torrent system below. On the left half of the picture, a proceeding of the unstable slope properties can be assumed due to small scarps in the vegetation covering the topsoil.

Figure 6-23: Shallow landslide at the eastern slope of the Lorenzerbach at appr. 1200 m. The landslide developed out of colluvium. The proceeding of the landslide can be assumed due to visible scarps in the vegetation at the left side of the picture.

Apart from shallow landslides, bank erosion is a common process that is evident especially along narrow sections of the Lorenzerbach in this sub-segment between 1250 m and 1200 m. Figure 6-24 depicts the Lorenzerbach at appr. 1200 m. The erosion of the torrent through deposits of fluvial debris transport or debris flow transport on the left-hand side of the torrent is clearly visible. On the right-hand side, predominantly fine-grained soil with a high water content enters the torrent. In the background, bank erosion and an associated shallow landslide are visible.

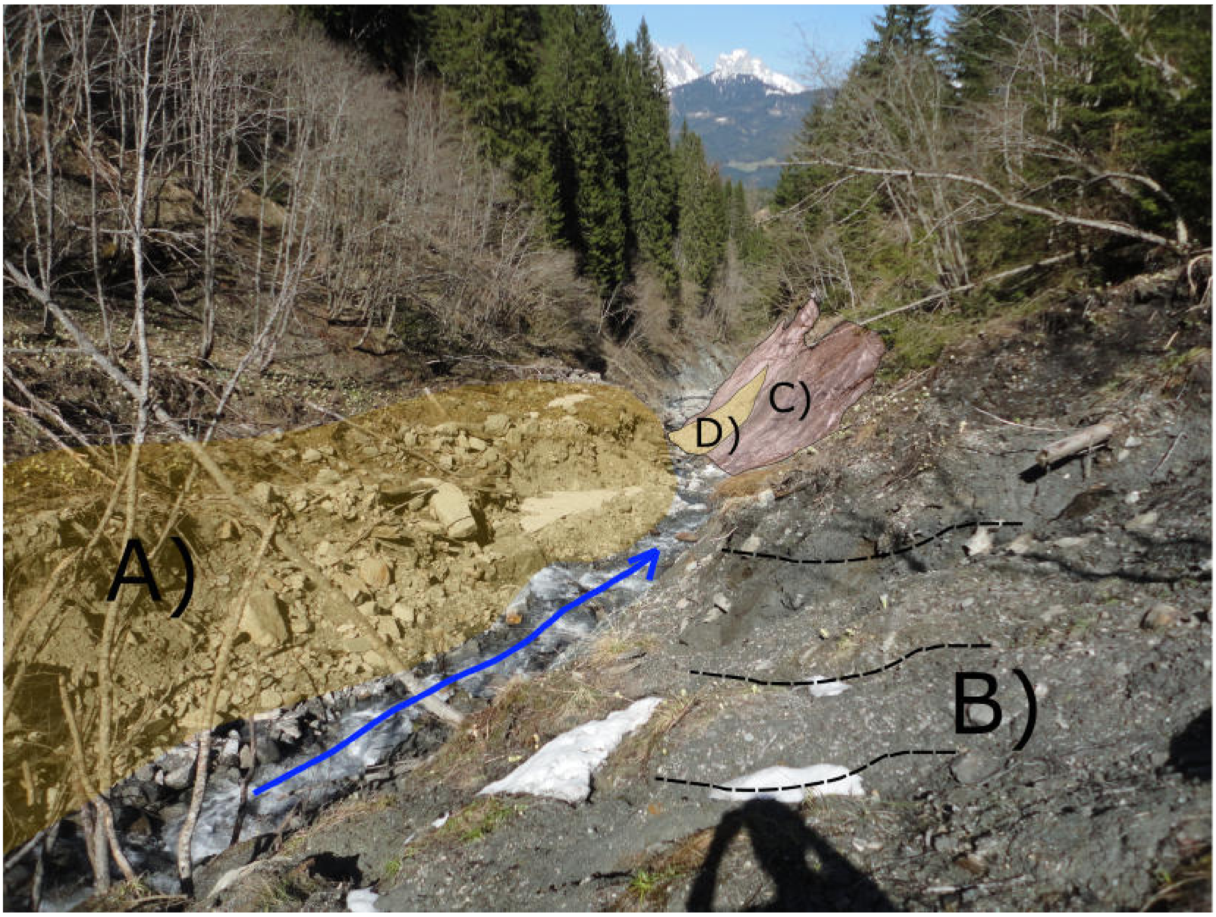


Figure 6-24: Lorenzerbach at appr. 1200 m: A) Deposits from fluvial-/debris flow transport. B) Saturated slope material susceptible to flowing. C) Eroded bank and shallow landslide deposit (D).

Gullies

Between appr. 1050 m and 990 m, the Lorenzerbach receives material input from steeply northwards oriented erosion gullies. The gullies have inclinations of > 100 % and possess a length of appr. 100 m to 260 m. In this area, evidence of at least fluvial debris transport is provided by debris fans, sometimes overlaid by levee deposits, indicating a debris flow transport mechanism. Also, characteristics of shallow landslides can be observed on the surrounding north and southwards directed adjacent slopes. Figure 6-25 depicts the Lorenzerbach at 1010 m and two erosion gullies on the right side of the torrent. The deposition of the material distracted the course of the Lorenzerbach towards left.

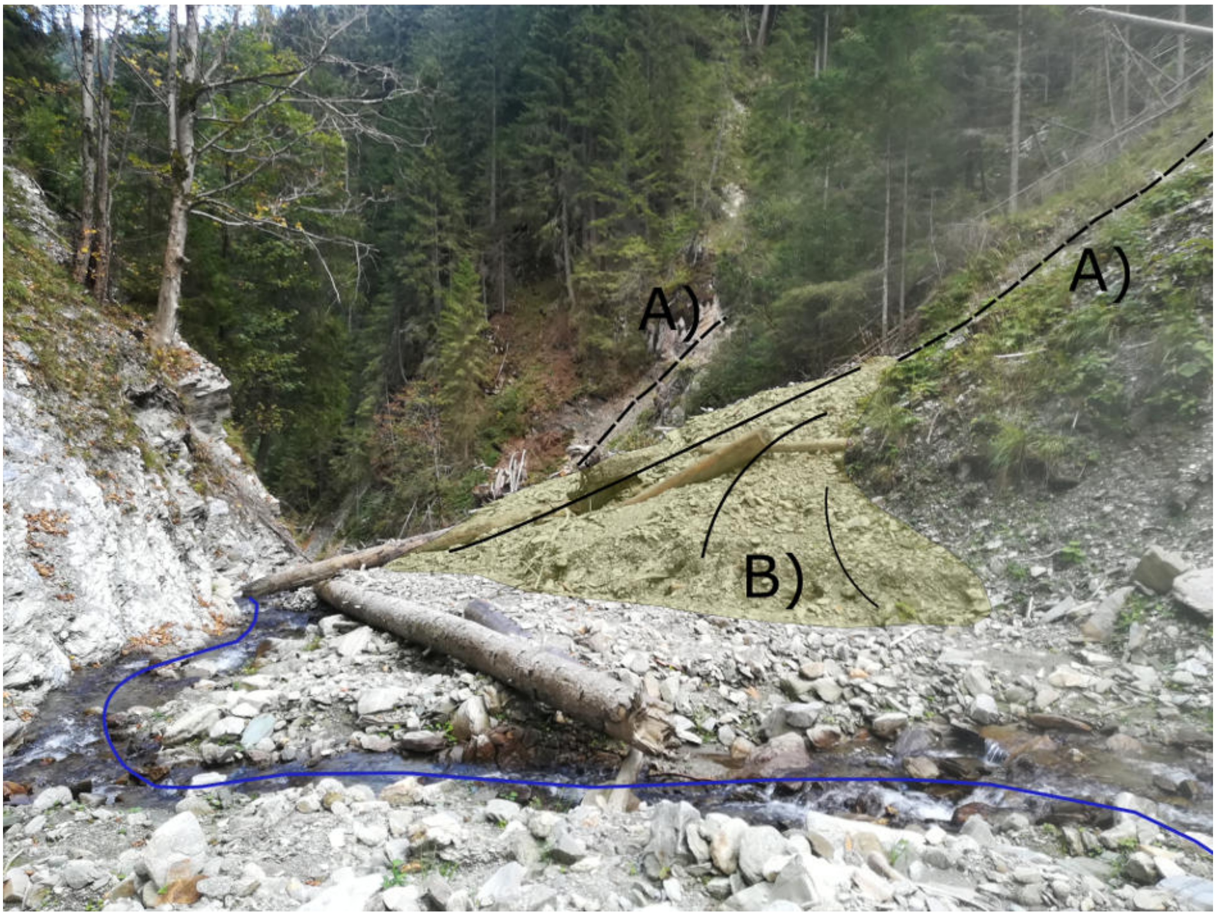


Figure 6-25: Lorenzerbach at 1010 m: Two steeply inclined erosion gullys (A) delivered material towards the torrent (B) and distracted its course towards left. In this area, also levee deposits can be found, which represent footprints of debris flows.

Orthophoto evaluation for the central study area

In the central part of the study area, orthophoto evaluation revealed numerous changes in slope- and torrent appearance related to fluvial erosion or slope processes (Figure 6-22). Quasi all processes occurred proximal to the hydrologic elements, landslides were detected to mostly be oriented quasi orthogonally on the nearest channel feature. Figure 6-26 shows the orthophoto comparison for tributary 4 and the Lorenzerbach (1). In between these epochs at tributary 4, a preexisting landslide got reactivated on the left slope. Additionally, several landslides were triggered at the right and left slopes of the Lorenzerbach.

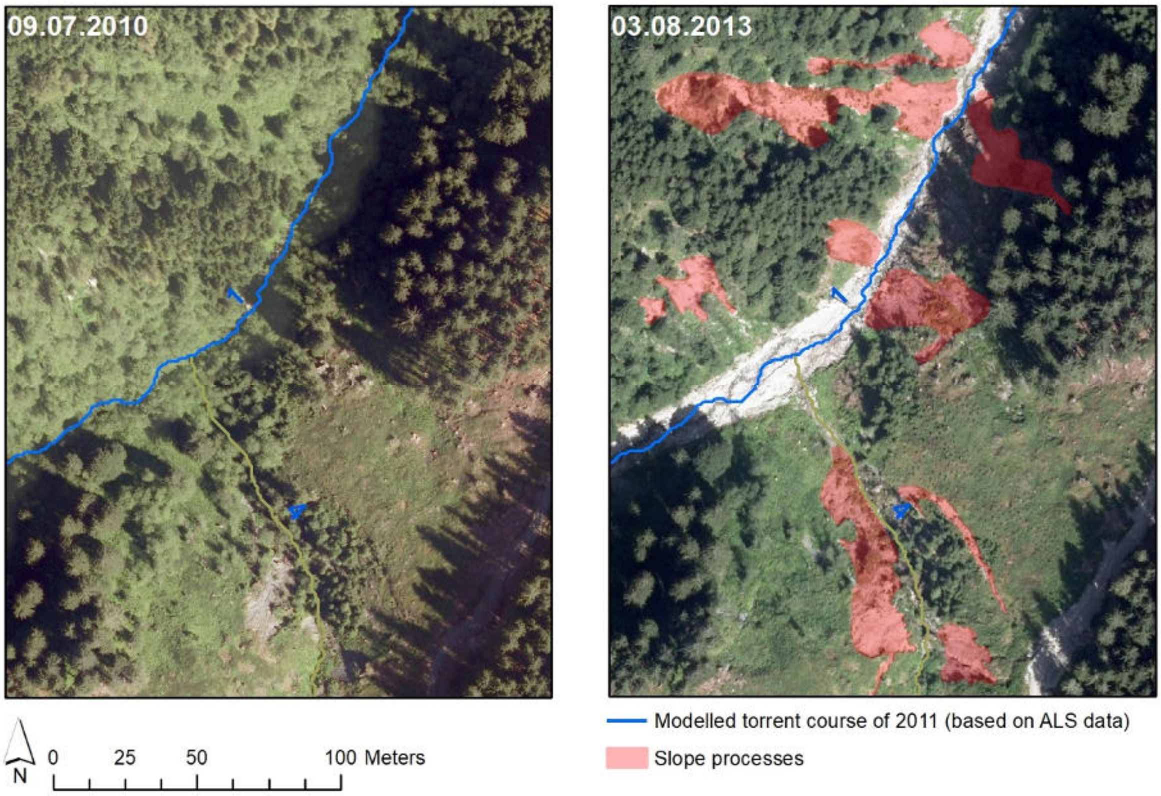


Figure 6-26: Orthophoto evaluation in the area of tributary 4. Several small landslides were triggered/reactivated in this section of the catchment.

Orthophoto studies in the area of the previously mentioned gullies revealed that a significant amount of slope material was mobilized in the investigated timespan. Large areas lost their vegetated cover through slope processes. Landslide initiation along the gullies can be followed more than 150 m towards the S of the Lorenzerbach. Depositional tendencies below the gullies are expressed through small debris fans which developed below. Apart from the gullies, numerous landslides were triggered at the adjacent slopes of the hydrologic feature. They in most cases are oriented quasi-orthogonal to the below-lying channel (Figure 6-27).

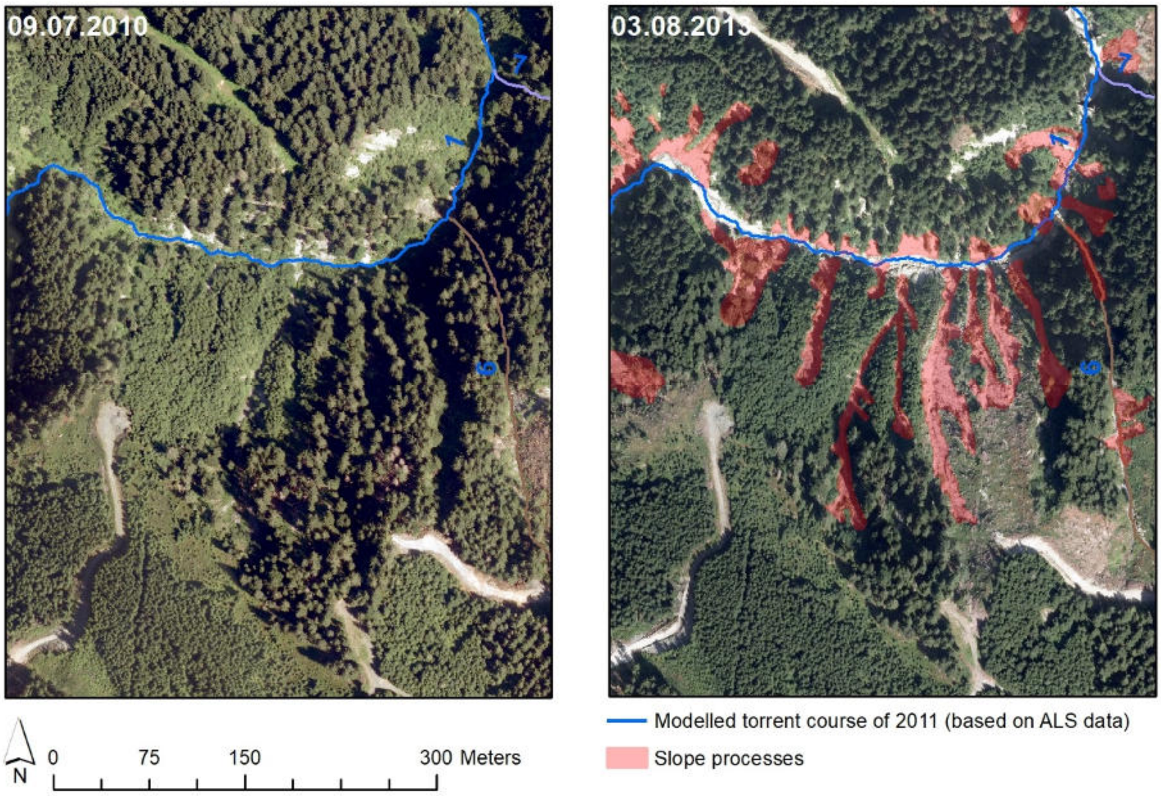


Figure 6-27: Orthophoto comparison between two dates in the central part of the catchment. Several landslides developed out of the slopes and mobilized a significant amount of material.

6.3.3 Lower study area

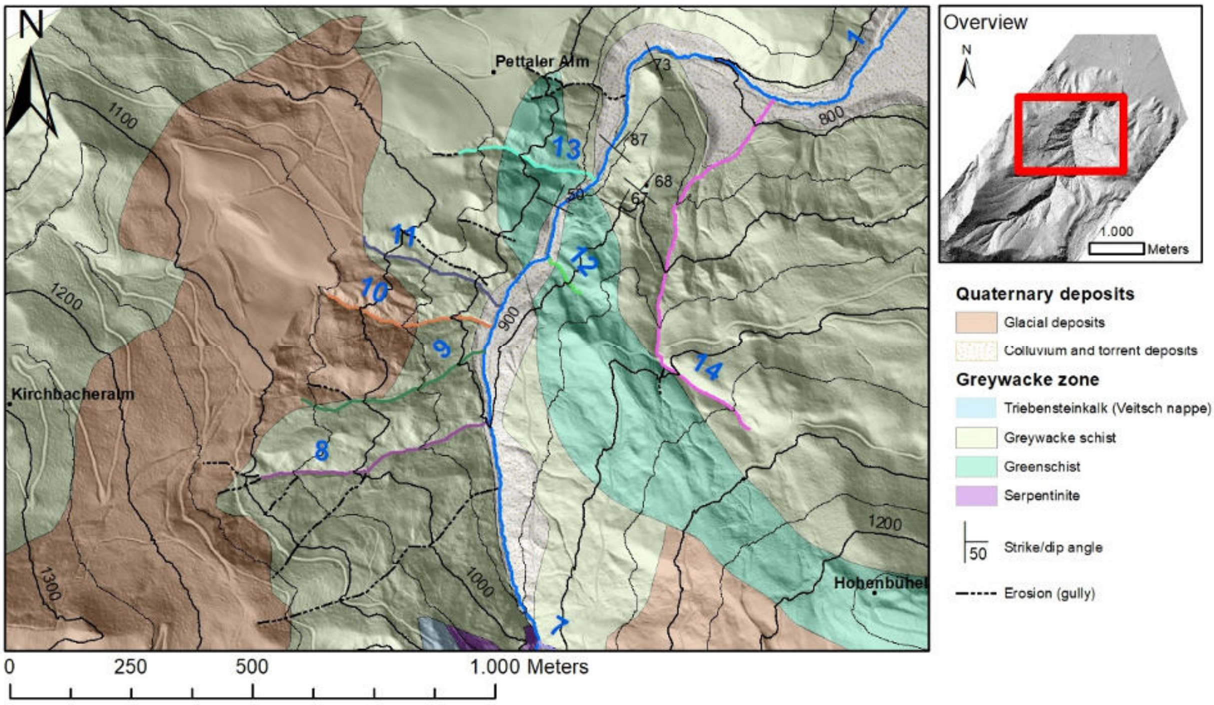


Figure 6-28: Geologic and hydrologic features of the lower study area. The slopes surrounding the Lorenzerbach, for most parts, are made up of greywacke schist. Also, an NW-SE striking band of greenschist is exposed. Higher-elevated areas are covered with moraine deposits. The eastern flanks of the Lorenzerbach are sometimes covered with colluvium. Torrent deposits are also evident.

The lower study area contains the geologic and hydrologic elements which are situated on the W- and NW flanks of the Hohenbühel mountain, and the eastwards-directed slopes below the Pettaler Alm and Krichbacheralm (Figure 6-28). In the NE part, the village of St. Lorenzen is situated on the alluvial fan deposits.

In this subarea, glacial deposits cover most parts of the higher-elevated western slopes, but also some parts of the eastern slopes southwards of the Hohenbühel. Fluvial deposits are located along the Lorenzerbach and laterally extend towards the alluvial fan deposits in the northeast. The adjacent slopes around the Lorenzerbach mostly comprise of greywacke schist. Locally, graphitic schists/phyllites could be identified in the field at the eastern slopes in the area of tributaries 8 to 11. Along the Hohenbühel towards the Pettaler Alm, an NW-SE striking greenschist body traverses the subarea.

Torrent properties

In this section, the Lorenzerbach flows towards the NW to NE and makes a sharp turn towards E-SE just before the village of St. Lorenzen. At the village, its course turns northwards again and exits the study area. The torrent inclination for the Lorenzerbach exceeds 20 % only above 900 m. Below, torrent inclination mostly lies around 10 %. The channel bed broadens in this section, and is predominantly filled with coarse gravels and cobbles, but also with sands representing the finer fraction.

At 900 m, 885 m, 880 m, 875 m 860 m and 840 m, tributaries 8 to 13 mound into the Lorenzerbach. These side channels are characterized by a torrent inclination of mostly > 40 % with narrow developed channel beds.

Slope processes in the lower study area

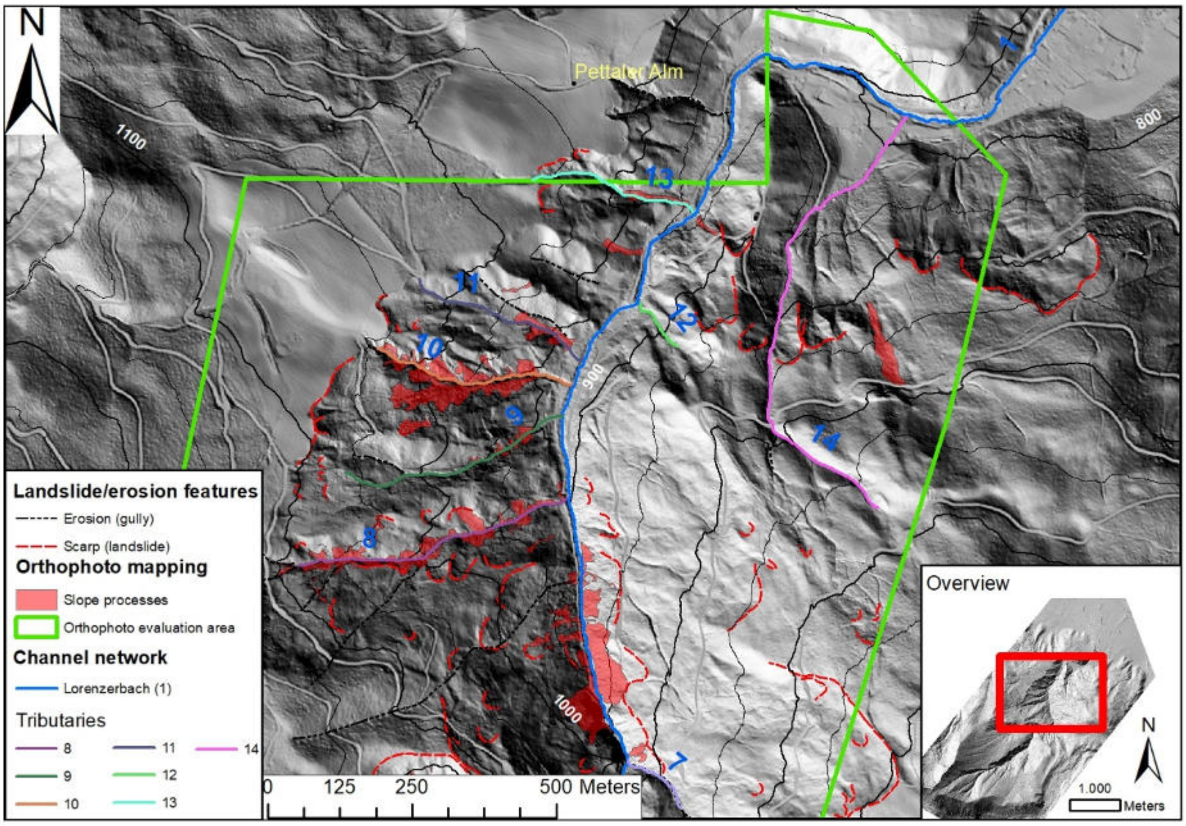


Figure 6-29: Slope processes in the lower study area: Numerous landslide scarps could be mapped along the slopes surrounding the channel network. Apart from that, several gullies are carved into the landscape. Orthophoto mapping showed, that many landslides were triggered along the Lorenzerbach and its tributaries. Most affected are tributaries 8, 10 and 11, and the sections of the Lorenzerbach above appr. 900 m.

In this section of the study area, landslide scarps could predominantly be mapped at the western and eastern slopes around the Lorenzerbach, and are well preserved along tributaries 8, 10, 11 and 14 (Figure 6-29). With orthophoto comparison, slope processes along the Lorenzerbach could be identified especially in the southern half of the subarea, and along the adjacent slopes of torrent segments 8, 10 and 11.

Shallow landslides

Along the Lorenzerbach, shallow landslides and possibly flowing processes could be mapped along the eastern slopes between 910 m and 950 m (measured at torrent niveau). Figure 6-30 shows a shallow landslide body on the eastern slope of the Lorenzerbach at 940 m with a section of fine-grained, water-saturated material, susceptible to flowing. On the opposing side of this landslide feature, landslide deposits from the western slope are visible.

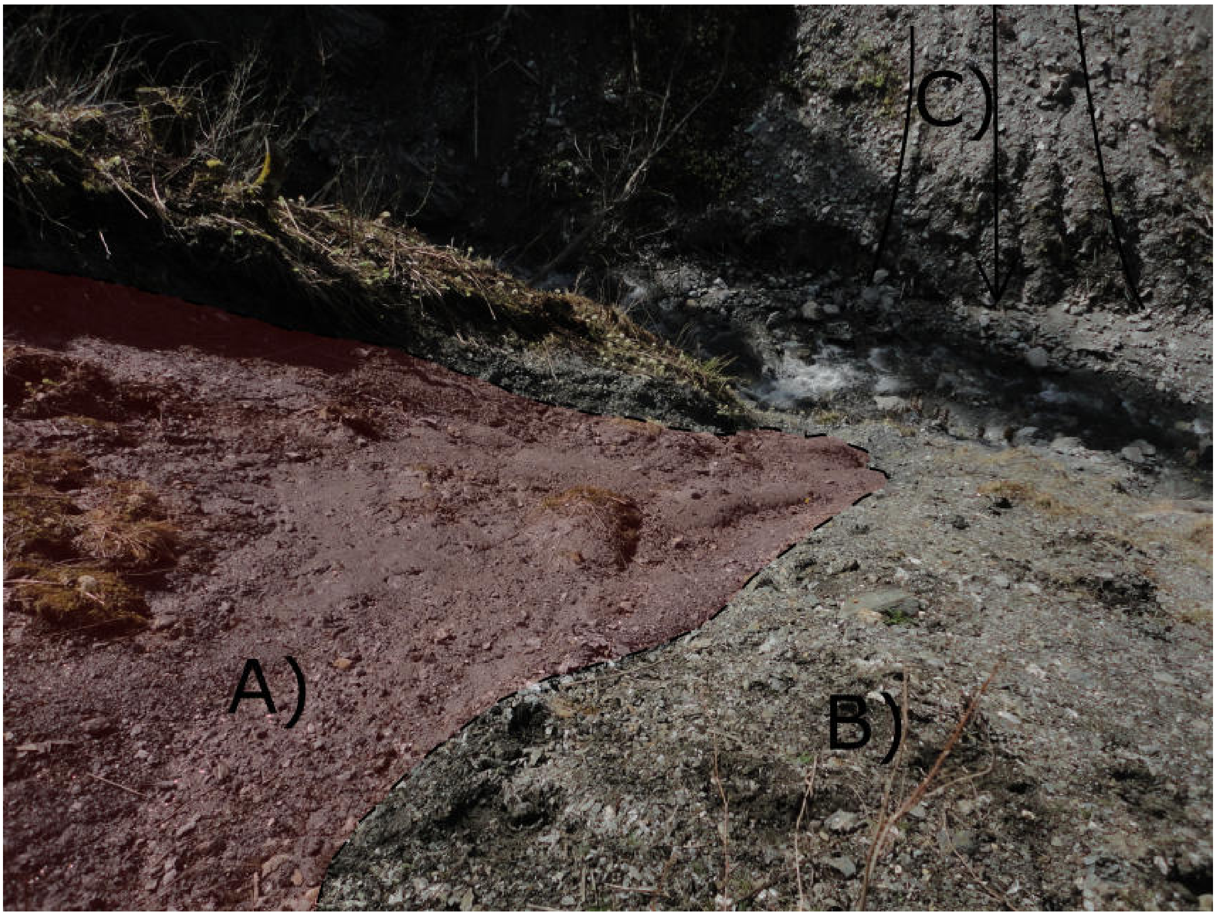


Figure 6-30: Predominantly fine-grained, water-saturated material (A) embedded in a shallow landslide (B) at the eastern slope of the Lorenzerbach in the lower study area between 910 m and 950 m. C) depicts a landslide with an eroded toe from the western slopes of the Lorenzerbach.

Orthophoto evaluation for the lower study area

Field studies, combined with desk studies revealed that a large amount of predominantly shallow landslides are situated in the proximity of tributaries 8, 9, 10 and 11. Through orthophoto evaluation, a drastic topographic change could be detected. Figure 6-31 compares the tributaries between the two overflights.

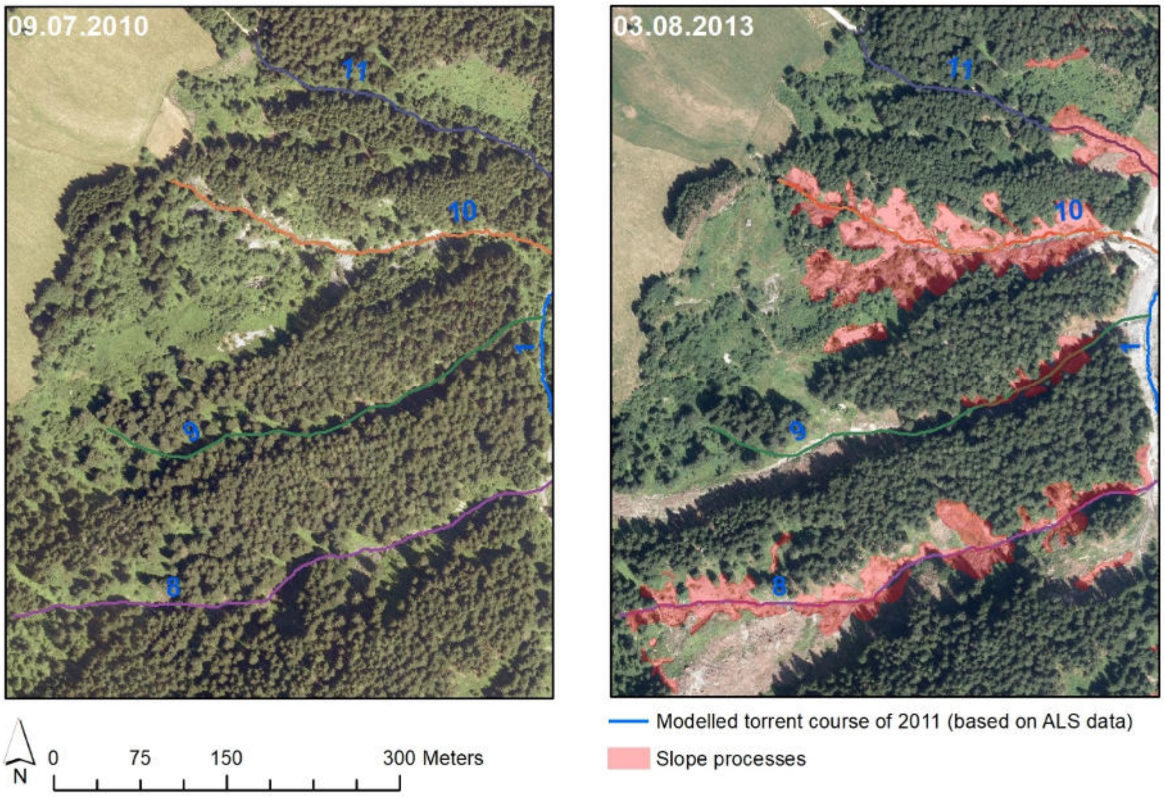


Figure 6-31: Orthophoto comparison in the area of tributaries 8, 9, 10 and 11: Significant impacts of landslides and fluvial erosion are evident. Preexisting landslides, especially along tributary 10, seem to have carved themselves further into the slope.

The initiation of the landslides mobilized large compartments of material/vegetation towards the channel elements. Additionally, it is visible, that deforestation works were conducted southwards of tributary 8. In the area of tributary 10, landslide indicators are already visible on 09.07.2010. Between the interval, the landslides seem to have developed further towards the slope out of preexisting landslide features (Figure 6-32).

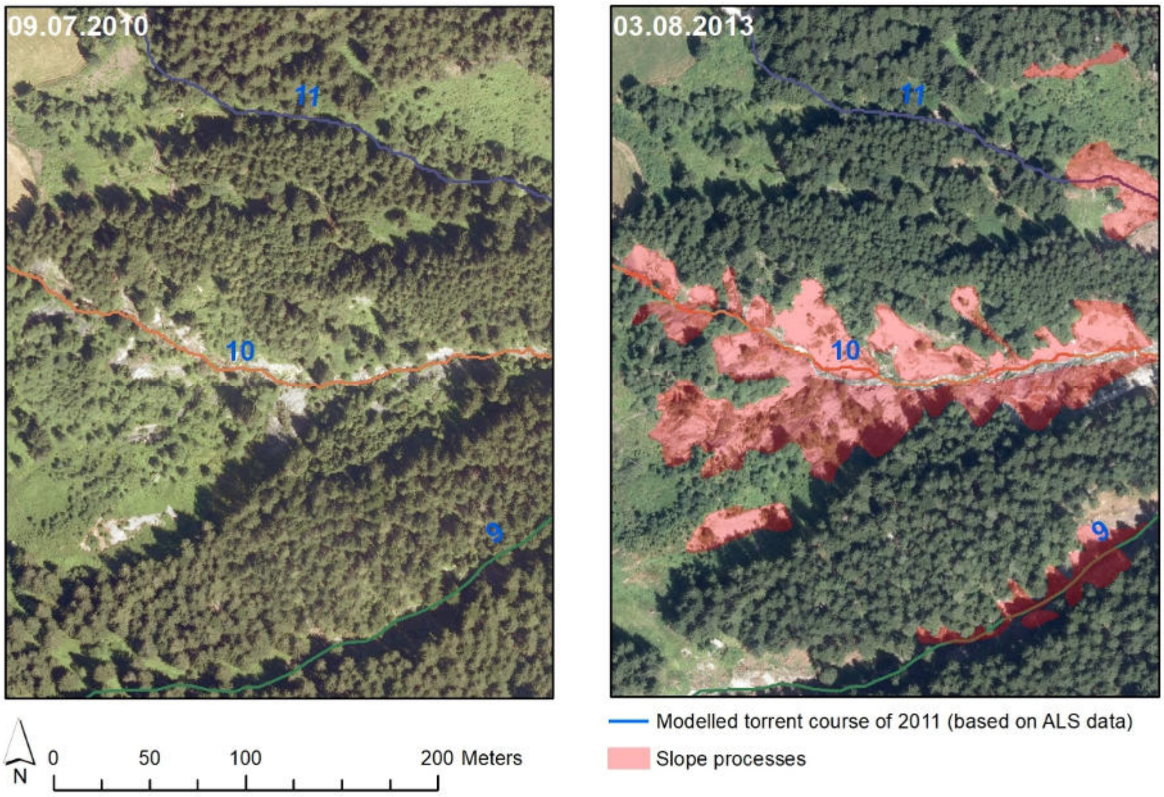


Figure 6-32: Orthophoto comparison in the area surrounding tributary 10: Preexisting landslides got reactivated, mobilizing large soil compartments and vegetation.

The orthophoto evaluations are supplemented by the field observations: Figure 6-33 shows the massive impact of small to medium-sized landslides on the morphology around the torrent. Apart from the landslide bodies themselves, the input of vegetation through failing organic soil bodies and tilting trees is evident.

Figure 6-33: Landslide-dominated landform surrounding tributary 10: Landslides mobilized large compartments of soil and vegetation. The mixture of landslide deposits and organic components accumulates in the channel.

6.4 Landslide statistics

By comparing the orthophotos from 09.07.2010 and 03.08.2013, 137 landslide polygons with a total area of 83,520 m^2 were mapped.

By using the polygons which derived from orthophoto comparison, a fishnet analysis was conducted to characterize typical areas for slope failure. Figure 6-34 depicts the average slope inclination for each of the 137 landslide polygons. A low or no landslide activity was determined for slope angles between 0° and 25° and >55°. Out of 137 mapped landslides, 111 were triggered at slope angles between 30° and 45°, 44 of which in the interval between 35° to 40°.

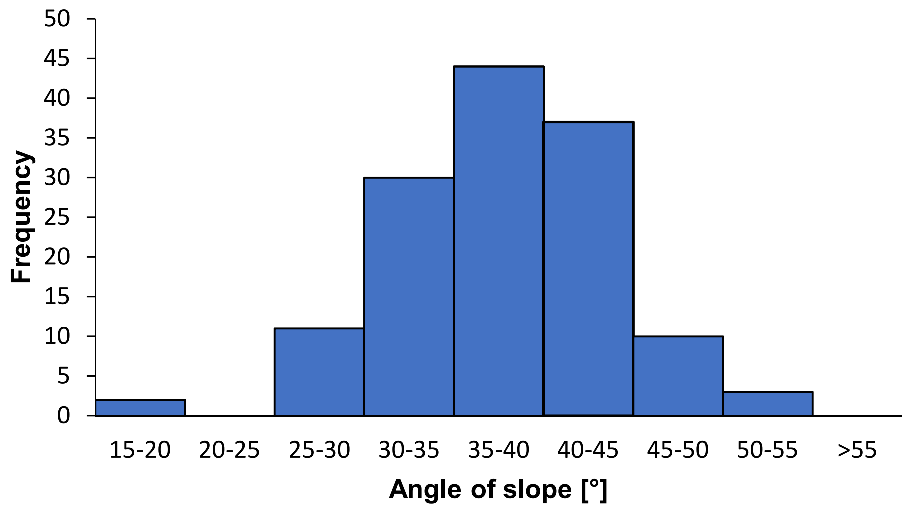


Figure 6-34: Distribution of slope angles affected by landslides with the results from fishnet analysis. Most landslides were triggered at slope angles between 35° and 40°.

To obtain the landslide initiation distance, the maximum planar distance for each landslide polygon towards the next channel element (based on the channel network as proposed in Chapter 6.2) was plotted (Figure 6-35). Most of the landslides were triggered proximal to the channel elements at distances below 90 m. Singular landslides were triggered > 250 m away from the next discharge feature. 51% of the slope processes were triggered in the interval between 20 m and 40 m.

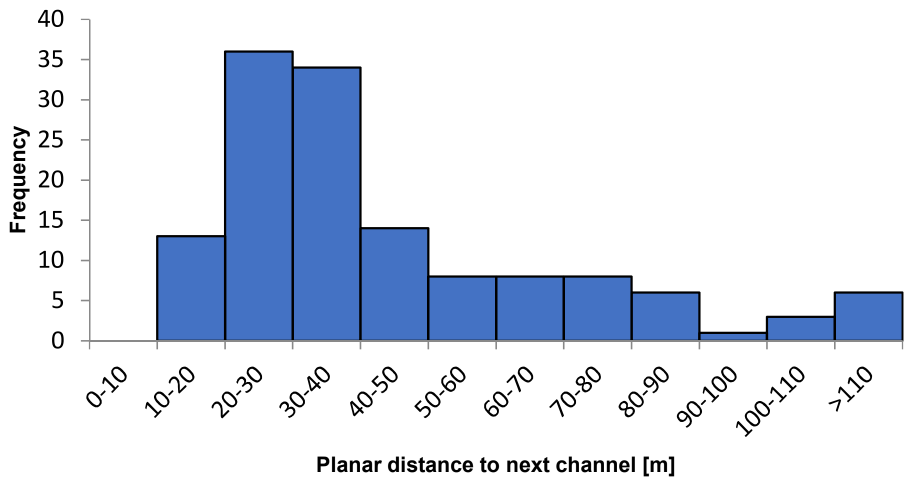


Figure 6-35: Initiation distance of landslides to the next discharge element.

To evaluate the distribution of slope processes related to the geologic units, the geology raster proposed in Chapter 6.3 was sampled with the 3x3m measuring sampling net (9260 sampling points). Most of the areas affected by landslides are located on greywacke schist and quaternary deposits (Figure 6-36). As the greywacke schist covers most parts of the orthophoto analysis area, it is no surprise that the peak is located there. The high number of slope processes in the Triebensteinkalk derives from the gullies situated in the central part of the study area. Over a relatively small area, a large number of landslides were triggered.

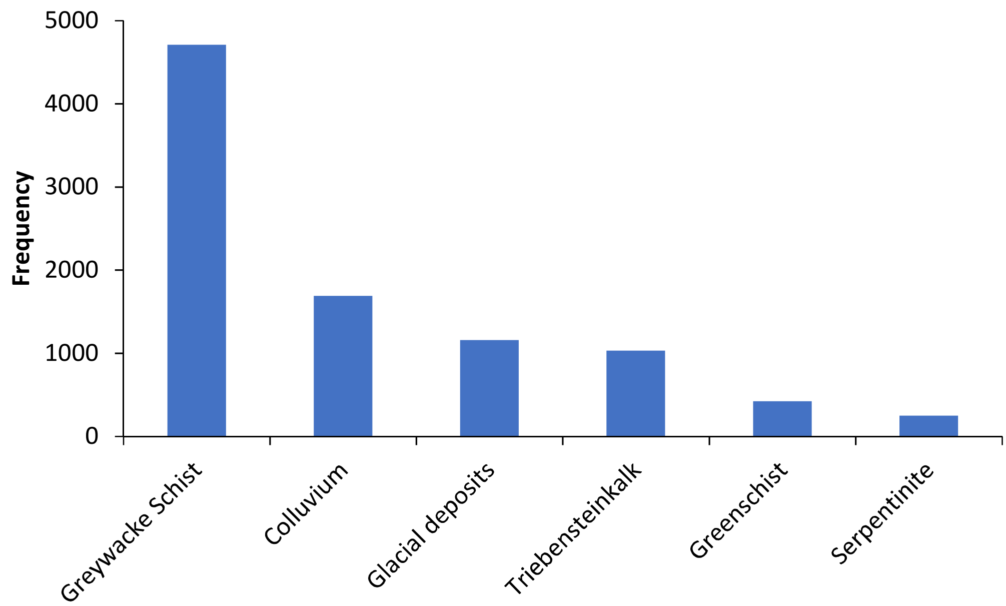


Figure 6-36: Distribution of landslides based on the lithologic units. Most landslides were triggered on greywacke schist and quaternary deposits.

The conducted landslide statistics correlate well with the findings from field studies: The landslide initiation is directly linked with the incision of the torrent elements, and consequently the steepening of the adjacent slopes. Thus, slope angles attune between 30° and 45° and the trigger distance from the next hydrologic element is rather low. For the landslide bodies that were triggered at angles < 20°, an oversaturation of the subsoil and consequently a flowing/creeping transport mechanism could be driving. The weathering effects acting on the greywacke schist also favor landslide development. Especially proximal to the discharge elements, decomposition processes yield a fine-grained slope cover, which can ultimately be mobilized due to water saturation and pore water pressures during periods of excessive rainfall.

6.5 Bedload estimation procedure after Gertsch 2009: Input data and results

6.5.1 Torrent segment delineation

For the application of the bedload estimation procedure proposed by Gertsch (2009), the channel network in the catchment of the Lorenzerbach was delineated into 11 torrent segments. Compared to the channel network proposed in Chapter 6.2, several tributaries had to be neglected, as in total 12 segments are allowed to be defined for the method Gertsch (Figure 6-37). The course of the Lorenzerbach is defined through segments 1, 3, 5, 7, 9 and 11. This derives from the numbering that is required for the estimation procedure.

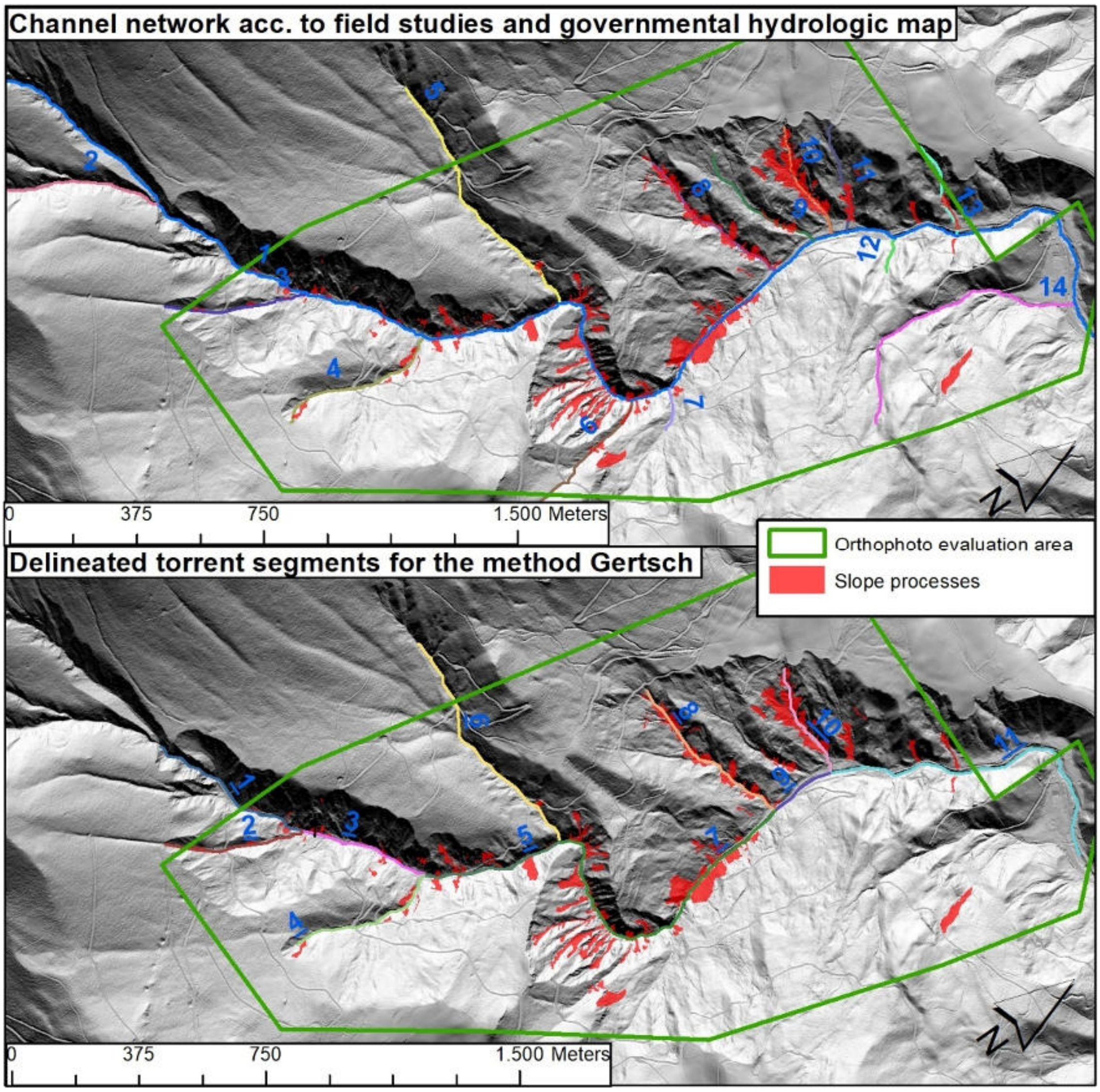


Figure 6-37: Channel network according to field studies (upper map) and the delineated torrent segments for the application of the method Gertsch (lower map). As only 12 torrent segments can be considered, several tributaries and the uppermost section of the Lorenzerbach had to be neglected.

The uppermost segment was defined just below the Wasserfallgraben as in this area an increased sediment availability through landslides and bank erosion could be observed in the field. The starting point of the uppermost segment equals the mounding point of tributary 2 into the Lorenzerbach. Tributaries 6 and 7 were neglected, as field evidence and orthophoto studies provided less significant hints for an increased bedload delivering capability compared to the below-lying tributaries. Compared to tributaries 8 and 10, tributaries 9, 11 and 13 display a far less pronounced expression of bedload mobilization processes. Orthophoto comparison revealed, that most material was mobilized in tributaries 8 and 10, indicating that these sections are more critical for the bedload household compared to tributaries 9, 11 and 13. Therefore, tributaries 9, 11 and 13 were neglected. Tributaries 8 and 10 are represented as torrent segments 8 and 10 in the framework of the bedload estimation procedure.

Tributary 14 is situated just a few hundred meters to the SW of the village of St. Lorenzen. Field studies and the orthophoto evaluation also indicated a low activity concerning slope- and torrent processes. Thus, it also was assigned less significant for bedload mobilization and furthermore was neglected for conducting the method Gertsch.

The delineated torrent segments largely correspond to the “abstracted channel network” proposed by Hübl et al. (2012) in the framework of the event documentation. This indicates that the most critical torrent segments could be identified through the GIS- and field-based studies.

6.5.2 Estimated torrent segment properties

Table 6-1 shows the assigned torrent segment properties. The loose material supply for each torrent segment was determined by evaluating the conducted field studies. Slope input was estimated with the landslide polygon area surrounding each torrent segment, which was multiplied with a factor for the average landslide thickness. Landslide thickness was calculated with the knowledge obtained by field observations concerning the landslide type. In total, a through slope processes mobilized cubature of 58,000 m^3 was estimated.

Table 6-1: Torrent segments, their material class, and estimated slope input.

Torrent segment	**Loose material class**	**Appr. area affected by landslides from orthophoto evaluation [m²]**	**Estimated slope input [m³]**
1	3 (loose material limited)	no data	**4,000**
2	1 (loose material unlimited)	454	**500**
3	3 (loose material limited)	1,508	**1,500**
4	3 (loose material limited)	1,223	**1,000**
5	3 (loose material limited)	5,263	**5,500**
6	3 (loose material limited)	512	**500**
7	2 (control structure)	32,799	**25,000**
8	2 (control structure)	9,370	**9,000**
9	2 (control structure)	1,287	**1,000**
10	2 (control structure)	12,426	**9,000**
11	2 (control structure)	4,700	**1,000**

For torrent segment 1, a total amount of 4,000 m^3 of slope input was estimated based solely on the field studies as information from orthophotos studies were not comprehensively available in its area. In this segment, mostly shallow landslides from bank erosion and discontinuity-controlled failure mechanisms yield the input of slope material. Material supply at the torrent bed was assigned sediment-limited, as, for the most parts of the torrent section, only a thin cover of torrent bed material was overlying bedrock. For torrent segment 2, the input of slope material was accounted at 500 m^3. The influence of landslides compared to other segments is relatively low. However, the material supply in the torrent bed is significantly higher, as the torrent bed does not uncover the underlying lithology and the "Feilenblaike" indicates a high material availability from a geomorphologic point of view. Thus, for this section, unlimited material supply was assigned for the torrent bed. Torrent segments 3 to 6 receive input of shallow landslides along the torrent slopes. In segments 4 and 6, the average landslide thickness was estimated to be below 1 m as no hints for the mobilization of deep-seated compartments were evident in the field or via the orthophoto studies. Torrent segments 3 to 6 are also characterized by a limited material supply in the channel bed (Figure 6-38).

Figure 6-38: Sediment-limited material supply in torrent segment 5 at appr. 1070 m: Material availability is controlled by the slope processes. In sections with limited material supply, bedrock is only covered by a thin layer of material along the torrent bed.

In torrent segments 7 to 11, the torrent bed was modified with check dams (Figure 6-39). Check dams successively reduce the sediment supply and inhibit a further incision of the torrent. Therefore, limited loose material supply through a control structure was assigned for the obstructed torrent segments.

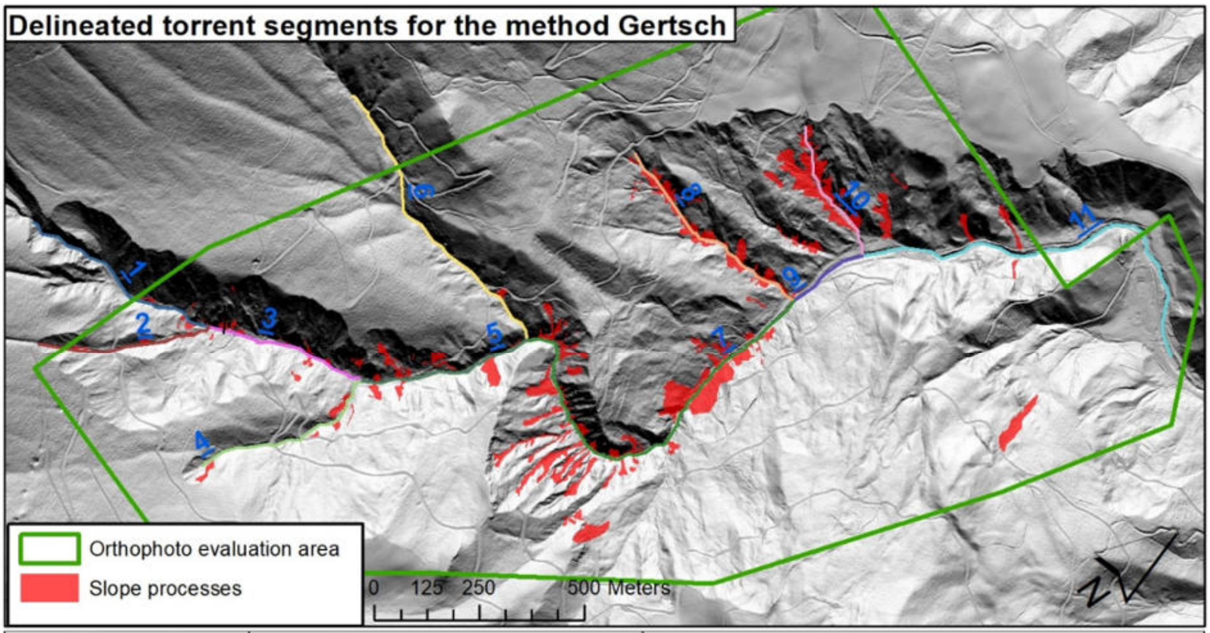
Figure 6-39: Check dams in torrent segment 7 at appr. 980 m: Check dams act as sediment-restraining barriers and limit the capability of the torrent to mobilize compartments of the torrent bed.

In the area around torrent segment 7, a large area of appr. 32,799 m^2 was affected by landslides. These landslides mostly developed out of gullies or represent shallow landslides with a low material input contribution. Therefore, the effective landslide thickness that is relevant for the method Gertsch was estimated to be below 1. Figure 6-40 depicts a landslide body at the E side of torrent segment 7 at appr. 920 m. This shallow landslide does not deliver large amounts of material to the torrent though covering a relatively large area. Similar considerations were applied for torrent segments 8, 10 and 11.

Figure 6-40: Landslide body at the E side of torrent segment 7 (Lorenzerbach) at appr. 920 m. Compared to the area that is affected by the landslide, its contribution of material is rather low.

6.5.3 Scenario

The scenario for the bedload estimation procedure was adjusted to the 2012 debris flow by using the findings from the event documentation by Hübl et al. (2012). The in-detail assigned scenario can be found in the appendix. For the Lorenzerbach, debris flow development was assigned as the key process from segment 7 on until segment 11. A debris flow mechanism was also assigned for torrent segment 2. However, the field studies from the event documentation indicate, that the debris flow from torrent segment 2 stagnated when it was entering the Lorenzerbach (or in the framework of the bedload estimation procedure torrent segment 3). The entry of slope material through landslides was in general set to >2 input locations, as various landslides were triggered along the torrent flanks. Negative factors in terms of torrent blocking were assigned for torrent segments 5 and 7, whereas in torrent segment 7 the blocking of the passage resulted in a debris flow development (Figure 6-41).



Torrent segment	Torrent processes	Slope processes
1	-Fluvial debris transport	-Input of slope material (4,000 m^3)
2	-Debris flow transport, stagnation when mounding into segment 3.	-Input of slope material (500 m^3)
3	-Fluvial debris transport, stagnation of debris flow from segment 2	-Input of slope material (1,500 m^3)
4	-Fluvial debris transport	-Input of slope material (1,000 m^3)
5	-Fluvial debris transport	-Blocking of the torrent passage through landslides (5,500 m^3)
6	-Fluvial debris transport	-Input of slope material (500 m^3)
7	-Debris flow, triggered through blocking of the torrent	-Material input of landslides (25,000 m^3) yields a blocking of the torrent and consequently debris flow development
8	-Fluvial debris transport	-Input of slope material (9,000 m^3)
9	-Debris flow transport	-Input of slope material (1,000 m^3)
10	-Fluvial debris transport	-Input of slope material (9,000 m^3)
11	-Debris flow transport	-Input of slope material (1,000 m^3)

Figure 6-41: Assigned torrent and slope processes for the bedload estimation after Gertsch.

6.5.4 Results from bedload estimation procedure after Gertsch (2009)

Figure 6-42 depicts the results that were obtained with the bedload estimation procedure after Gertsch (2009). The untranslated original german output can be found in the appendix.

Torrent segment	Torrent segment length [m]	AEG [km²]	Average torrent inclination JGA [%]	Material class	JGA/JGAob	Accumulated Energy-Index E-Iakk	Material input through landslides [m³]	Mobilized material input [m³]	Transport Process in the Torrent	Function of the torrent segment	Deposition factor	Deposited cubature [m³]	Yield rate [m³/m]	Eroded cubature [m³]	Bed load balance [m³]	Accumulated bed load after the torrent segment [m³]
1	519	0,51	45,6	limited	1,00	0,0	4000	4000	FD	Erosion			3	1557	5557	5557
2	422	0,03	57,3	unlimited	1,00	0,0	500	500	DF	Erosion			4	1688	2188	2188
3	399	0,70	23,5	limited	0,46	19,5	1500	1500	FD	Erosion			3	1197	2697	10442
4	468	0,22	37,5	limited	1,00	0,0	1000	1000	FD	Erosion			2	936	1936	1936
5	429	1,47	16,0	limited	0,52	40,7	5500	5500	FD	Erosion			4	1716	7216	19594
6	756	0,00	28,1	limited	1,00	0,0	500	500	FD	Erosion			1	756	1256	1256
7	1034	2,58	15,9	limited, constr.	0,72	62,5	25000	15000	DF	Erosion			12	12408	27408	48258
8	543	0,14	37,8	limited, constr.	1,00	0,0	9000	6300	FD	Erosion			2	1086	7386	7386
9	199	3,85	9,3	limited, constr.	0,35	91,4	1000	1000	DF	Erosion			2	398	1398	57042
10	359	0,00	44,2	limited, constr.	1,00	0,0	9000	6300	DF	Erosion			1	359	6659	6659
11	1044	4,35	8,8	limited, constr.	0,33	105,8	1000	1000	DF	Deposition	0,9	57330,9			-57331	6370
Total bed load at fan apex [m³]:																**6.400**

Figure 6-42: Results from the bedload estimation procedure after Gertsch (2009). The figure lists all assigned torrent- and slope parameters and the calculated bedload cubatures.

The bedload estimation procedure assigned erosion as torrent function for torrent segments 1 to 10, calculations for torrent segment 11 determined deposition as driving function. The yield rate assigned for most torrent segments with erosion as torrent function ranges between 1 m^3/m to 4 m^3/m with eroded cubatures of 359 m^3 to 1,716 m^3. Torrent segment 7 showed a significantly higher yield rate of 12 m^3/m resulting in an eroded cubature of 12,408 m^3. As deposition was determined for torrent segment 11, the deposited cubature was calculated to be 57,331 m^3.

The calculated material input from slopes was fully mobilized in all torrent segments where the cubature delivered by landslides was below 9,000 m^3. In torrent segments 7, 8 and 10 the material was determined to get partially mobilized with a mobilization factor of 60% for torrent segment 7 and 70% for torrent segments 8 and 10. The sum of the mobilized cubature from slope input and the eroded cubature through torrent processes results in a positive bedload balance for all torrents where "erosion" was determined as torrent process and a negative bedload balance for torrent segment 11, where "deposition" was the torrent function.

The accumulated bedload cubature at the lowermost point (fan apex) which represents the delivered bedload cubature at the previously defined scenario amounts 6,400 m^3. After torrent segment 9, the maximum cubature was calculated to amount 57,042 m^3. Torrent segment 10 added 6,659 m^3 to the cubature after torrent segment 9, meaning that the maximum mobilized cubature amounts 63,701 m^3. In torrent segment 11, this quantity got reduced by 57,331 m^3 as the estimation procedure assigned a deposition of 90% of the previously transported bedload.

7 Discussion

Field studies in combination with GIS-based processing were applied to analyze the processes in the catchment of the Lorenzerbach. In essence, the torrent system with its properties could be described. Slope processes were on a large scale identified by comparing orthophotos before- and after the 2012 event, displaying a significant impact of the geomorphological processes on the slope and torrent elements. These signals were compared to the field evidence, which allows determining the mass transfer mechanisms at the torrents and their adjacent slopes. The findings are now discussed and related to the debris flow/flood potential in the catchment of the Lorenzerbach.

The bedload estimation method after Gertsch (2009) was applied based on the results from field- and desk studies. Observations made in the course of the event documentation were considered to develop a scenario which corresponds to the debris flow event of 2012. The obtained results are now discussed by comparing them to findings from other studies.

7.1 Processes controlling the debris flow susceptibility of the Lorenzerbach

Based on the findings from GIS- and field-based studies, the catchment of the Lorenzerbach can be subdivided into 4 process areas, which display special characteristics concerning their torrent and slope processes, and consequently their role in bedload mobilization and transportation (Figure 7-1).

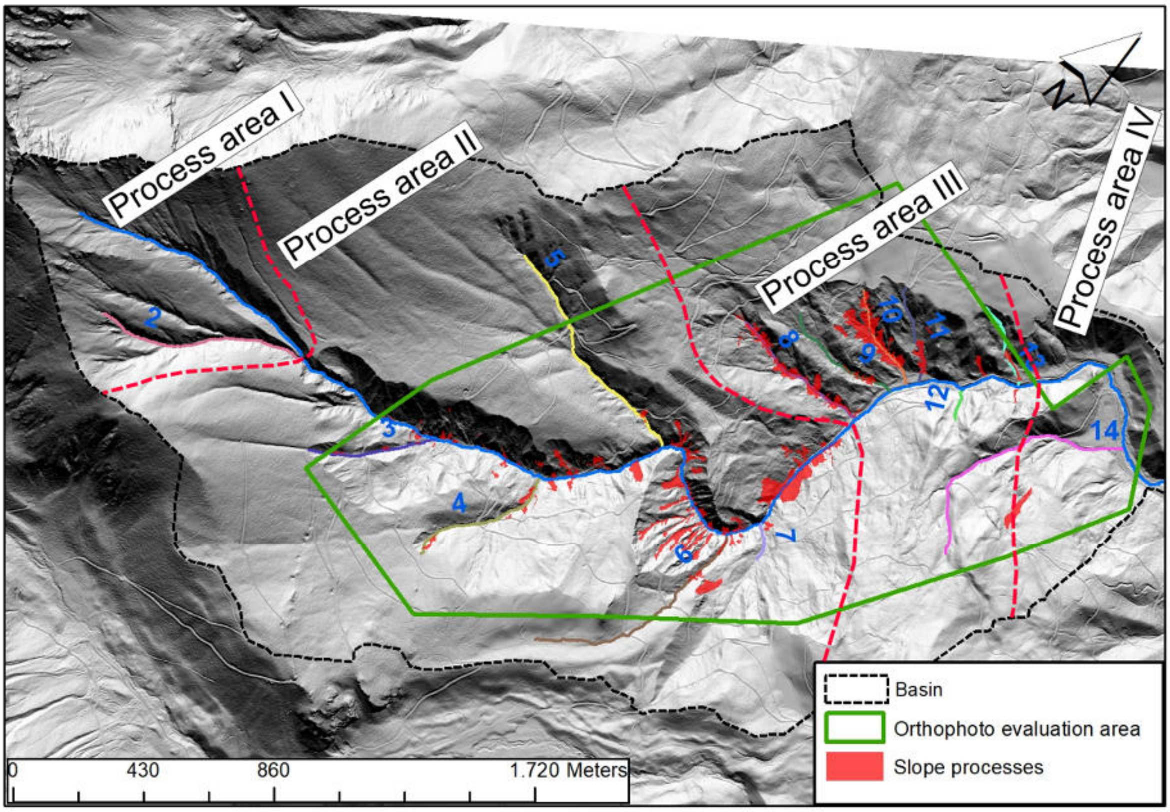


Figure 7-1: Subdivision of the catchment of the Lorenzerbach into four process areas. Process area I is characterized through sediment-starved conditions along the torrent bed. In process area II, landslides play a key role in material mobilization. Tributaries were most active in process area III. Process area IV is characterized by a depositional regime.

Process area I is characterized through sediment-starved conditions along the torrent bed. Segments showing sediment supply were only observed in cases where landslides delivered material from the flanks to the torrent. Since high torrent gradients were observed, it can be assumed that the provided relief energy in the slightly vegetated area of the Almspitz east face might contribute to the high transport capability of the discharge elements. This could indicate that high erosive forces are present, rather than accumulating ones, which yields sediment-limited conditions as bedrock material often is exposed at the torrent bed. Additionally, the lack of vegetation might also contribute to higher water availability for the torrents as less water is retained (Hegg et al. 2001). As the slopes were determined to be covered mostly with fine-grained quaternary deposits, which tend to have a low hydraulic conductivity, surface runoff might be favored during heavy rain events as a result of low infiltration rates.

Concerning the slope processes, in process area I, significantly fewer landslide features could be mapped compared to the lower parts of the catchment. Here, input from slope to torrent mostly occurred because of the erosion of strongly jointed rock masses or older landslide bodies. Bank erosion was observed but is not as much developed compared to the lower torrent segments. Also, discontinuity-controlled failure mechanisms could be mapped. As the uppermost part consists of more competent lithologies, decomposition processes that might yield greater slope instabilities might not be as relevant as in the lower parts. Because of that, landslides in process area 1 might only play a subordinate role in bedload input. However, single landslides might block the underlying torrent passage, which could have large effects on the process development of elements below.

In process area II, torrent inclinations drastically decrease after the knickpoint in the torrent profile. Here, a significantly higher sediment availability could be revealed. Since torrent gradients decrease, deposition of transported bedload might be favored due to a decline in the transport capability of the water. Additionally, the input of slope material through bank erosion and shallow landslides is more prevalent in these areas, possibly resulting in runoff-limited conditions. A large number of landslides could be mapped in the field and via orthophoto studies. These landslides are in almost every case situated proximal to the next torrent and mostly occur at slope angles >20°, which is typical for slope failures (Costa 1984). Additionally, the underlying geology consists of weaker rocks (mainly schists, phyllites) which might explain the deeper incision of the torrent elements. Slope instability might be a result of the combination of incising torrents, weathering and subsurface/surface impacts of hydrologic/hydrogeologic processes. Though, most landslides were determined to be shallow landslides, which tend to mobilize rather small cubatures compared to deep-seated landslides, their impact results from their sheer frequency of occurrence. However, Hungr (2005) stated that even one small landslide body has the capability of producing a hillslope debris flow. Additionally, field observations revealed their impact on the adjacent torrent system: As most sections of the central part of the torrent system are rather narrow, the input of slope material can result in temporary blocking of the torrent. As a natural dam develops, water levels can rise behind the dam, leading to a failure of the dam after its stability limit is exceeded. Consequently, large compartments of sediments, and a flood wave or water spate with high flow velocities and transport capabilities can develop. This ultimately can induce the development of a debris flow surge. Figure 7-2 shows a schematic depiction of the impact of slope processes on the torrent at the central part of the mapping area (in the vicinity of the gullies).

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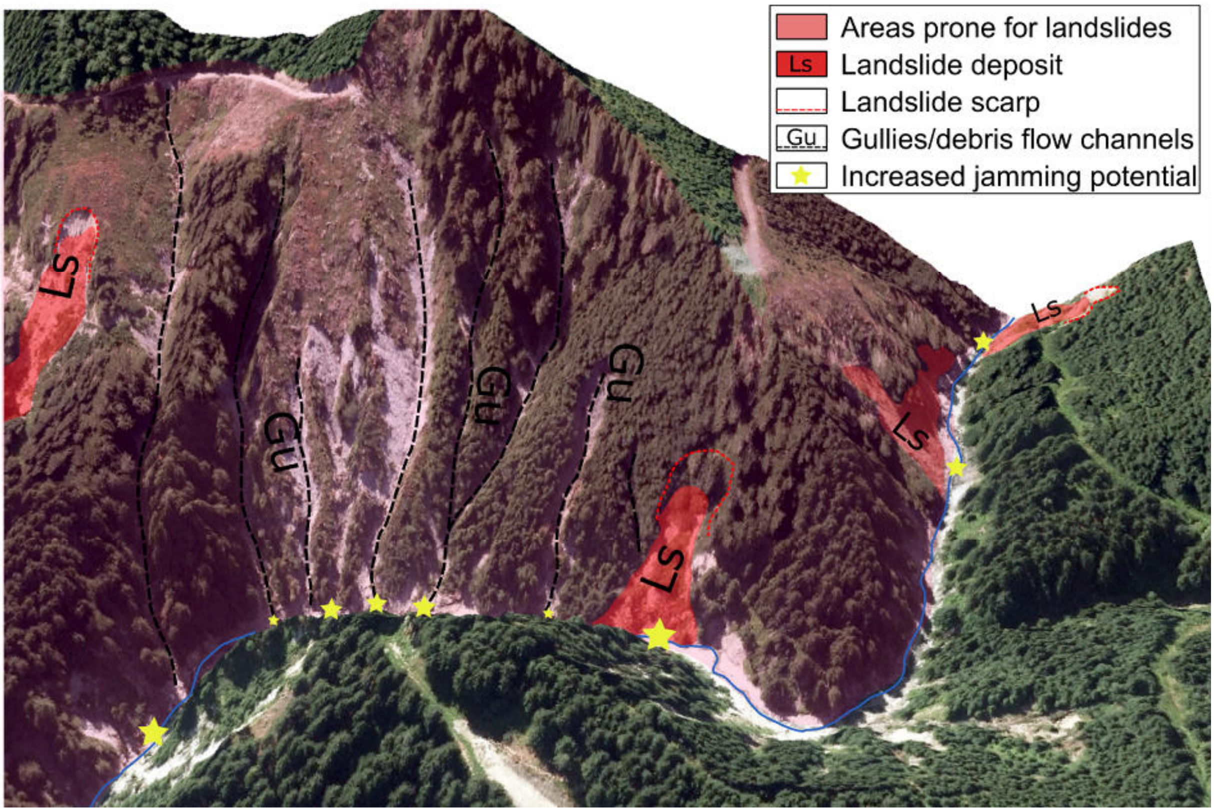

Figure 7-2: Schematic sketch of the landslide features and their influence on the jamming potential in the central parts of the catchment: As most channel sections are developed rather narrow, the input of landslide material could result in the blocking/jamming of the underlying torrent. Consequently, a dam develops which can breach. Thereby, large amounts of material are mobilized and can result in a debris flow.

These landslides also play an important role in the entry of coarse organic matter such as trees or branches. This input can induce log jamming. These log jams act as sediment-restraining barriers that can breach during large flood events (Jochner et al. 2015) and consequently yield an entry of larger masses of organic matter. This correlates well with the observations made in the course of the event documentation. In their studies, Hübl et al. (2012) determined a volume of 4,000 loose cubic meters of wood, which was transported by the Lorenzerbach into the village of St. Lorenzen. By comparing the orthophotos, it was clearly visible that large areas lost their vegetated cover as a direct result of slope processes.

In process area III, the Lorenzerbach broadens on his thalweg, providing more accommodation space to deposit previously transported bedload. In this section, the Lorenzerbach does not receive large amounts of material from slope processes through its directly surrounding flanks. In contrast, the tributaries situated to the W of the Lorenzerbach show a high capability of mobilizing material through landslides and bank erosion due to steep torrent gradients. However, the probability of blocking the underlying torrent passage (Lorenzerbach) is significantly lower, as more accommodation space and lower gradients are present, compared to the situation in process area II.

At the lowermost section of the study area (process area IV), no significant slope- and torrent processes could be identified. This section might be dominated by a depositional regime during times of increased bedload transport, as only low torrent gradients are present. The sharp turn of the torrent course towards E might also favor bedload sedimentation.

Recapitulating the results, it can be assumed that especially the slope processes in process area II are responsible for the debris flow potential of the Lorenzerbach. Apart from delivering large amounts of material to the Lorenzerbach, a blocking of the torrent passage could also provide enough energy to overcome the sections with a lower torrent gradient, lying beneath. As a consequence, a debris flow surge can develop, which can carry its destructive potential towards the village St. Lorenzen. These assumptions are congruent with the witness reports from local residents after the 2012 event. They described that the flood flow declined for a few minutes before a debris surge with large amounts of tree stems struck the village (Hübl et al. 2012).

7.2 Geologic impacts on the torrent morphology of the Lorenzerbach

The longitudinal channel profile of the Lorenzerbach shows two distinct knickpoints. According to Whipple et al. (2013), such perturbations can be evoked by tectonic activity or contrasting rock properties. Figure 7-3 compares the torrent profile with the proposed geologic map.

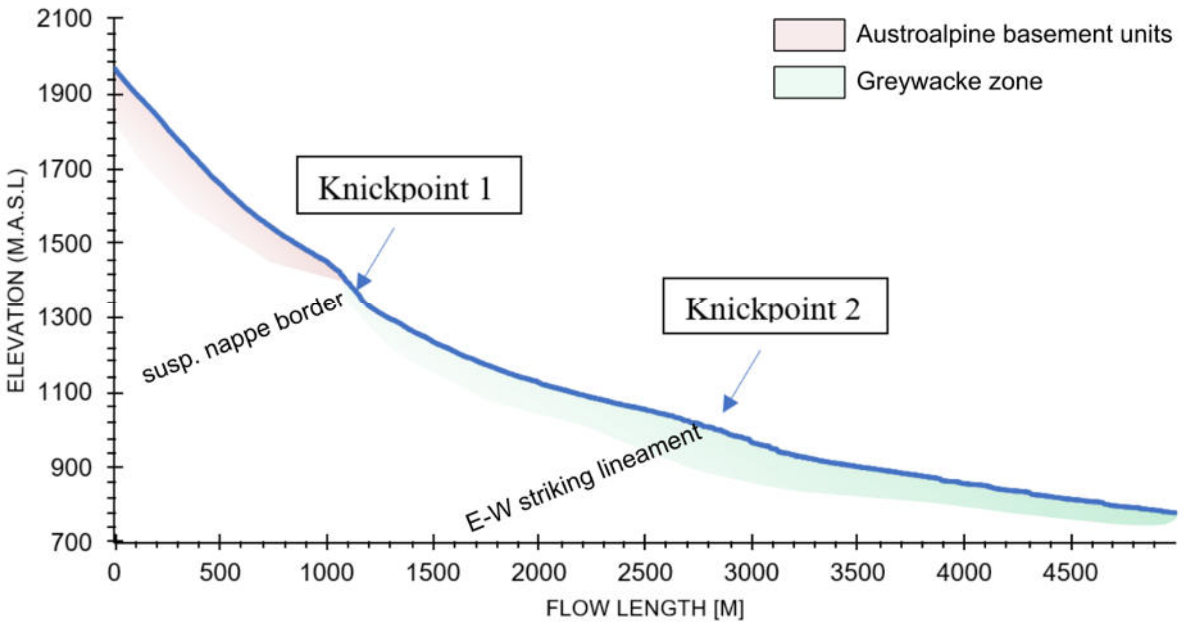

Figure 7-3: Cross section of the Lorenzerbach and its coherence with geologic features.

It is evident that the first knickpoint correlates well with the proposed nappe border between the Austroalpine basement units and the Greywacke zone. A tectonic weakening could favour the erodibility, yielding an increase in torrent inclination. On the other hand, tributary 2 enters the Lorenzerbach just a few meters above the knickpoint. Thus, higher flow rates might be achieved in the area, yielding a higher erosive force below. Additionally, the Austroalpine basement units tend to be more competent and provide a higher erosion resistance than the carbonates, schists, and phyllites that follow the crystalline rocks. As this very steep section of the torrent system could not be investigated in the field due to its inaccessibility, questions remain concerning the nappe border and possible influence of tectonic processes to the channel geometry.

Knickpoint 2 is situated at around 1050 m.a.s.l. It is way less pronounced than the first knickpoint. In this area, the Lorenzerbach makes a sharp turn towards E-NE. Here, the Triebensteinkalk and the serpentinite are exposed. It is striking that tributary 5 represents a prolonged E-W striking lineament of the shifting torrent pathway. It would be possible, that the sharp turn of the Lorenzerbach is induced or at least favored by a tectonic element. However, no tectonic features could be identified in field investigations as most parts of this section were obscured by sediments. A similar change in flow direction is visible in the lowermost part of the catchment, shortly before the village of St. Lorenzen.

7.3 Results of the Method Gertsch compared to other studies

According to the hazard zone plan, for the Lorenzerbach, an estimated bedload volume of 25,000 m^3 for an event with a return period of 150 years is assigned. Media sources account the total delivered cubature from 2012 at 15,000 m^3 (Feuerstein 6/10/2013), which differs profoundly from the 6,400 m^3 determined with the bedload estimation procedure. In order to investigate the plausibility of the calculated cubatures, research findings of Janu and Mehlhorn (2013) are used. In their studies, the amount of bedload deriving from torrent- and slope processes was calculated by comparing the ALS dataset of 2011 with a laserscan dataset that was created directly after the event of 2012 (Figure 7-4).

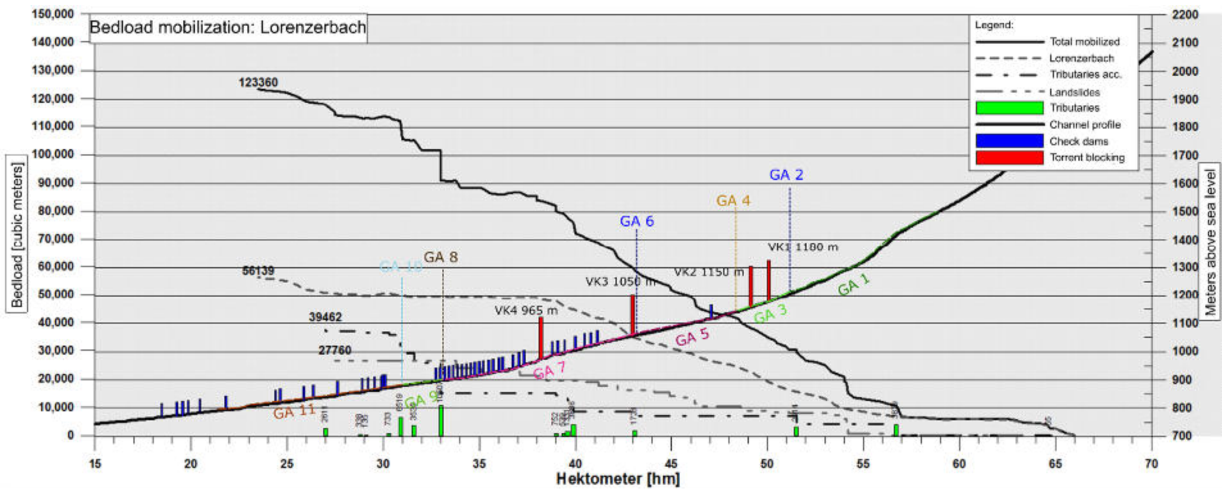

Figure 7-4: Bedload cubature model modified after Janu und Mehlhorn (2013) in respect of the defined torrent segments (GA 1 to 11) in the course of the application of the bedload estimation procedure after Gertsch, 2009.

By comparing this diagram with the cubature that derived from the bedload estimation procedure after Gertsch (Table 7-1) it is evident that the calculated amount of bedload for torrent segments 2, 6, 8 and 10 (which represent tributaries) match well with the findings from Janu and Mehlhorn (2013) with a maximum, but acceptable, deviation of ~30%. Thereby, cubatures were mostly underestimated with the method of Gertsch. Torrent segment 4 was not considered in the study of Janu and Mehlhorn (2013), which indicates that its activity might not have been significant enough to appear in the above-mentioned study. However, in the course of the event-documentation, Hübl et al. (2012) determined that this segment was significantly influenced by fluvial erosion. Following the method of Gertsch, a bedload volume of 1,936 m^3 was determined for this segment.

Table 7-1: Comparison of the bedload cubatures from the bedload estimation procedure after Gertsch with the results from DEM-subtraction after Janu & Mehlhorn (2013).

Torrent Segment (bedload estimation procedure after Gertsch) [m³]	**Bedload balance in the torrent segment [m³]**	**Total bedload after the torrent segment (method after Gertsch [m³])**	**Cubature after Janu and Mehlhorn (2013) [m³]**
Torrent segment 1 (Lorenzerbach)	5,557	5,557	~16,000
Torrent segment 2	2,188	2,188	2,914
Torrent segment 3 (Lorenzerbach)	2,697	10,442	~25,000
Torrent segment 4	1,936	1,936	*no data*
Torrent segment 5 (Lorenzerbach)	7,216	19,594	~35,000
Torrent segment 6	1,256	1,256	1,728
Torrent segment 7 (Lorenzerbach)	27,408	48,258	~50,000
Torrent segment 8	7,386	7,386	10,507
Torrent Segment 9 (Lorenzerbach)	1,398	57,042	~51,000
Torrent segment 10	6,659	6,659	6,519
Torrent segment 11 (Lorenzerbach)	-57,331	6,370	56,139
Total cubature	**-**	**6,367**	**56,139**

Along the upper parts of the Lorenzerbach, significant deviations were identified (torrent segments 1, 3 and 5). After torrent segment 1, a gap of already ~10,500 m^3 is evident. The reason for this gap might be, that the torrent system upstream of torrent segment 1 was neglected in the estimation procedure of the present study. However, the amount of mobilized bedload correlates very well in torrent segments 7 and 9. According to the findings of Janu and Mehlhorn

(2013), 56,139 m^3 of material were restored by the Lorenzerbach, compared to 63,701 m^3 (which is present where torrent segment 10 mounds into torrent segment 11) with the method Gertsch. This indicates that the bedload volumes might get overestimated when the deficit of ~10,500 m^3 after torrent segment 1 is taken into account. However, it has to be considered that the calculated values by Janu and Mehlhorn (2013) correspond to a way longer timespan, and do not only cover the event of July 2012. Given that, it is likely that at least a small proportion of bedload-relocating processes took place before the catastrophic event.

The determined sediment yield rates for most torrent segments were below 5 m^3/m and are typical for segments, where transit is the torrent function. Such yield rates are relatively low and can be expected under stable bed conditions. Because the material supply was determined to be limited, either through a thin sediment cover or check dams, the values seem plausible. This is congruent with the findings from the event documentation: Hübl et al. (2012) indicated, that for most sections (until torrent segment 7) along the Lorenzerbach transit was the driving torrent function. The yield rate of 12 m^3/m in torrent segment 7 derived from torrent blocking, and the subsequent breaching of the dam.

The total cubature that struck St. Lorenzen is estimated at ~15,000 m^3 (according to a media article (Feuerstein 6/10/2013)). If this value is plausible, the bedload estimation procedure would have delivered a significantly lower bedload value. This significant difference might derive from the deposition factor of 0.9, that was determined for torrent segment 11 by the model, yielding the deposition of 57,331 m^3. Gertsch (2009) states, that the bedload estimation procedure might fail if longer torrent segments with inclinations of <10 % are defined. As torrent segment 11 possesses an average inclination of 8.5 % over a length of 1082 m, this deposition factor might be too high.

If this influence remains unconsidered, the estimation procedure shows a good correlation compared to studies of Janu and Mehlhorn (2013) and the findings from the event documentation. This indicates that the Swiss-developed method is applicable to catchments of the Austrian Alps in cases where long torrent segments with a low gradient are absent.

8 Conclusions

The mountain torrent system in the catchment of the Lorenzerbach is an outstanding example of the complexity of the interactions between geologic factors, slope/torrent processes, and properties. Studies showed that by comparing orthophotos from two epochs, coupled with ALS-data evaluation and field studies, provide a sound approach in order to determine the most critical processes when it comes to the debris flow potential. Still, several questions remain. Slope processes triggered due to weathering processes and most likely also hydrogeologic impacts would also have to be investigated at a more detailed level to also identify dormant landslides and their possible impact on the debris flow potential in the study area. The question arises, whether such in-depth investigations (by trying to understand each element of the catchment e.g. geology, hydrogeology, hydrology, pedology, and botany) are economical for daily engineering practice. In the case of St. Lorenzen, several retaining structures were built after the catastrophe of 2012, most likely providing enough accommodation space for future debris flow or flood events, though probably not all above-mentioned elements could be considered. This is aggravated by the fact that processes can only be identified with a high degree of certainty if they already left footprints in the field. The studies presented in this thesis were conducted after a catastrophic event. Consequently, it is an even harder task to determine relevant processes prior to an event.

Gertsch (2009) developed a process-based approach which tries to estimate the bedload volume based on the contemplation of various system elements and their effects on the whole system. The estimation procedure can be applied by only using GIS-Data, or with a field-supplemented approach. In the framework of this study, the field supplemented method was chosen to quantify the delivered bedload for the 2012 debris flow event. Based on findings from the event documentation and field studies, an adequate scenario was assigned regarding the torrent- and slope processes. The obtained results for most sections correlate well with results from other studies and literature values. This indicates that a sound estimation is possible with this approach, even though the tested catchment is rather untypical compared to steep Swiss mountain torrents, where the method was developed. In the next step, the results could be compared to other estimation methods and be applied in steeper torrent systems. Perceptions made out of further investigations could be used to refine the empirical relations. Statistics from orthophoto evaluation could thereby contribute valuable data.

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Appendix

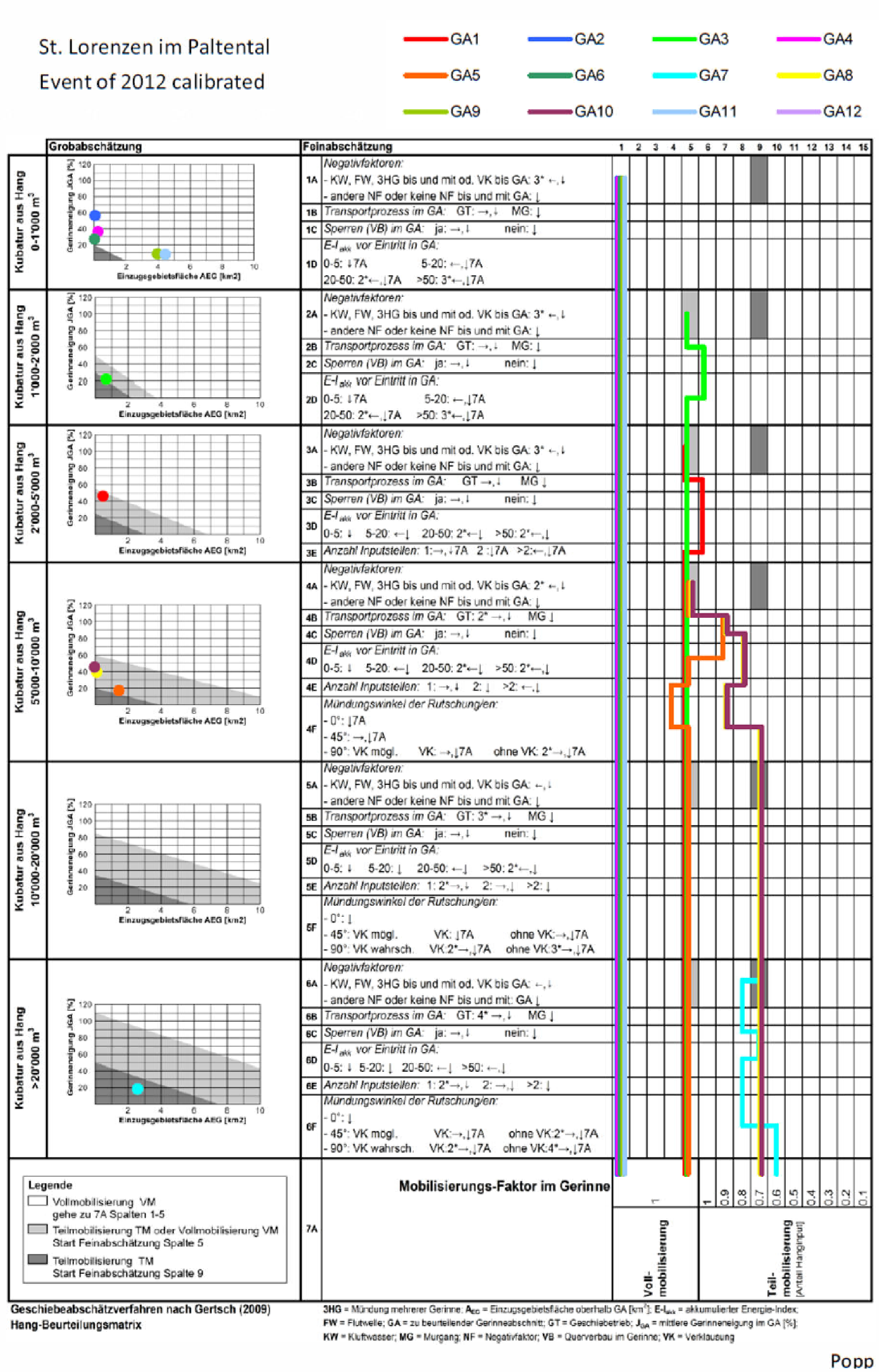
The excel sheets that derived through the application of the estimation procedure are appended. It comprises a results-sheet, the slope- and the torrent evaluation matrix.

Geschiebeabschätzung Grossereignis nach Gertsch (2009)

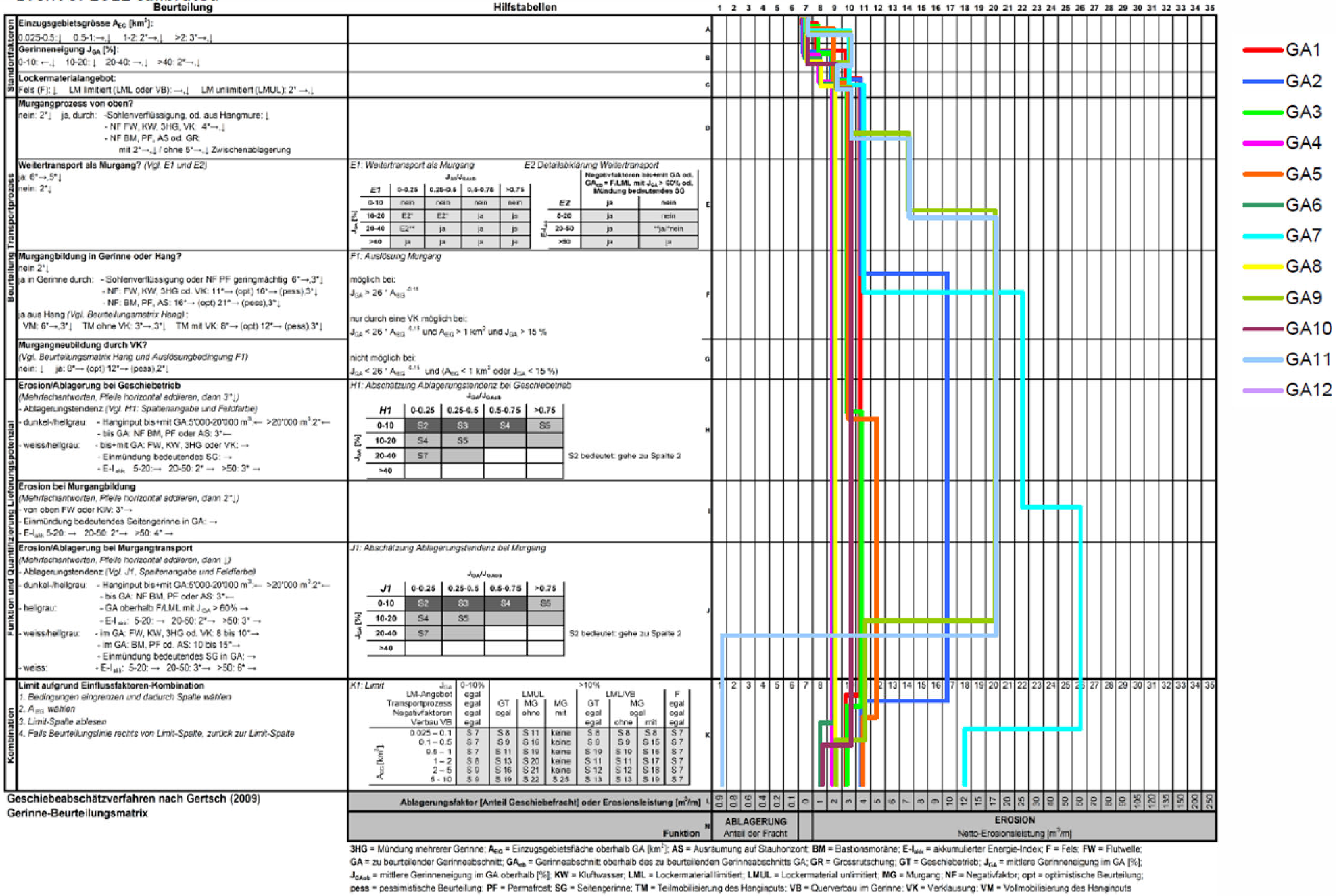
Bach, Gemeinde: St. Lorenzen im Paltental
Szenario: Event of 2012 calibrated
Bearbeiter/in, Datum: Popp

Gerinneabschnitt	Horizontale Gerinnelänge [m]	Einzugsgebietsfläche oberhalb AEG [km²]	mittlere Gerinneneigung JGA [%]	Lockermaterialangebot	JGA/JGAob	Akkumulierter Energie-Index E-Iakk	Geschiebelieferung aus dem Hang [m³]	mobilisierter Hanginput im Gerinne [m³]	Transportprozess im Gerinne	Funktion des Gerinneabschnitts	Ablagerungsfaktor	abgelagerte Kubatur [m³]	Erosionsleistung [m³/m]	erodierte Kubatur [m³]	Geschiebebilanz im Gerinneabschnitt [m³]	aufsummierte Geschiebefracht nach diesem Gerinneabschnitt [m³]
1	519	0,51	45,6	limitiert nat.	1,00	0,0	4000	4000	GT	Erosion			3	1557	5557	5557
2	422	0,03	57,3	unlimitiert	1,00	0,0	500	500	MG	Erosion			4	1688	2188	2188
3	399	0,70	23,5	limitiert nat.	0,46	19,5	1500	1500	GT	Erosion			3	1197	2697	10442
4	468	0,22	37,5	limitiert nat.	1,00	0,0	1000	1000	GT	Erosion			2	936	1936	1936
5	429	1,47	16,0	limitiert nat.	0,52	40,7	5500	5500	GT	Erosion			4	1716	7216	19594
6	756	0,00	28,1	limitiert nat.	1,00	0,0	500	500	GT	Erosion			1	756	1256	1256
7	1034	2,58	15,9	limitiert, Verbau	0,72	62,5	25000	15000	MG	Erosion			12	12408	27408	48258
8	543	0,14	37,8	limitiert, Verbau	1,00	0,0	9000	6300	GT	Erosion			2	1086	7386	7386
9	199	3,85	9,3	limitiert, Verbau	0,35	91,4	1000	1000	MG	Erosion			2	398	1398	57042
10	359	0,00	44,2	limitiert, Verbau	1,00	0,0	9000	6300	GT	Erosion			1	359	6659	6659
11	1044	4,35	8,8	limitiert, Verbau	0,33	105,8	1000	1000	MG	Ablagerung	0,9	57330,9			-57331	6370
12																

Geschiebefracht am Kegelhals [m³]: **6.400**


St. Lorenzen im Paltental
Event of 2012 calibrated
GA1 GA2 GA3 GA4 GA5 GA6 GA7 GA8 GA9 GA10 GA11 GA12
Grobabschätzung
Feinabschätzung
Kubatur aus Hang 0-1'000 m³
Kubatur aus Hang 1'000-2'000 m³
Kubatur aus Hang 2'000-5'000 m³
Kubatur aus Hang 5'000-10'000 m³
Kubatur aus Hang 10'000-20'000 m³
Kubatur aus Hang >20'000 m³
Gerinneneigung JGA [%]
Einzugsgebietsfläche AEG [km2]
Negativfaktoren:
Transportprozess im GA
Sperren (VB) im GA
Anzahl Inputstellen
Mündungswinkel der Rutschung/en
Mobilisierungs-Faktor im Gerinne
Voll-mobilisierung
Teil-mobilisierung [Anteil Hanginput]
Legende
Vollmobilisierung VM gehe zu 7A Spalten 1-5
Teilmobilisierung TM oder Vollmobilisierung VM Start Feinabschätzung Spalte 5
Teilmobilisierung TM Start Feinabschätzung Spalte 9
Geschiebeabschätzverfahren nach Gertsch (2009)
Hang-Beurteilungsmatrix
3HG = Mündung mehrerer Gerinne; AEG = Einzugsgebietsfläche oberhalb GA [km²]; E-Iakk = akkumulierter Energie-Index;
FW = Flutwelle; GA = zu beurteilender Gerinneabschnitt; GT = Geschiebetrieb; JGA = mittlere Gerinneneigung im GA [%];
KW = Kluftwasser; MG = Murgang; NF = Negativfaktor; VB = Querverbau im Gerinne; VK = Verklausung

Event of 2012 calibrated



Geschiebeabschätzverfahren nach Gertsch (2009)
Gerinne-Beurteilungsmatrix