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Influential factors on the occurrence and characteristics of debris flow events in alpine regions: case studies from two geologically different regions in Styria

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Sandra Traper BSc

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Zusammenfassung

Die vorliegende Diplomarbeit beschäftigt sich mit Murgangsereignissen in zwei alpinen Einzugsgebieten mit unterschiedlicher Lithologie in der Steiermark. Einflussfaktoren sowohl auf die Auftretenswahrscheinlichkeit einer Mure in einem Gerinne als auch jene Einflussparameter, welche die Wahrscheinlichkeit der Konnektivität einer Mure mit dem Hauptgerinne bestimmen, werden anhand von Daten des Kleinsölktales im Naturpark Sölktäler und des Johnsbachtales im Nationalpark Gesäuse untersucht. Beide Gebiete sind durch immer wieder auftretende Murgänge, welche auch das Gerinne erreichen (Konnektivität) und zu Aufstauungen und Überflutungen mit beträchtlichem Schaden führen können, gekennzeichnet, wie das Starkregenereignis 2010 im Kleinsölktal gezeigt hat. Eine Kombination von Literaturrecherche und auf Digitalen Höhenmodellen basierenden GIS-Analysen sowie statistischen Auswertungen mit Hilfe logistischer Regressionsfunktionen werden angewandt. Einzelne Einzugsgebiete werden mit ArcGIS ausgewiesen und auf Basis dieser Raumeinheiten wird der Einfluss von Faktoren aus dem Bereich der Topographie, der Landnutzung und –bedeckung sowie der Lithologie analysiert. Die Resultate der logistischen Regressionsmodelle erzielen gute Erklärungswerte basierend auf diesen Einflussvariablen; im Kleinsölktal können 83.3% aller Fälle hinsichtlich dem Auftreten von Muren richtig zugeordnet werden, im Johnsbachtal 95.8%. Konnektivität von Muren kann mit den Modellen bei 74.3% der Fälle richtig vorausgesagt werden. Variablen aller Faktorenbereiche (Topographie, Landnutzung/-bedeckung, Lithologie) üben in verschiedener Stärke und Richtung Einfluss auf die Wahrscheinlichkeiten aus. Während im Kleinsölktal vor allem topographische Faktoren (Einzugsgebietsgröße sowie Ausrichtung und Neigung der Region) und Parameter der Landbedeckung und Lithologie Einfluss auf die Entstehung von Muren haben, dominiert im Johnsbach der Einfluss der Lithologie und Landbedeckung. Die Konnektivität von Murgängen wird durch ein Zusammenspielen von Einzugsgebietsgröße, Faktoren der Landbedeckung und Aspekte der Gerinnetopographie erklärt. Mit Hilfe der errechneten Wahrscheinlichkeiten können gefährdete Einzugsgebiete in beiden Regionen ausgewiesen werden.

Abstract

The present thesis deals with the occurrence and characteristics of debris flow events in two alpine catchments in Styria, which are characterized by different geological settings. Factors that influence the occurrence as well as the connectivity of debris flows, potentially clogging up rivers and flooding valleys, are investigated on the basis of data from the Kleinsölk valley, located in the natural preserve Sölktäler, and the Johnsbach valley, located in the natural park Gesäuse. Both areas are prone to debris flow events and have experienced debris flows in the recent history. Particularly one event involving heavy precipitation triggered numerous debris flows in the Kleinsölk valley in 2010 and traces can still be identified in the scenery. Influential factors regarding the occurrence and characteristics of debris flows are analyzed by a combination of literature review and empirical analyses, mainly statistical analyses focusing on logistic regression models. After delineating drainage basins in both study areas using GIS-software, factors of influence regarding area and channel topography, land use/cover and lithology are examined. The results of the logistic regression models reveal high numbers of correctly assigned cases with 83.3% correctly assigned cases regarding the occurrence of debris flows in the Kleinsölk valley and 95.8% in the Johnsbach valley. Models investigating the connectivity of debris flows are able to assign 74.3% of all cases correctly in both areas. Variables from all categories (topography, land use/cover, lithology) influence the occurrence and connectivity of debris flows in different intensities and directions according to these results. While the occurrence of debris flows in the Kleinsölk valley is mostly attributed to factors of topography (area size, aspect and slope of the area) as well as variables regarding land use/cover and lithology, the Johnsbach valley exhibits a dominant influence of factors of land use/cover and lithology. Connectivity of debris flows is influenced by factors regarding land use/cover and aspects of channel as well as area topography in both regions. Based on these results, catchment areas that are prone to experience debris flows and connectivity can be identified in both regions.

Table of contents

List of abbreviations

DEM	Digital Elevation Model
GIS	Geoinformation Software
SPSS	Statistical Package for the Social Sciences
DF	Debris flow
CONN	Connectivity
W	Watershed

List of figures

List of tables

1. Introduction

In recent times natural processes like debris flows or landslides have been the focus of increasing attention worldwide due to several cases of events that have caused severe harm and loss of infrastructure in affected areas. Because of the damage involved in such events, it seems that particularly mitigation and prevention measures of debris flows and landslides are at the core of debates on the topics. Several aspects linked to global change have led to changes in frequency and magnitude of such events and further changes, which affect the occurrence of natural hazards, are predicted (e.g. STOFFEL et al. 2014; CANNON & DEGRAFF 2009). Aspects of global change lead to an increase of several forms of natural processes and because of settlement and use of areas that were not settled in the past, more and more people are directly affected by landslides or debris flow events nowadays (see WINTER et al. 2008). Especially debris flows can cause great damage and loss of infrastructure or even human lives in different parts of the world. However, not only areas far away are affected by those kinds of natural events, but especially alpine and mountainous regions like many parts of Austria are prone to the often harmful consequences. Each year Austrian media cover several types of natural disasters and a quick online search for landslides and debris flow events already reveals the relevance of the topic by a multiplicity of results available.

In the recent history, one event in particular received great attention in the media and among experts because of the intensity and damage of the occurrence. In July 2010, one heavy rainfall event led to numerous debris flows in the region of the Kleinsölk valley in Styria. Since several debris flows connected to the river in the valley, flooding of the area and neighboring villages followed as a consequence. However, this is not the only severe example and several other events have caused similar damage in other parts of Austria. As debris flow events often involve substantial damage, research on these types of natural processes that can turn into natural disasters frequently focuses on mitigation and recovery measures after an event. However, an investigation of a landslide and debris flow prone area before and after such events can help to raise awareness of and discover important preparatory factors that can contribute to the occurrence and characteristics of a landslide in the first place. The importance of "the identification and the quantitative assessment of the factors leading to the initiation, propagation and deposition of debris-flows" is also mentioned by CARRARA et al. (2008: 353f.), highlighting the necessity of investigating particularly influential factors of those phenomena in alpine regions.

The susceptibility of alpine regions to natural processes that can pose a hazard has been a topic for humans since the beginnings of settlement in those areas about 7,000 years ago. While many organizations have been established in order to deal with and take care of the impacts of natural events and their dangers in the meantime, the processes can still be dangerous. Due to aspects of climate change and changes of land use practices people are facing different situations today and risk assessment in alpine regions has to be adapted. (see MANNSBERGER 2009: 12)

Based on these introductory considerations, the main research question that guides this thesis can be expressed as follows:

Which factors influence the development and characteristics of debris flows?

In other words, which combinations of preparatory factors in an area play a decisive role in triggering a debris flow as well as in promoting the connectivity of a flow with the valley bottom, potentially clogging a river with debris. The main focus on influential factors in these considerations is especially relevant since there are numerous aspects of landscape conditions, land use practices, geological as well as topographic conditions involved in calculating the probability of the occurrence as well as the connectivity of debris flow events. However, it often seems to be difficult to determine which factors are more important or more decisive in preparing, triggering and maintaining the movement of a debris flow than others.

The answer to this question, which guides the whole thesis, should be achieved by a theoretical as well as a practical approach to the topic. Two different regions are investigated with regard to these issues, namely the Kleinsölk valley and the Johnsbach valley, both located in Styria, Austria. Those two areas that have been chosen are suitable for such an investigation based on their increased susceptibility to debris flows in general and debris flow events in the last years, which can be detected on aerial photographs. Moreover, the different geological settings of both regions contributed to their selection.

The overall and rather broad main research question can be subdivided in several sub-questions, focusing on detailed aspects regarding influential factors. This thesis furthermore deals with and attempts to answer the following problems with regard to the main research question:

- (1*) In how far can the methods proposed in the thesis be relevant and help to bring new insights into this field of research?*
- (2) *Which debris flows showed signs of connectivity and managed to reach the channel system of both valleys, which did not and why?*
- (3) *What differences concerning debris flows can be observed in the two geologically different regions regarding influential factors?*

The present thesis will approach the topic and provide answers to those questions with a combination of a theoretical review of literature and an empirical study conducted in the two study areas in Styria by following these steps:

Subsequent to this introduction to the topic and presentation of the research question and aims, the second chapter will provide theoretical background knowledge as a basis for the next chapters. The phenomena of debris flows, their classification among other forms of mass movements as well as the concept of connectivity with regard to debris flows and channel systems and important characteristics of Alpine catchments will be presented.

The third chapter will introduce the two study areas in Styria in more detail. On the one hand the Kleinsölk valley in the natural preserve Sölktäler and on the other hand the Johnsbach valley in the natural park Gesäuse will be characterized according to their geographical characteristics, the geological setting, land use and land cover forms as well as significant debris flow events in the past.

The fourth chapter focuses on a description of the approach that was adopted in the empirical part of the thesis as well as the methods applied. After a presentation of the data sets used in the investigations, the different steps in preparing and analyzing the data as well as methods that are applied are characterized in detail, followed by a description and illustration of the processing of data with GIS-based analyses as well as statistical analyses.

Chapter five presents the results from the DEM-based GIS-analyses and those obtained by computing logistic regression models, while chapter six discusses those results and their implications regarding the research question. Throughout the discussion of data results, inferences will be drawn to the theoretical concepts that have been introduced in chapter two of this thesis. The thesis ends by providing concluding statements and referring back to the research question and aims of this thesis.

2. Theoretical Background

In order to provide theoretical background knowledge and findings from research that provide the basis for the empirical analysis later in this thesis, important concepts and terms will be introduced and explained in the following sections. Two important phenomena that are at the center of investigations in this paper are debris flows as a form of mass movement and type of natural process that can lead to destructive effects in mountain areas on the one hand, and the concept of sediment connectivity regarding debris flow movement on the other hand. Therefore, a characterization of those concepts will be provided, followed by an overview of important characteristics of Alpine catchment areas.

2.1. Debris flows

Debris flows as a type of natural process in Alpine regions are at the center of this study and, therefore, will be introduced first. The following sub-sections will provide an overview of the most important characteristics of this type of mass movement and deal with triggering and preparatory factors that contribute to initiating debris flows as well as with areas that are most susceptible to this phenomenon. Other related types of processes (e.g. fluvial transport, hyperconcentrated flow) that have also played a role in generating the debris flow inventory for the analyses will also be presented shortly. In the course of the paper, however, only the term debris flow will be further used to describe the mass movements in the study areas, even though several similar phenomena are included.

2.1.1. Definitions and characteristics

A first approach to descriptions of the phenomenon of debris flows in literature on natural processes and hazards as well the investigation of studies that deal with debris flows already reveals the complicated task of defining the term. It appears that drawing boundaries between several similar phenomena in these categories is not that simple. CARRARA et al. (2008: 354), in their study on debris flows in Alpine environments, introduce one of the difficulties of working on debris flows in the numerous different conceptions of the term:

> [T]he term 'debris-flow' is commonly used to indicate a wide spectrum of slope-instability phenomena that may significantly differ in mechanical properties of the material (fine particles vs. rock boulders, etc.), geomorphological setting of the process (open slope, channel, etc.) and hydrological conditions (high or low water content, etc.).

By applying the term debris flow to different similar phenomena located in a rather broad spectrum, drawing clear boundaries proves difficult and researchers often define the concept with different foci in mind as well as with a diverse depth of detail.

However, despite differences regarding certain characteristics of debris flows as well as usages of the term, scholars agree that debris flows are commonly considered as a type of mass movement or a form of mass wasting. LORENZINI & MAZZA (2014: 1) are among those who start their definition of debris flows from a definition of the general concept of mass movement. They identify the position of debris flows as "a cross between mass-wasting and solid-transport processes in streams" (LORENZINI & MAZZA 2014: 1).

A more detailed classification of debris flows in this spectrum of events is necessary since LORENZINI & MAZZA (2004: 4) include "[e]ach perceivable fall movement in a set of materials, however variable" in the concept of mass wasting. In other words, "the detachment and fall of considerably sized rocky masses due to prevalent gravitational force, especially along considerably steep versants, thus causing an accumulation of the same material downhill" describes different forms of mass movements according to their research (LORENZINI & MAZZA 2004: 4). Looking at this definition reveals that several diverse processes can be classified in the category of mass wasting, with overlapping characteristics of the various types in the spectrum (LORENZINI & MAZZA 2004: 4).

Therefore, several authors (e.g., TAKAHASHI 1981; LORENZINI & MAZZA 2004) have attempted to draw boundaries between the different processes involved in mass wasting and classify distinctive forms of mass movements according to fixed criteria. LORENZINI & MAZZA (2004: 9) base their classification of forms of mass movements on "characteristics of material, the type of movement and velocity" (see Fig. 1).

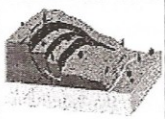
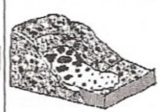
		VELOCITY		
MATERIAL	NATURE OF MOVEMENT	SLOW	MODERATE	FAST
CONSOLIDATED	FLOW			Rock avalanche
	SLIDE		 Rockslide	 Rock fall
UNCONSOLIDATED	FLOW	 Creep	Earthflow/ Mudflow	Debris avalanche
		Solifluction	Debris flow	
	SLIDE	 Slump	 Debris slide	

Figure 1 Types of mass movements distinguished on the basis of velocity, material characteristics and nature of movement (Source: LORENZINI & MAZZA 2004: 9)

Figure 1 illustrates the classification of different types of mass movement provided by LORENZINI & MAZZA (2004: 9). Debris flows are categorized as a flow movement with moderate velocity and mostly consisting of unconsolidated material. However, earthflows as well as mudflows are also characterized by similar descriptions, leading to fuzzy boundaries between those concepts.

Another classification of debris flows and a positioning within the broad spectrum of mass movements, or what TAKAHASHI (1981: 57) termed "massive sediment motion[s]", was presented in an early study on debris flows in 1981. TAKAHASHI (1981) was one of the first to engage with debris flows in greater detail. Those motions mentioned in his study include "the falling, sliding, or flowing of conglomerate or the dispersion of sediment, in which all particles as well as the interstitial fluid are moved by gravity [...]" (TAKAHASHI 1981: 58).

The following figure (Fig. 2) illustrates the four types of sediment motions distinguished by TAKAHASHI (1981).

Type of flow	Sediment support mechanism	Interstitial fluid	Velocity	Travel distance	Deposit
Fall, landslide, creep	Fall, jump, roll, slide	Air and water	Free fall~ 2,3 mm/y	~2· fall height	Talus
Sturzstrom	Grain inter-action? Fluidization?	Air (Vacuum)	< 50 m/s	200 m~ 10 km	Sturzstrom deposit
Pyroclastic flow	Fluidization Grain inter-action?	Hot air Volcanic gas (Water)	< 50 m/s	≦ 60 km	Pyroclastic deposit
Debris flow (lahar)	Grain inter-action Matrix strength Buoyancy	Water Clay slurry (Hot water)	20 m/s~ 0.5	200 m~ 10 km	Debris cone

Figure 2 Types of subaerial massive sediment motions (Source: TAKAHASHI 1981: 58)

In the figure above (Fig. 2), debris flows are seen as a type of sediment motion which includes interaction between grain particles as well as water and deposits characteristic debris cones.

In a more recent paper, TAKAHASHI (2007: 6) provides a further sub-classification of debris flows. According to this work, debris flows can be sub-divided into several types. A debris flow therefore either is a "stony-type debris flow", a "turbulent-muddy-type debris flow" or a "viscous debris flow" (TAKAHASHI 2007: 8ff.).

A similar sub-classification of all mass movements that are characterized by a flow-movement is also provided by LORENZINI & MAZZA (2004: 6), who distinguish between "slurry flows" and "granular flows", depending on the amount of water in the process (see Fig. 3).

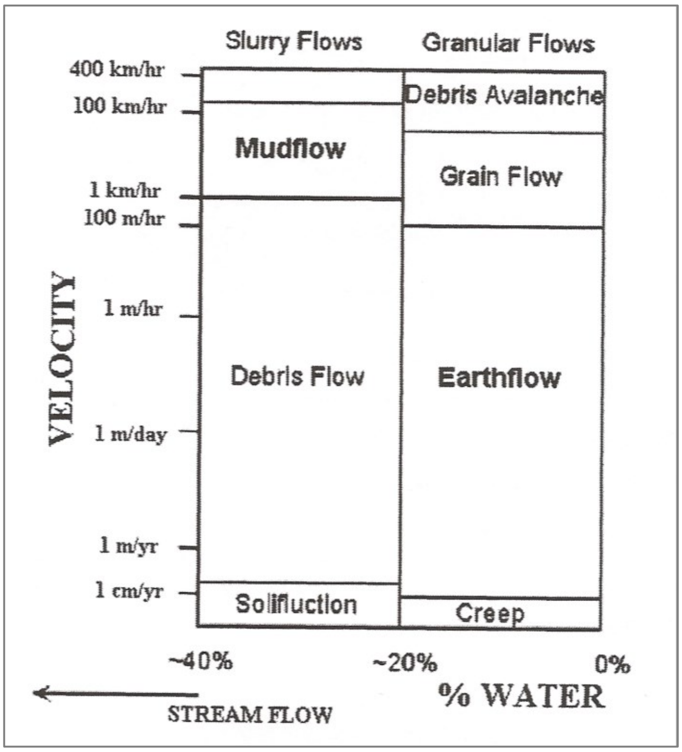


Figure 3 Differentiation of several types of sediment flows (Source: LORENZINI & MAZZA 2004: 7)

In this classification (Fig. 3), debris flows are positioned in the category of "slurry flows" (LORENZINI & MAZZA 2004: 7). Taking the general description of "slurry flows" with the importance of fast saturation into account, debris flows in this category are described as "mixtures of concentrated air-'saturated' or water-'saturated' sediments, which proceed extremely rapidly along slopes under the action of gravity with velocities between 1 m/y[ear] and 100 m/h" (LORENZINI & MAZZA 2004: 6).

Having defined the position of debris flows in the vast spectrum of mass movements and, more detailed, in the category of sediment flows, significant characteristics of this type of mass wasting shall be explained. A description of the features of a debris flow often focuses on the substances and types of material involved in the process. The importance of the existence of different elements in a debris flow, of course including water, is also discussed by HUNGR (2000: 483). He describes the phenomenon of debris flows as being "characterized by highly unsteady, surging flow behavior" which he attributes to the great variety of different "substances" that play a role in a debris flow, namely "water, grain dispersions, mixtures of colloidal and granular particles in water and large solid particles such as boulders and timber" (HUNGR 2000: 483).

LORENZINI & MAZZA also focus on different materials in a debris flow and discuss the existence of various sizes of sediment (2004: 6). This diversity in grain and sediment size seems to be a significant characteristic of the phenomenon that differentiates it from similar occurrences and is also mentioned by IVERSON (2014: 15). Regarding predominant grain sizes IVERSON expands the explanations provided by LORENZINI & MAZZA (2004) and also notes different shapes of sediment, which are responsible for the first part of the term debris flow. The lack of only one "characteristic grain size" makes it difficult to understand "grain-fluid and grain-grain interactions" in debris flows. The second part of the term debris flow is attributed to the motion during a debris flow event, in which "rearrangement of grain contacts is pervasive" (IVERSON 2014: 15).

IVERSON (2014: 15) further estimates highest velocities of debris flows of 10 meter per second. Other researchers have come to similar figures in their estimations of debris flow speeds. For example, TURNBULL et al. (2015: 87), who provide the definition of debris flows as "gravitational mass movements of rock incorporated in a fluid matrix of fine sediments suspended in water" list speeds between 10 ms^{-1} and lengths of 100 to 1000 m. However, they also acknowledge that severe debris flows can even surpass these limits and reach 80 meter per second.

In addition to providing characteristic figures for sizes and speeds, TURNBULL et al. (2015: 87) analyze debris flows with respect to other related phenomena. In order to distinguish this form of mass movement from similar types, they see the function of water in a debris flow as significant on its dynamics.

NETTLETON et al. (2005: 48), in their work on debris flows in Scotland, use another important criterion to describe and classify debris flows, namely the location of the flow on a slope or in a gully, depending on area topography and lithology. The two categories distinguished on this basis are "Hillslope (Open-Slope) Debris Flows" and "Channelised Debris Flows" (see Fig. 4).

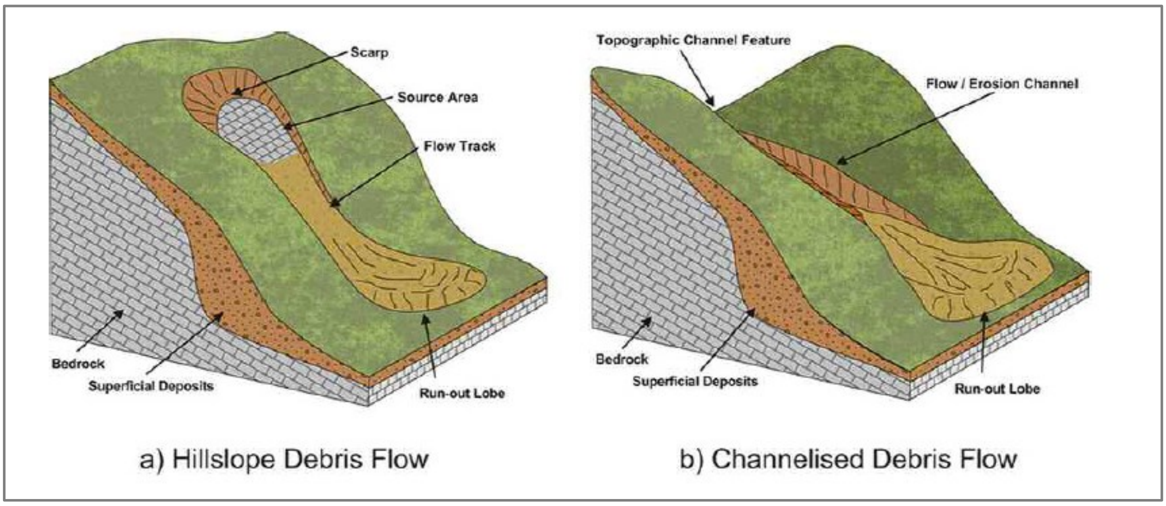


Figure 4 Illustration of the characteristics of two types of debris flows (Source: NETTLETON et al. 2005: 49)

The figure above (Figure 4) illustrates the origination of hillslope debris flows on steep slopes without channels and the initiation of the latter category in already existing gullies, following these paths. However, boundaries between the two categories are not that clear and a debris flow can start as the first category and then reach already existing channels (NETTLETON et al. 2005: 48ff.). LORENTE et al. (2003: 683) also discuss the location of debris flows in channels or on slopes and distinguish "[c]onfined and unconfined debris flows" in this regard.

These differentiations are particularly important with regard to the empirical part of this thesis. In this study, the focus is on debris flows and related phenomena that occurred in already existing gullies and channels in Alpine catchments.

Taking the definitions and classifications provided in this section (by HUNGR 2000; LORENZINI & MAZZA 2004; NETTLETON et al. 2005; IVERSON 2014) into account, leads to the inference that boundaries are drawn differently and different researchers use different terms. The phenomenon of debris flow is not clearly distinguishable from mudflows or earthflows and even forms of fluvial transport or hyperconcentrated flows in gullies show some similar characteristics. This also applies to the study conducted in the course of this paper, where debris flows and similar related phenomena are grouped together and investigated under the heading 'debris flow'.

2.1.2. Debris flows and Alpine environments

In addition to the knowledge about important characteristics of debris flows, an awareness and identification of the most susceptible areas worldwide can help to handle those phenomena. LORENZINI & MAZZA (2004: 41) identify "three types of environments" in which debris flows are most common. According to their research, especially "[s]emiarid areas; Alpine areas [and] Volcanic areas" are prone to debris flow events and their effects. Looking at Alpine regions in more detail reveals the processes of "snow melting, [...] scarce vegetation and a noncontinuous water supply" as leading conditions for debris flow occurrences in those areas (LORENZINI & MAZZA 2004: 42). These findings are important with regard to the empirical part of this thesis as both study areas are located in Alpine environments and therefore suitable for an investigation.

INTERPRAEVENT (2009), a research company that investigates natural disasters in Alpine regions, also discusses the importance of debris flows particularly in Alpine environments. Together with avalanches, rock falls and flooding, debris flow events belong to group of natural processes that are most frequent in those regions and often pose a hazard to human activities (INTERPRAEVENT 2009: 13). Since the beginning of settlement in Alpine regions about 7,000 years ago, humans have to deal with the consequences of taking more and more of these fragile Alpine environments as living spaces and cope with increasing frequency of natural hazards like debris flows (MANNSBERGER 2009: 12).

A detailed examination of debris flows in an alpine environment is provided by CARRARA et al. (2008), who classify those occurrences among "the most dangerous gravity-induced surface processes that cause severe damage to dwellings, roads and other lifelines" (ibd. 2008: 353) in those regions. These considerations make the phenomenon particularly suitable to be studied in alpine regions like the two study areas located in Styria. Another study that has taken place in a mountain region was conducted by LORENTE et al. (2003: 683), who see the suitability of studies on debris flow events in the Pyrenees and alpine regions in "the steep slopes, the high availability of debris in both channels and hillslopes, the presence of metamorphic and Flysch rock outcrops and the relatively frequent occurrence of high intensity rainstorms". All these factors can contribute to frequent debris flow events in those environments and make them suitable for investigations on factors influencing occurrences.

2.1.3. Debris flows and human settlement/humans

Having established that Alpine regions are particularly prone to debris flow events due to several features of landscape conditions, further factors that contribute to the importance of those phenomena in mountains are humans and aspects of their way of living. Several rather fragile parts of alpine environments have been settled in the last decades, leading to an increased vulnerability of habitations (see INTERPRAEVENT 2009). Not only debris flows endanger settlements in those regions but also other forms of mass movements or natural processes, e.g. flooding. However, it seems that some forms of natural processes in alpine regions have attracted more attention than others with regard to the impact on humans and human settlements. These general considerations lead to the question why debris flows in particular seem to be significant and receive considerable attention in studies conducted in alpine and mountainous regions (e.g. LORENTE et al. 2003; CARRARA et al. 2008). The attention that particularly debris flows attract is due to what LORENZINI & MAZZA (2004: 1) see as their status "among the most frequent and destructive of all geomorphic processes". Those forms of mass movement cannot only lead to destruction of natural areas but can also endanger human settlements and construction. Studies on debris flows are significant and highly topical issues in recent times because of what LORENZINI & MAZZA (2004: 1) identify as an "increase in anthropisation of the mountainous areas of a number of countries worldwide". Due to the fact that areas that are prone to debris flow events in the first place (as described in the previous section) are settled nowadays, particularly mitigation measures or methods to identify areas that are especially susceptible is important (LORENZINI & MAZZA 2004: 1-2). Moreover, a tendency of humans to settle below steep slopes in mountainous areas can be recognized, which is seen as an "increase in human penetration over the territory" (LORENZINI & MAZZA 2004: 2).

In order to integrate the factor human into a general assessment of debris flow risk, three aspects mentioned by LORENZINI & MAZZA (2004: 2) have to be considered when it comes to debris flows and their possibility of occurrence in certain areas. Those factors are "the nature of the slope (coherent or noncoherent), the quantity of water in the material, the gradient and instability of the slope" (LORENZINI & MAZZA 2004: 2). Especially the two latter factors seem to be connected with humans' impact on the environment according to their research (ibd. 2004: 2). This makes it interesting to look at the phenomenon with regard to factors that can contribute to making slopes unstable.

2.1.4. Triggering and preparatory factors

Since the empirical part of this paper focuses especially on factors that influence the occurrence as well as characteristics of debris flows, an overview of important factors that either trigger or provide important conditions for a debris flow to occur shall be provided.

LORENZINI & MAZZA (2004: 3) define "[g]ravity [as] [...] the active force responsible for any event linked to mass wasting". As debris flows have been categorized as one type of mass wasting, gravity without doubt plays an important role in triggering debris flows and steep areas provide the ideal precondition for gravity to set off debris material. In addition to the necessary force of gravity, the actual initiation can be triggered by several influences, for example "violent rainfall, earthquakes [...], tectonic activity" or different actions that are linked to human settlements and ways of living (LORENZINI & MAZZA 2004: 4). Substantial amounts of rainfall as a triggering factor for debris flows is particularly interesting with regard to the regions under investigation in this thesis. In one of the two study areas in Styria, the Kleinsölk valley, a severe thunderstorm had led to unusual amounts of rain, which then triggered numerous debris flows on the slopes. The peculiarities of this weather event and its effects will be discussed in more detail at a later stage in this thesis.

TURNBULL et al. (2015: 87) list similar factors that are linked to triggering the initial movement of debris flows and they particularly regard "land instability and heavy rainfall" as the two most common factors. The importance of precipitation in triggering a debris flow is also mentioned by YU et al. (2012: 598), who see rainfall as significant when it comes to debris flow occurrences since it acts as a "trigger condition" as well as "transport media" for debris flows and similar phenomena.

However, not only factors such as heavy precipitation that immediately trigger a debris flow are important to consider when investigating debris flow hazards in a region but also factors that contribute in making an area susceptible to events of mass wasting in the first place. These factors are not particularly triggering factors, but rather provide the preconditions that can then either promote or prevent mass movement events. NETTLETON et al. (2005: 53) therefore divide factors that contribute to the occurrence of a landslide or debris flow into preparatory and triggering factors in their study on debris flow hazards in Scotland. Regarding landslides and debris flows, mostly factors from both categories together are responsible for mass wasting occurrences. Moreover, factors of both categories can act as "internal" as well as "external causes" when it comes to their contribution to such events (NETTLETON et al. 2005: 53). Examples of preparatory factors regarding landslide and debris flow occurrence are, amongst others, high slope angle values of areas, the vegetation pattern of an area, weather conditions and climatic factors (NETTLETON et al. 2005: 55).

MCMILLAN et al. (2005: 30) list similar factors and talk about those aspects under the heading of "Hazard factors". According to their classification, contributing factors can either be "Geological", "Geomorphic", "Geotechnical", "Hydrological", concerned with aspects of "Vegetation" or "Land use" or can be "Meteorological" or "Topographic". More information on influential factors belonging to these categories will be provided in further chapters concerned with the methods used in this thesis (see section 4.2.2.).

It is important to note that most factors discussed as triggering and as preparatory factors for debris flows mostly cause such events collaboratively via mutual influence. According to NETTLETON et al. (2005: 55), climatic factors and aspects of weather, for example, lead to "freezing and thawing processes" in mountainous areas, which "weaken the soil and rock structure" in winter. In summer soils can dry out during days and weeks of dry and hot weather, leading to "large cracks" in the surface (ibd. 2005: 55). Those open spaces can then be filled with water when thunderstorms and heavy rainfall occur. All "[t]hese weathering processes result in weakened soil structures and loss of material strength" and increase the susceptibility of slopes to debris flows (ibd. 2005: 55). The processes involved in weathering of slope rocks described so far, frequently lead to layers of "weak soils overlying harder rocks which provide an interface or potential shear surface" and act as the ideal precondition for "slope failure" (ibd. 2005: 55). Therefore, underlying rock formations, weather conditions, soil properties as well as climatic conditions should not be discussed separately.

The study conducted in course of this thesis will include and focus on several of those factors discussed so far (see section 4.2.2.). Since debris flows rely on substantial amounts of water in the processes of initiation as well as movement, rainfall and large amounts of water are presupposed as contributing factors in the empirical part of this paper. Assuming water as present in the regions, the focus of this study is on factors of lithology, topography and land use and their contribution in making an area susceptible to the occurrence of debris flows if enough rainfall acts as the main triggering factor.

2.2. Hillslope-channel connectivity

Another important scientific concept that is crucial for the empirical part of this thesis is the concept of connectivity. The study does not only investigate the occurrence of debris flows but also the possibility of debris flow material reaching the main channel in a valley and connecting to it, possibly leading to clogging and flooding.

Looking at work by BRACKEN & CROKE (2007: 1749) on connectivity in hydrology reveals that the concept became increasingly important in the last years in its application in the discussion of "runoff generation and flood production". BRIERLEY et al. (2006: 165) also discuss the increased importance of "notions of connectivity", with several possible combinations of interactions regarding humans and landscapes. While the term connectivity has been classified into several sub-categories in previous studies (e.g. BRACKEN & CROKE 2007), mostly the usage of "sediment connectivity" is present in current studies (e.g. BRACKEN et al. 2015).

Starting with a general definition of the term, BRACKEN et al. (2015: 177) explain sediment connectivity the following way:

> Sediment connectivity is the connected transfer of sediment from a source to a sink in a system via sediment detachment and sediment transport, controlled by how the sediment moves between all geomorphic zones in a landscape.

According to Bracken et al. (2015: 177), these descriptions of sediment connectivity include motions "on hillslopes, between hillslopes and channels and within channels".

This first approach to the concept of sediment connectivity and the regions involved in connecting sediment already reveals the importance of this concept for the investigation of one part of the research question (characteristics/connectivity of debris flows) that guides this paper. In the course of this thesis particularly debris flows as transport medium of sediment and debris material between hillslopes (or gullies on hillslopes) and channels and rivers on valley floors are examined. BRIERLEY et al. (2006: 166) further describe the connections of "slope-channel and channel-floodplain", which is investigated in the two areas in Styria in this thesis, as "[*l*]*ateral* linkages".

Factors that influence sediment connectivity include "the interplay of structural components (morphology) and process components (flow of energy/transport vectors and materials" (BRACKEN et al. 2015: 178). One important factor for sediment connectivity to occur "is a source of readily entrainable sediment" (ibd. 2015: 178). If this precondition is met, the further transportation of the material available is influenced by "the spatial configuration of connections between sediment source areas, the energy of key sediment-transport vectors and the relationship to morphology" (ibd. 2015: 178).

Applying these findings on the investigation in the empirical part of this paper leads to numerous significant factors that can influence the connectivity of a debris flow to the main river in the valley. Factors that are included and analyzed regarding the influence on connectivity in those two study areas are topographic factors with regard to the area as well as the channel in a drainage basin, and factors of current land use/cover and the effects of those patterns.

CAVALLI et al. (2013: 31) particularly examine connectivity processes in alpine catchments and define connectivity of sediment as "the degree of linkage which controls sediment fluxes throughout landscape, and, in particular, between sediment sources and downstream areas". These processes are particularly relevant in Alpine regions and headwaters due to the "complex and rugged morphology, and heterogeneity in type, extent and location of sediment sources" which leads to massive irregularities of processes involved in the transport of sediments. HECKMANN & SCHWANGHART (2013) also examine an alpine catchment with regard to sediment connectivity. In their study conducted in Austria, debris flows resulted as significant processes with regard to sediment connectivity between hillslopes and channels. The debris flows investigated either managed to reach the valley floor and connected to the river or "only redistribute[d] sediment on the talus" (HECKMANN & SCHWANGHART 2013: 91). Both types of debris flows (connected and not connected) are also present in the two study areas in Styria that are investigated in this thesis and the factors that influence the connectivity of those phenomena will be discussed in the empirical part of the paper.

2.3. Alpine catchments

As the empirical study in this paper is conducted on the basis of drainage areas or watershed areas in both study regions (Kleinsölk valley and Johnsbach valley), a definition and short characterization of watersheds will be provided.

Following Pidwirny's (2006) notes on the drainage basin concept, a drainage basin can be defined as "the topographic region from which a stream receives **runoff**, **throughflow**, and **groundwater flow**". The following figure (Fig. 5) shows the "nested nature" (Pidwirny 2006) of such basins, in which all basins marked in red belong to the two bigger basins marked in yellow. A similar classification of watershed areas with a subdivision of bigger drainage basins into several smaller ones has also been essential in the empirical part of this thesis (see section 4.2.1).

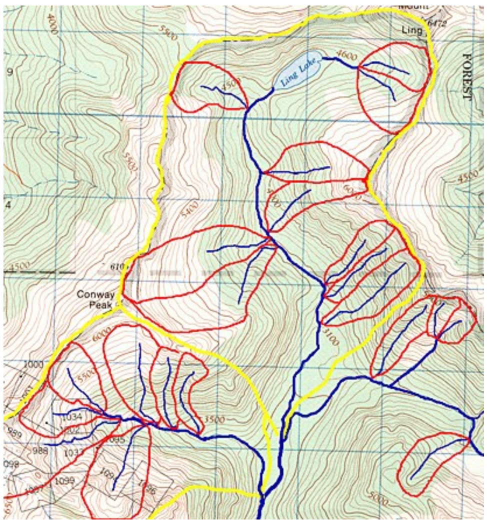


Figure 5 Classification of drainage basins (Pidwirny 2006)

An important characteristic of drainage basins is that they are "open systems" (Pidwirny 2006). According to Pidwirny (2006), rain water as well as water from melting snow and sediments are input factors. On the other hand, water and sediments leave the system by processes such as "**evaporation**, **deposition**, and streamflow" (ibd. 2006). Various variables and factors, for example "topography, soil type, bedrock type, climate, and vegetation cover" influence the ways in which water and sediments come into the system, leave it as well as their transportation within it (ibd. 2006). These features of drainage basins are particularly important for the research question in this thesis as water and sediments provide the sources as well act as the transport medium for debris flows.

In addition to the openness of such systems, the form of drainage basins is a further characteristic feature. According to STRAHLER & STRAHLER (2005: 463), watersheds are "more-or-less pear-shaped" and together they form a "**drainage system**".

Catchment areas or watersheds are important for the occurrence of a debris flow in the channel of such an area since the whole area that belongs to one watershed provides the source of water and sediments, which are both important factors and elements involved in debris flow processes. On the hand water, sediment and debris are significant in triggering a debris flow (part one of the research question – occurrence of a debris flow), on the other hand those factors influence the motion of a debris flow. By influencing as well as ending movement, connectivity (part two of the research question - characteristics of a debris flow) is determined.

3. Study areas

Having established the basis for the following analyses by providing definitions and theoretical background knowledge of important terms and concepts, the next sections of this thesis focus on the two study areas in Styria.

The two regions under investigation, which are both prone to debris flow events, were chosen because of their different geological settings and recent debris flows that are observable in aerial photos. Both study areas are located in the district of Liezen in Styria (see Fig. 6). One area is part of the natural preserve Sölktäler, namely the Kleinsölk valley (marked in red), the other one belongs to the national park Gesäuse, the Johnsbach valley, named after the river flowing through the valley (marked in blue). In the following, the two areas are described according to their geographical characteristics, mainly focusing on the predominant climatic conditions, landscapes, geology, the hydrological setting, land cover and land use practices as well as on important and interesting debris flow events in the areas.

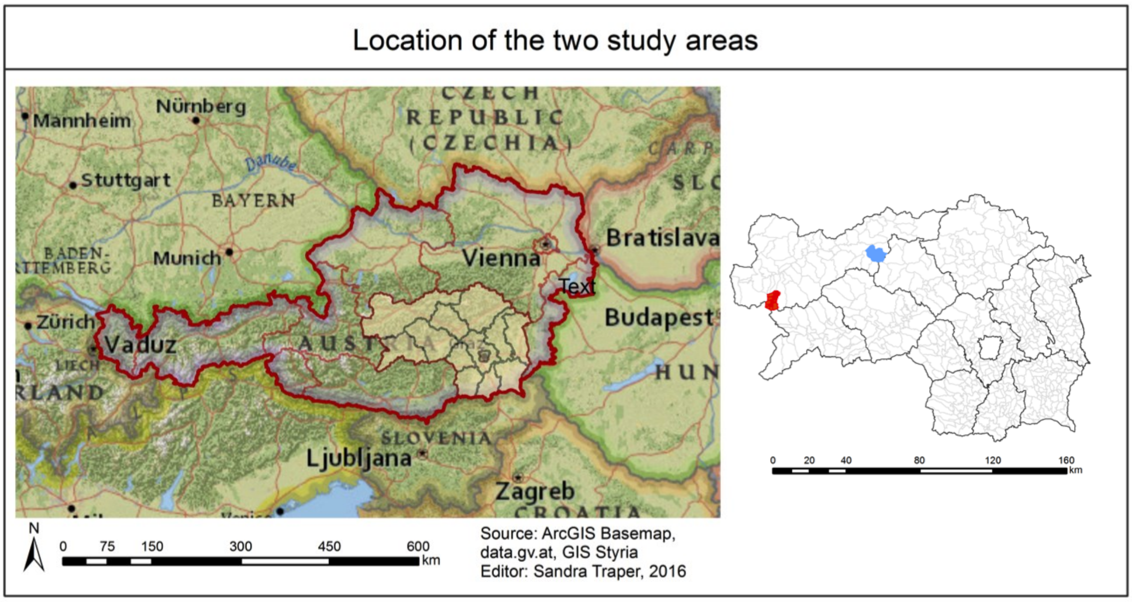


Figure 6 Location of the two study areas in Styria

3.1. Kleinsölk valley

After having located the two study areas in Styria in the district of Liezen, the following sections focus on the Kleinsölk valley (marked in red in Fig. 6) and serve as an introduction to the characteristics of the area in order to illustrate its suitability for the empirical part of this thesis.

3.1.1. Geographical overview

The Kleinsölk valley is part of the natural preserve Sölktäler, located in the eastern part of Styria, and forms a tributary valley of the bigger Enns valley. The following map (Fig. 7) provides an overview of the natural preserve and its valleys. The part of the natural preserve that is of greatest interest with regard to this paper is marked in blue (Kleinsölk valley and Schwarzenseebach valley). The other valley in this map is the Großsölk valley.

Figure 7 Overview of the natural preserve Sölktäler (Source: NATURPARK SÖLKTÄLER n.d.)

The Organization of Natural Preserves in Austria provides the following figures regarding characteristic numbers of the whole Sölktäler area: The region covers an area of 27,700 ha, with altitudes ranging from 660 m at the valley floors of the Enns to 2,747 m at the Hochwildstelle, the highest peak in the area (VNÖ. n.d.).

The most important aspect regarding the hydrological setting of the area is the river Enns, which is the biggest stream in the northwestern part of Styria with a length of 254 km from its river head in Salzburg in a tributary valley of the Flachau valley to the part of Upper Austria where it flows into the Donau. The catchment area of the river is the fifth largest drainage basin in Austria and covers an area of 6,080 km^2. The average rate of discharge is estimated with 201 m^3/s at the city of Ennsortskai in Upper Austria. (see ENNSTALWIKI 2014a)

The empirical part of the paper focuses on one particular part of the Kleinsölk valley, namely the Schwarzenseebach valley, which is located southwest of the village Kleinsölk and has a length of around 7.5 km. It is also referred to as Kleinsölker Obertal. The main river in this part of the valley is the Schwarzenseebach with its spring in the Schwarzensee (see ENNSTALWIKI 2014b). However, despite a primary focus on this particular part of the Kleinsölk valley, in the remainder of this thesis the term Kleinsölk valley will be used for referring to sub-parts of the valley.

As can be observed in most Alpine valleys, the present appearance and landscape conditions in the valleys belonging to the natural preserve Sölktäler are connected to past conditions, particularly to glacial stages. BOHNER et al. (2013: 72), who investigated the Sölktäler with regard to diverse effects of mudflows on the region, have drawn connections to the glaciation in times of the Pleistocene as point of origin regarding the characteristic look of the valleys nowadays. Back then, the whole area was buried under an ice cover, leading to the "U-shaped valleys with steep slopes" that are now typical features of the landscape (ibd. 2013: 72). Particularly those valley configurations contribute to making the area susceptible to debris flow events (ibd. 2013: 72).

The climatic conditions are mainly "sub-oceanic", in which "the mean annual precipitation exceeds 1,100 mm and the mean annual air temperature is approximately 5.8 °C, varying from -2.6 °C in January to 14.6 °C in July" (BOHNER et al. 2013: 72). For investigations of debris flows and other forms of mass movements especially the summer months are important to analyze with regard to weather conditions. These months are characterized by days of heavy precipitation and thunderstorms (ibd. 2013: 72). The peak of thunderstorm events can be located in July, with 6.64 days with weather conditions that included thunderstorms on average (ZAMG 2002). Taking a closer look on the rainfall situations in the summer months reveals monthly sums of precipitation of 107.5 mm in May, 156.3 mm in June, 160.8 mm in July and 143.5 mm in August. These months also experience the highest number of days with precipitation above 10 mm in general (May: 13, June: 17, July: 15.8, August: 14.2). (ZAMG 2002)

The point in time under investigation regarding the occurrence and characteristics of debris flows in the Kleinsölk valley in this study focuses on one important weather event that had led to numerous debris flows in the area. Therefore, this particular day and time will be characterized regarding weather conditions in more detail. The rainfall event under discussion that had led to the abundance of debris flow events in the study area happened in July 2010. The intense rainfall within several hours, "300 mm in 2 hours" according to BOHNER et al. (2013: 72), triggered several debris flows in the region. While no people were harmed during the event, "substantial damage to roads and bridges" resulted from the event (ibd. 2013: 72).

3.1.2. Geology

In addition to the general geographical characteristics as well as hydrological setting and climatic conditions, an understanding of the dominant rock formations in the region is important for an analysis of the spatial distribution of debris flows. As can be seen in Figure 8, a map provided in an information brochure about the park by VEREIN NATURPARK SÖLKTÄLER. (n.d.), the natural preserve Sölktäler is located in the crystalline mountains of the Niedere Tauern. The region is mostly composed of gneissic rocks and schist, with areas covered in debris and moraine material and colluvium on the valley floors.

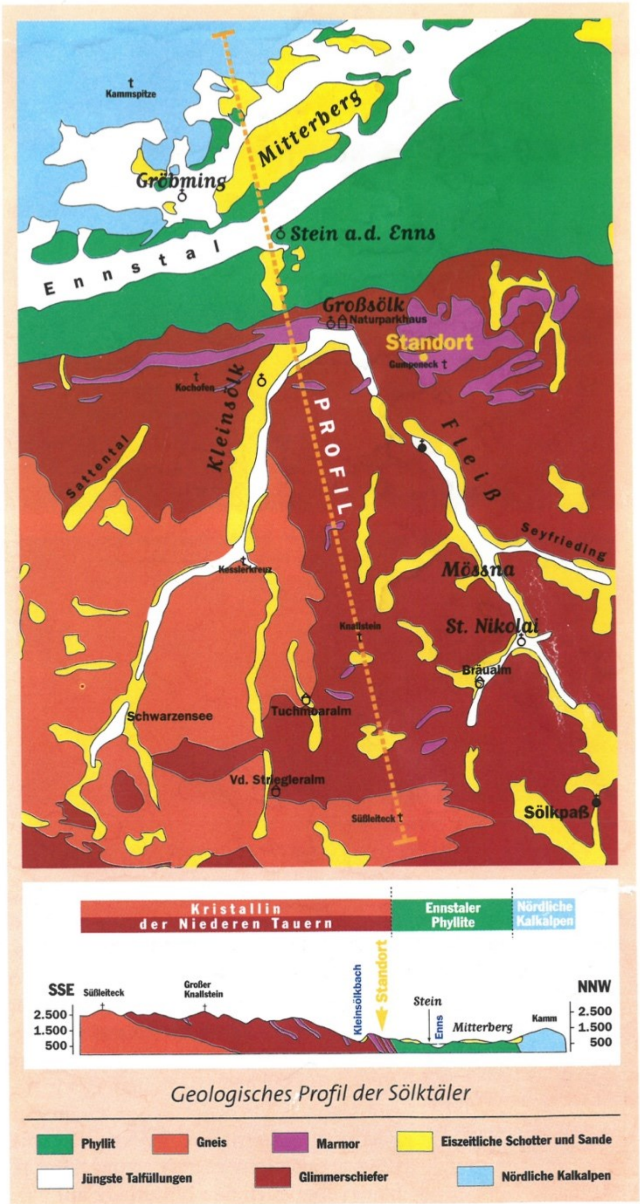


Figure 8 Lithological map of the natural preserve Sölktäler (Source: VEREIN NATURPARK SÖLKTÄLER n.d.)

BOHNER et al. (2013: 72) provide similar descriptions of the lithological setting of the area and see different forms of gneissic rocks and sediments that have their origin in glacial eras as significant. The Geological Map of Austria 1 : 1,500,000 by the GEOLOGICAL SURVEY OF AUSTRIA (2000) illustrates a domination of paragneiss, orthogneiss and mica-schist in the natural preserve Sölktäler.

The connections of those rock formations and debris flows as well as a more detailed description of several lithological classes will be provided in the empirical part of the thesis.

3.1.3. Land use/ land cover

Dominant forms of land use and current land cover can act as further influential factors when it comes to debris flow events and forms of mass movements and will therefore be described shortly. The area of the natural preserve Sölktäler has been settled for a long period of time and those settlements entailed a change in several forms of land use over the last hundreds of years. SCHERBICHLER'S (2002: 22ff.) comparison of different forms of land use over time, beginning with the first records in the Josephinian land register in 1787 until 2001, shows a reduction of agricultural lands and an increase of forested areas as well as a still persistent importance of mountain pastures in the Sölktäler. Detailed descriptions of the locations and characteristics of mountain pastures in the Sölktäler can be found in LOSERIES-LEICK (2002a), detailed information on the development and change of forest areas and forestry in the last hundreds of years are discussed in LOSERIES-LEICK (2002b). The importance of vast mountain pastures and forest areas in the region is also mentioned by SCHOBER (2006: 25) in his dissertation on the morphological processes in alpine catchments, focusing on parts of the Sölktäler. Further important landscape characteristics include mountain lakes and extensively farmed meadows (ibd. 2006: 25). Similar to SCHOBER'S reference to mountain lakes, the Organization of Natural Preserves in Austria (VNÖ n.d.) regards water as the most important element in the area with regard to land use/cover and landscape conditions. According to their further descriptions of the region, high mountain peaks as well as lakes, mountain pastures, forests and meadows dominate the landscape. Regarding forests, spruce is the dominant tree type in the area; in higher altitudes spruces are complemented with larches and Swiss stone pines. Meadows and mountain pastures are located at different altitudes and villages are not only restricted to flat areas either. Concerning land use, agriculture and forestry are the dominant forms of land use in the area. (VNÖ n.d.)

3.1.4. Debris flow events

As the study conducted in the course of this thesis focuses on past debris flow events in both study areas, an overview of the significance of debris flows and traces of past occurrences will be discussed. Regarding debris flow events within the boundaries of the natural preserve Sölktäler, especially one year is still remembered actively because of its severity and the amount of individual debris flows that occurred within a short time span. In 2010, one heavy rainfall event led to numerous debris flows in the Kleinsölk valley, more precisely in the

Schwarzenseebach valley. Those occurrences are at the focus of the investigation in the empirical part of the paper.

The event that will be investigated in the following happened on July 17th 2010. Between 6.30 pm and 12 pm a severe thunderstorm brought heavy precipitation that in the course of the following hours triggered numerous debris and mud flows due to the fact that the heavy rain released debris from the slopes. The area most affected of the event was the region around the Breitlahnalm. Furthermore, since several debris flows reached the valley floor and dammed up the river, waves and flooding of the village of Stein an der Enns followed. The damage of the event was estimated to reach 10 million euros. (see ENNSTALWIKI 2016)

Even five years after that event the impacts of this thunderstorm and debris flows that were triggered in the course of the day are still visible in the landscape. Traces of the events of 2010 can be identified on the following photographs, taken in fall 2015 (Fig. 9 a&b). The channels and gullies, in which debris flows occurred, are still visible and the valley floor, which was flooded due to debris flows connecting to the river, still shows signs of that flooding and dead trees are dominant in the landscape.

Figure 9 Traces of past debris flow events in the Kleinsölk valley (Photos: TRAPER 2015): a) channel and debris cone of past debris flows in the center; b) dead trees on the valley floor due to flooding caused by the severe debris flow event in 2010

In order to inform the population about the happenings in July 2015, several presentation boards have been installed alongside the road in the Kleinsölk valley (see Fig.10 a&b). The severity of the event has led to a detailed discussion of the dangers and effects of those forms of natural disasters.

Figure 10 Presentation boards in the Kleinsölk valley (Photos: TRAPER 2015): a) & b) Information on the debris flows and their effects in 2010 are provided along the road in the Kleinsölk valley

3.2. Johnsbach valley

The second study area in Styria that provided the data for the empirical part of this thesis is the Johnsbach valley in the national park Gesäuse. The following lines serve to introduce this region with a focus on the same characteristics as in the Kleinsölk valley (geographical information, geological setting, land use/cover and past debris flow events).

3.2.1. Geographical overview

The Johnsbach valley is part of the national park Gesäuse in the northern part of Styria. The following map (Fig. 11) by KFU GRAZ (2016) illustrates the shape of the valley, the catchment area of the river as well as the national park boundaries.

The catchment of the Johnsbach covers an area of 65 km². On average the valley's altitudes range between 600-700 m in the valley sections and more than 2.300 m on the highest peaks. Regarding climatic parameters, an average temperature of 8°C in the valley and 0°C on the mountain peaks is observed; the average precipitation sum ranges between 1.500 and 1.800 mm. (see KFU GRAZ 2016)

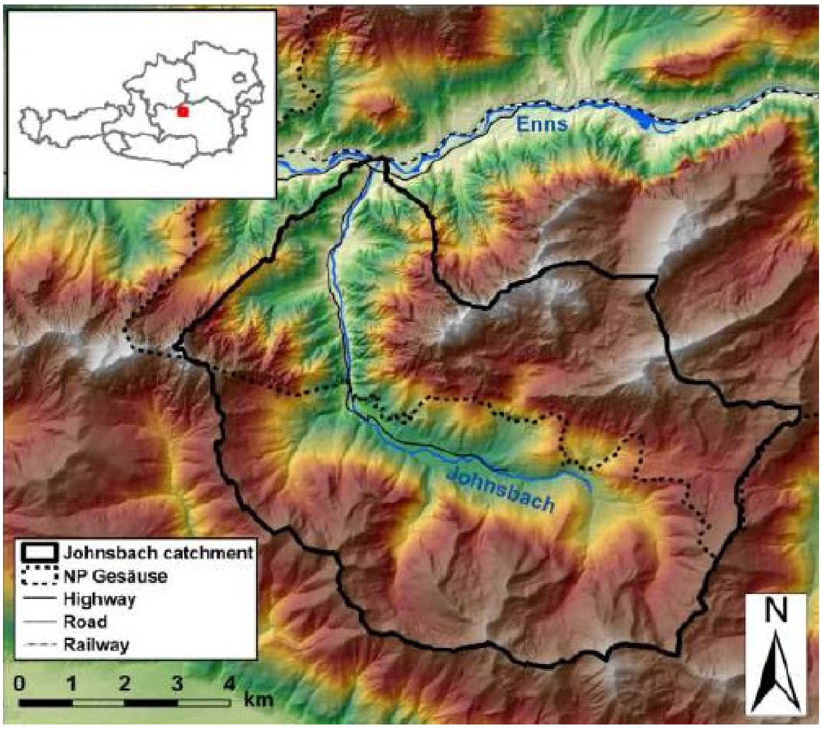


Figure 11 Catchment area of the Johnsbach and boundaries of the national park Gesäuse (Source: KFU GRAZ 2016)

The river flowing through the valley and providing the name for the region (Johnsbach) is a feeder of the Enns river. Figures regarding the hydrology of the Enns river have been provided in section 3.1.1. of this thesis. The Johnsbach has a length of 13.5 km in total (SCHMIED 2008: 4). In the preface to a publication on the Johnsbach by the national park Gesäuse, SCHMIED (2008: 4) analyzes the general characteristics of the river, which are interesting to note with regard to mass movements. He explains that the flow direction of the river is divided into two main parts, illustrated in the map in figure 11. The first part of the Johnsbach flows from west to east in a valley that separates the limestone rocks of the Hochtor-Reichensteingruppe and the greywacke zone. However, after the village Johnsbach a sudden change of the flow direction can be observed and the river flows from south to north and passes areas of different types of limestone (Dachstein limestone, Wetterstein limestone and dolomites) until it reaches the Enns river. Particularly this second part of the river is characterized by frequent gullies in the landscape and traces of past debris flow events (SCHMIED 2008: 4).

This dichotomy of the area around the Johnsbach does not only involve the flow direction of the river but also appearances of several other aspects are divided in two distinct parts. LIEB & PREMM (2008: 12f.) regard the first part (coming from the Enns river) as characterized by rocky slopes that form a narrow valley, in contrast to the upper area of the valley, which is composed of vast areas with numerous meadows and pastures.

The nearest weather station that provides climatic data for the Johnsbach valley is located in Admont at an elevation of 646 m. Measured at this location, the mean annual temperature shows an average of 6.6°C, with highest temperatures from May to August (between 11.7°C and 16.3°C). The mean monthly precipitation sum is highest between May and August (114.0mm to 198.3mm) with an annual sum of 1,399.9 mm. Similar to the conditions in the Kleinsölk valley, May, June, July record the most days with thunderstorms. (see ZAMG 2002)

3.2.2. Geology

While most factors considered so far have been identified as being rather similar in both study areas (landscape conditions, climate, glacial landforms), the geological setting and dominant rock formations show important differences in both regions. In contrast to study area 1, which is mostly comprised of crystalline rock formations, the Johnsbach valley is largely composed of different forms of limestone. BÜCHNER (1970: 3), in his dissertation on the geology of the mountains in the Gesäuse, classifies the Gesäuse as belonging to the part of the Northern Limestone Alps that is located in Styria. Regarding the morphology of the area and coming back to the already discussed dichotomy in this region, BÜCHNER (1970: 3) identified a contrast between steep rock faces and high mountains, which are built of limestone and dolomite, and the more gentle, forested hillsides composed of clastic rocks. While BÜCHNER (1970) focuses primarily on the northern and southwestern parts of the Gesäuse, the southern part shows a different setting. The upper Johnsbach valley already belongs to the greywacke zone with different dominant rock formations.

This dichotomy in geological aspects is also mentioned by KFU Graz (2016), who divide the valley in two parts, namely parts that belong to the Northern Limestone Alps with Dachstein limestone and dolomite as the dominant rocks and other parts that are part of the greywacke zone with mainly porphyr and schist. The following map (Fig. 12) by LIEB & PREMM (2008: 13) illustrates the lithological conditions in study area 2.

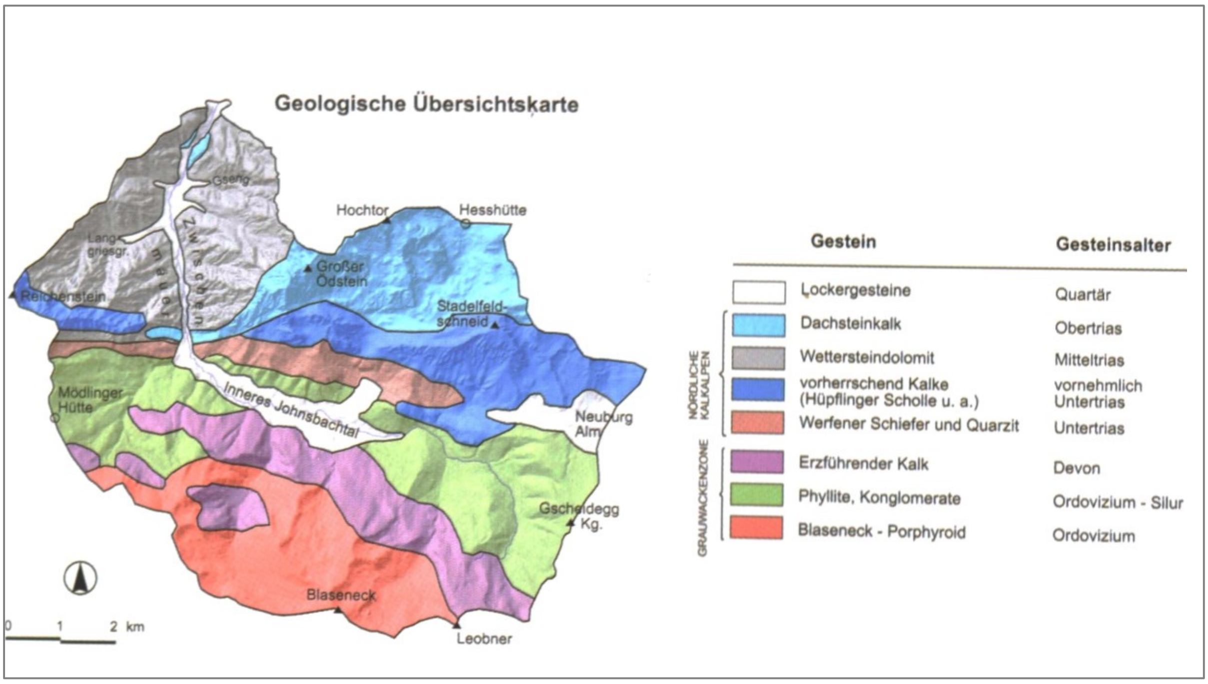


Figure 12 Lithological map of the Johnsbach valley (Source: LIEB & PREMM 2008: 13)

A further important characteristic of the valley is its high diversity in several aspects. KFU GRAZ (2016) lists the geological setting as one aspect of the valley that shows high diversity in its characteristics, together with aspects of geomorphology, hydrology and meteorological data amongst others.

3.2.3. Land use/ land cover

Similar to the predominant land use forms in the Kleinsölk valley, the Johnsbach valley in the national park Gesäuse is mainly characterized by different forms of agriculture and forestry (KFU GRAZ 2016). Looking at the composition of different forms of land use and land cover in more detail reveals a dominance of forested areas. About half of the national park area is covered in forest. While spruces have dominated most forest areas in the national park in order to support the production and processing of wood in the past, today more mixed forests composed of spruce, fir, and beech trees are planned (NATIONALPARK GESÄUSE GMBH. n.d.*a*). In contrast to study area 1, which is dominated by forest and grassland areas, study area 2 also includes vast areas covered in rock/debris. More information on the distribution of several land cover classes will be presented in the empirical part of this thesis.

3.2.4. Debris flow events

While in the Kleinsölk valley one particular debris flow event (July 2010) provides the data for the empirical part of the paper, no such severe event has happened in the Johnsbach valley in recent years. However, the area is also prone to debris flows and those natural processes are common in the area, especially on the slopes in the north/south-oriented part of the valley, which is characterized by steep slopes and an abundance of rock/debris material. Due to the existence of gullies in the mountain slopes as well as the presence of debris material, debris flows are common forms of natural hazards in the valley (SCHMIED 2008: 4). A further characteristic of the area that promotes debris flows is the rather fast weathering of limestone, particularly the dolomitic stones in the area. This leads to plenty of available debris material that can be transported on the slopes and in the gullies after heavy precipitation (NATIONALPARK GESÄUSE GMBH. n.d.*b*).

In contrast to study area 1, in which the investigation of debris flows in aerial photography is based on one particular event, the general situation regarding debris flows was used as the basis for analysis in the Johnsbach valley. One point in time (the year 2010) was picked and the situation observable at that time, based on traces of debris flows in the landscape, was investigated.

An exploration of the area in October 2015 highlighted the significance of debris flows and similar events in that area. Similar to the appearances of slopes and valley floors in the Kleinsölk valley, several channels and gullies in the landscape, which have experienced debris and mud flows in the last years, could be detected (see Fig. 13 a&b).

Figure 13 Traces of debris flow events in the Johnsbach valley (Photos: TRAPER 2015): a) & b) debris inside channels on slopes in the northern part of the valley - signs of recent events

4. Methods

In order to answer the research question proposed in the introduction to this thesis, a combination of methods, which has been also used in several studies investigating similar situations in different study areas, has been chosen. The main contents of this approach include DEM-based GIS-analyses and statistical analyses using logistic regression in order to investigate significant influential factors for debris flows occurrences and characteristics.

This approach of combining GIS-analyses and logistic regression as a type of multivariate statistical analysis has been followed inter alia by RUPERT et al. (2008), who predicted the occurrence of debris flows in areas that were recently burnt in California in a similar manner, RAMANI et al. (2011), who looked at landslides in India, or ANGILLIERI (2013), who investigated debris flows in the Andes with a combination of GIS-analyses and statistical work. Further studies that followed similar approaches in the course of their investigations will be presented in the following chapters when discussing the election of influential factors on debris flow occurrences and characteristics.

The investigation of factors influencing the occurrence and characteristics of debris flows in this thesis is primarily based on knowledge about past events in the regions. Several researchers assume and propose that mass movements as debris flows and landslides mostly happen in similar settings and under similar circumstances, which makes an examination based on past debris flow occurrences a reasonable approach (e.g. CARRARA et al. 2008: 354; ELKADIRI et al. 2014: 4821; TURNBULL et al. 2015: 87). Therefore, the analysis of debris flows in this study is based on assumptions that have inter alia been expressed by REGMI et al. (2014: 249). REGMI et al. (2014: 249) stated that results are based on the notion that those forms of mass movements will happen under similar conditions and settings like past events and that the results from these investigations are only applicable if certain conditions which were used to obtain influential factors in the course of the analyses (e.g. current land use/cover setting) do not change dramatically.

Regarding the main steps involved in this approach, RUPERT et al. (2008: 2f.) provide a rather detailed and clear explanation of steps in their analysis. They identify three main moves involved in the DEM-based GIS-analyses as well as statistical analyses. First, catchment areas in their study were delineated with the help of GIS-software and then categorized into watersheds that experienced debris flows after wildfires and those that did not. RUPERT et al. (2008) then computed values regarding independent variables for each catchment area and calculated several logistic regressions. Several different models with different combinations of independent variables were computed in order to find the most suitable one (ibd. 2008: 3).

Following a similar approach, DEM-based GIS-analyses have been conducted using ArcGIS 10.0 in the course of my analyses; statistical analyses have been computed with the help of IBM SPSS Statistics 23. The analyses were either performed using already compiled data, which were analyzed, evaluated and prepared, or data had to be collected and mapped. The types of data sets used as well as the steps involved in preparing and analyzing initial data will be described in the following section.

4.1. Data

Before presenting the sources and processes of acquiring the data sets for my investigations, remarks on the acquisition of data for research questions related to natural processes in general shall introduce the topic.

Acquisition of data for research questions in natural sciences can entail possible difficulties and particularly remote areas are not easy to monitor. INTERPRAEVENT (2009: 23ff.) discusses the problems and challenges involved in obtaining usable data in the Alps regarding processes like mass movements. The challenges of acquiring data is linked to the conditions of the environment under discussion. Problems are often related to weather conditions since particularly events that happen at a small scale cannot be measured with the same accuracy as larger events. Furthermore, while measurements along valley floors are easier to conduct, higher areas are not that easy to monitor. (see INTERPRAEVENT 2009: 23)

A further important aspect is that, especially when it comes to natural processes, measurement of events in great detail always involves uncertainties. Otherwise, one would have to know in advance when something is about to happen to monitor all phases of an event (INTERPRAEVENT 2009: 24). These difficulties in measuring and collecting data of debris flows and similar phenomena lead to the importance of another data source, namely "traces in nature" or "silent witnesses". Those witnesses can help in interpreting events afterwards. When it comes to debris flows, for example, characteristic deposits can help to reconstruct an event and determine characteristic parts of the flow based on those debris deposits. The debris flow inventory in this thesis has also been built on the basis of the identification of traces of past events in aerial photos. Past debris flow occurrences as well as their characteristics and significant sub-parts were identified and categorized based on an interpretation of aerial images.

The following table (Table 1) provides an overview of the data sets used in course of the following analyses.

Table 1 Data sets used in the analyses

Data set	*Content*	*Year*	*Format*	*Resolution*	*Source*	*Description*
Kleinsölk valley						
Dem_1m	Digital Elevation Model	2011	Raster	1m	Provincial Government of Styria	
Dem_10m	Digital Elevation Model	2007	Raster	10m	Department of Geography and Regional Research Vienna (IfGR)	
Aerial_photos	Aerial images	2008/13	Raster	1m	Department of Geography and Regional Research Vienna (IfGR)	
Land_cover/use	Map of land cover/land use classes of the area	2015	Vector		Mapped by Pablo Rigual based on aerial photography (2011) and interpretation	5 land use/land cover classes
Lithology	Map of lithological classes	2016	Vector		Mapped by Traper & Stender based on data by GIS Styria	14 geological classes

Continuation Table 1

Johnsbach valley						
Dem_1m	Digital Elevation Model	2010	Raster	1m	Provincial Government of Styria	
Dem_10m	Digital Elevation Model	2004	Raster	10m	National Park Gesäuse	
Aerial_photos	Aerial images	2010	Raster	1m	Provincial Government of Styria	
Land_cover/use	Map of land cover/land use classes of the area	2016	Vector		Based on Habitalp, mapped and adapted by Stender	5 land use/land cover classes
Lithology	Map of lithological classes	2016	Vector		Mapped by Traper & Stender based on data by GIS Styria	19 geological classes

One of the most significant data sets were the Digital Elevation Models (DEMs) of both study areas. A Digital Elevation Model is often used for research questions and analyses regarding the relief of an area (ZEPP 2014: 290). Digital Elevation Models are types of raster data sets in which cells store information on altitudes. Depending on the resolution of the data set, different forms of accuracy can be achieved (ibd. 2014: 290). MCMILLAN et al. (2005: 42) also made use of Digital Elevation Models in their study on landslide hazards in Scotland and define those data sets the following way:

> Digital elevation models (DEMs) are models of the Earth's surface that can be used within a GIS environment to identify and quantify many aspects of topography such as slope angle and slope height, which can be incorporated into an assessment of potential slope instability.

This description explains the significance of those models for research questions similar to the one guiding this thesis. The Digital Elevation Models used in course of my analyses had a resolution of 1 m, which means that the points that determine the altitude of the cells have a distance of 1 m. Those 1m-models were used for the delineation of watersheds as well as for the extraction of topographic factors. The 10m-models of both study areas were used as a base layer for generating maps and visualizing data due to their larger area coverage.

In addition to the DEMs, other important data sets in this study were the aerial photos of both regions. These images with a resolution of 1 m were used for the generation of a debris flow inventory by analyzing traces of past debris flow events. Both data sets have been obtained from the Provincial Government of Styria. The images of the Kleinsölk valley have been produced in the time span between 2008-2013, the ones of the Johnsbach valley visualize the situation in 2010. Those images are significant for this study since they served as the basis for generating the necessary debris flow inventories.

The data sets regarding the land use/land cover classes and the lithological setting of both study areas will be discussed in more detail separately in the following sections.

4.2. GIS-Analyses

After having introduced the general approach to answering the research question as well as the data sets, the next sections of this thesis will focus on the steps involved in the DEM-based GIS-analyses. As also done by RUPERT et al. (2008), RAMANI et al. (2011), ELKADIRI et al. (2008), ANGILLIERI (2013) and CHEN et al. (2014) when preparing their data for similar research questions, data was modified and organized with the help of a GIS-software, in my case with ArcGIS 10.0.

The 1m-Digital Elevation Models of both study areas served as basis for all GIS-analyses. By computing digital relief analyses automatic delineations of watershed areas as well as calculations of values regarding slope, aspect and curvature of cells and areas is possible, which is important regarding problems and questions in connection with mass movements (ZEPP 2014: 290f.).

4.2.1. Watershed delineation

In order to prepare the data for investigations and to obtain watershed areas as basic areas for further analyses, the 'Hydrology Tools' in the 'Spatial Analyst' section of ArcGIS 10.0. were used. The first step involved the use of the 'Fill-function' so that possible errors or missing data in the raster data set could be removed. This function "[f]ills sinks in a surface raster to remove small imperfections in the data" (ESRI 2012a). The importance of using this tool before analyzing data on a hydrological level and starting a watershed delineation is explained with the description that "[i]f the sinks are not filled, a derived drainage network may be discontinuous" (ESRI 2012b). For both study areas the Digital Elevation Models of 2010 with a resolution of 1 m were used at this step.

After getting rid of and repairing possible faulty pixels in the data set with the 'Fill function', the 'Flow direction' of the raster data set was computed. The operating mode of this function can be summarized as "[c]reat[ing] a raster of flow direction from each cell to its steepest downslope neighbor" (ESRI 2012c). In order to use the watershed tool and delineate individual watersheds in the research areas, the 'Flow accumulation' function had to be used next, which "[c]reates a raster of accumulated flow into each cell" (ESRI 2012d). The raster data sets for both areas obtained by following this step had to be reclassified. By grouping values into one of two classes ('1' or 'NoData'), the raster data sets were prepared for the next move in delineating watersheds, which involved setting pour points. The threshold between those two classes had to be set manually. In both study areas the mean of the available values was used as a boundary. In order to obtain catchment areas in a region based on the steps done so far, in a next move pour points had to be placed at points where one channel flows into another channel. This step was not carried out automatically, but points had to be set manually by the user in order to indicate the endpoints of channels.

The last step in delineating catchment areas by using the 'Hydrology Tools' in ArcGIS was accomplished with the help of the 'Watershed' Tool. This function "[d]etermines the contributing area above a set of cells in a raster" (ESRI 2012e) and the tool used the already computed flow direction raster together with the snap pour point raster to delineate the various individual catchment areas of a region. The following figure (Fig. 14) shall provide an overview of the processes and steps involved in the delineation of watersheds. The first column visualizes the steps involved in the preparation of watershed areas that have been described so far.

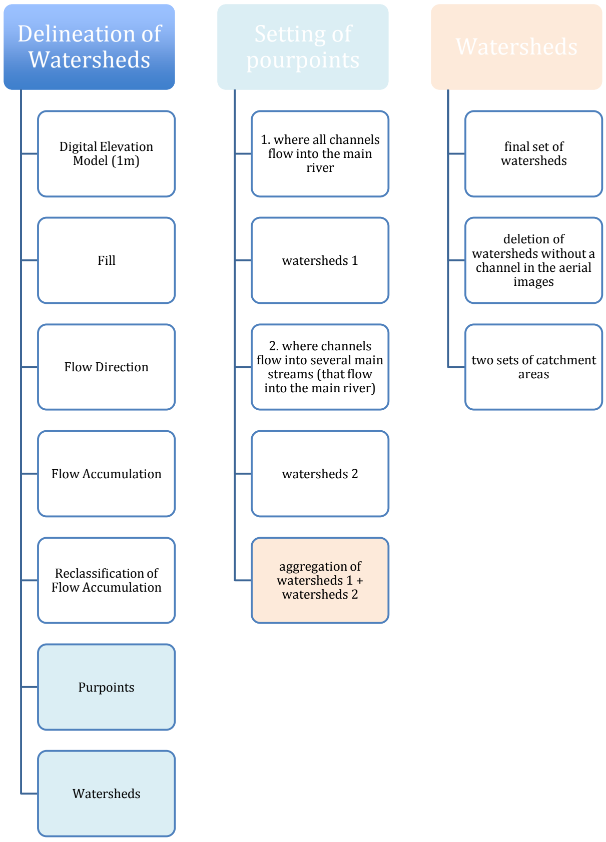


Figure 14 The process of delineating watershed areas using ArcGIS

In order to include all possible catchment areas in which debris flows had occurred according to the aerial images, the following steps were performed in two separate moves (illustrated in the second column in the flowchart in Fig. 14). First, all channels and streams that flow and discharge into the main river in the valley were considered. Looking at the first research area, the Kleinsölk valley, this step included all streams and channels that flow into the Schwarzenseebach. In the second study area in the Gesäuse all channels flowing into the Johnsbach were included at that stage. The catchment areas obtained were then investigated with regard to their area sizes. In order receive comparable and meaningful samples in both data sets, bigger watersheds, in which several debris flows had happened in smaller channels, were further subdivided by setting pour points at the estuaries of smaller channels into the bigger channel. Otherwise, some catchment areas would have been fairly small in comparison to these rather big areas. By differentiating those bigger areas into smaller ones, average area sizes could be approximated.

Taking these considerations into account, 4 drainage basins that were obtained by setting pour points at the estuaries into the Schwarzenseebach were further subdivided in the Kleinsölk valley; in the Johnsbach valley in 5 of the watersheds obtained in the first step further pour points were placed. However, in order to not lose important data from the bigger watersheds, which also showed remnants of significant debris flows and signs of connectivity, all catchment areas were included in the following analyses.

The steps described so far led to the following distribution of catchment areas. Figure 15 illustrates all catchment areas obtained by using the 'Hydrology Tools' in the Johnsbach valley.

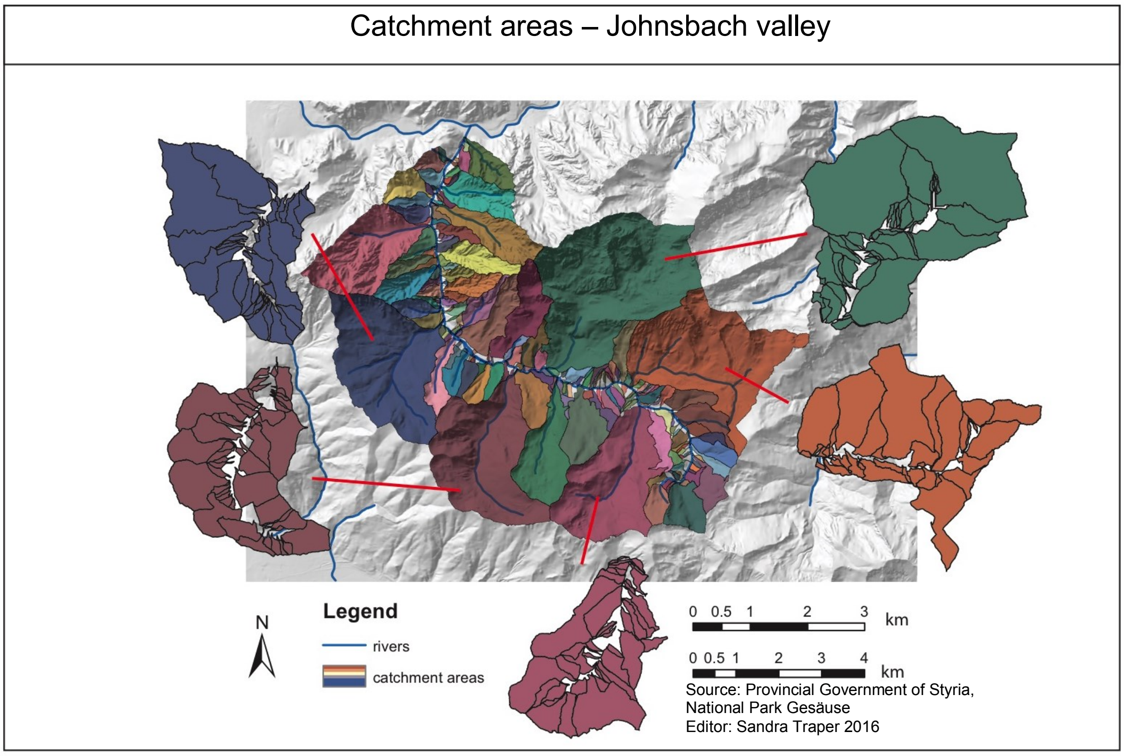


Figure 15 Result of the delineation of catchment areas in the Johnsbach valley

The following map (Fig. 16) illustrates the resulting situation regarding catchment areas in the Kleinsölk valley.

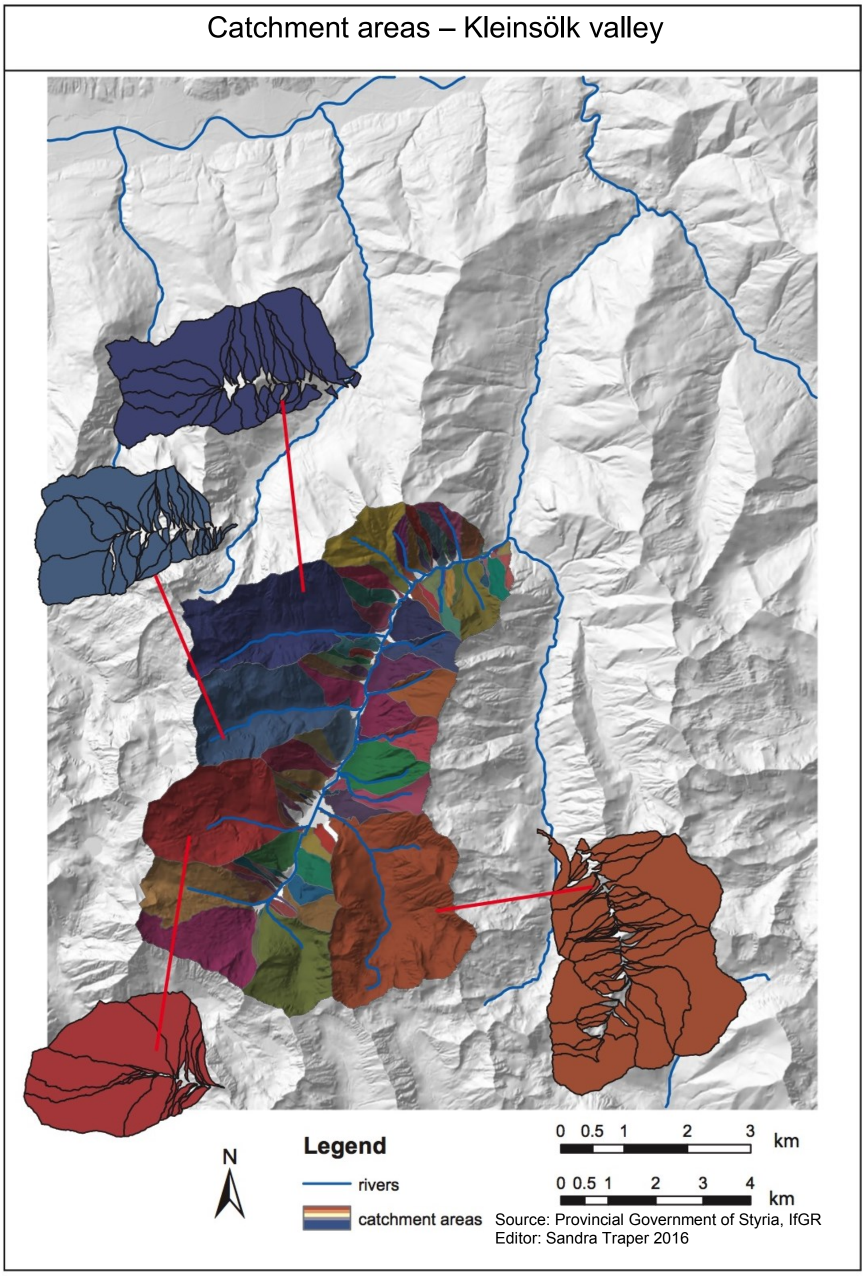


Figure 16 Result of the delineation of catchment areas in the Johnsbach valley

The steps in delineating watersheds described on the previous pages and illustrated in the first and second column in the flowchart in Fig. 14 led to a total of 246 watersheds under investigation in the Kleinsölk valley and 384 in the Johnsbach valley.

A further categorization focused on the overall number of catchment areas in both regions (see column three in Fig. 14) as reclassifying the flow accumulation grids in both areas with the mean value as a threshold had led to the inclusion of watersheds, in which no channel in the landscape was distinguishable in the aerial photographs. Therefore, in addition to the data set with 246 watersheds for the Kleinsölk valley and 384 watersheds for the Johnsbach valley, another smaller set of drainage basins was prepared for both areas. These second data sets only included those watersheds that showed a clearly distinguishable channel in the aerial photos since the focus of the analysis in both regions was on debris flows in already existing channel systems. This final step led to the creation of two possible data sets for both study areas; one which included all watersheds computed by ArcGIS and one which only included those watersheds from the automatically delineated ones, in which channels could be visually verified (see column three of the flowchart in Fig. 14).

The next important step aimed at generating a debris flow and connectivity inventory in order to investigate and answer the two parts of the research question of this thesis. Therefore, the aerial photos of the two study areas were examined with regard to the occurrence and characteristics of past debris flows. All catchment areas received an additional attribute that served to explain if a debris flow had occurred in that particular catchment area and if a debris flow had reached the main channel. For this purpose two new fields were added to the attribute tables of the catchment areas, marking them with either '1' or '0', '1` meaning that a debris flow had occurred or that the debris flow had reached the main channel, whereas the description '0' identified catchments which did not experience debris flows or connectivity.

Executing these steps with the data sets for both research areas led to the following distribution of catchment areas with debris flows and connectivity in both study areas (see Table 2):

Table 2 Watersheds, debris flows and cases of connectivity in both study areas

	Number of watersheds	Number of watersheds with DF	Number of watersheds with CONN
Kleinsölk valley			
Watersheds in total	246	80	51
Watersheds (only where channels were seen in the aerial photographs)	161	80	51
Johnsbach valley			
Watersheds in total	384	29	13
Watersheds (only where channels were seen in the aerial photographs)	96	29	13

In order to not only obtain values regarding influential factors for the whole catchment areas but also for two more significant sub-areas, further pour points were set in order to acquire two more layers of sub-areas. For the catchment areas that were marked with a 'Yes' or '1' regarding a recent debris flow event, pour points were set at the initial point of the debris flow that could be identified in the aerial images in order to enable an additional focus on the part of the catchment above the starting point of the debris flow. The third layer focused on the upper sector of all catchment areas, no matter if a debris flow had occurred or not, and pour points were set at the origin of each channel, leading to a smaller sub-area in the upper part.

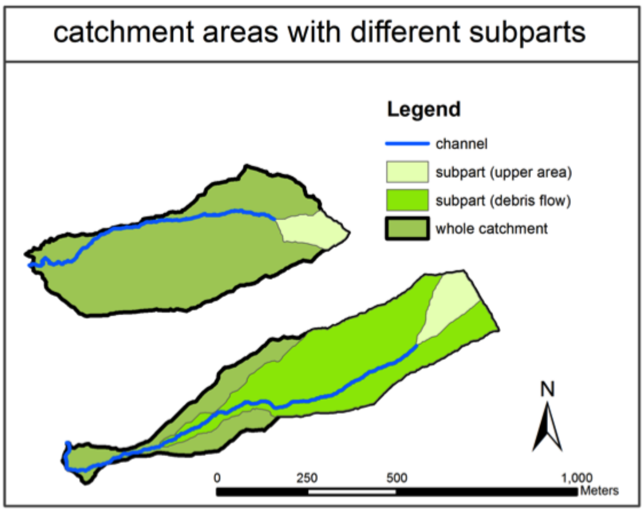


Figure 17 Catchment areas and important sub-areas

Figure 17 illustrates the further division of catchment areas into different sub-areas based on two randomly chosen examples from the Kleinsölk valley.

Having established the basis for extracting influential factors, the next steps focused on an extraction and preparation of factors that can lead and influence the occurrence as well as characteristics of debris flows.

4.2.2. Influential factors

The following pages serve to describe the processes of extracting separate values regarding influential factors for debris flow occurrences and characteristics. The choice and selection of factors of influence was based on two major considerations regarding suitability as well as availability of factors. First, studies that had followed a similar approach for either debris flow or landslide occurrences were investigated with regard to their choice of variables in combination with a research on what current literature regards as significant. The selection of factors among different researchers showed similarities as well as differences. The most important findings will be presented shortly in order to explain the selection of factors for my analyses.

From studies with similar research questions and methods, RUPERT et al. (2008) included 28 independent variables, which portrayed "basin morphology, burn severity, rainfall, and soil properties" in their study in debris flows in areas burnt by wildfires in California (RUPERT et al. 2008: 1). RAMANI et al. (2011: 505) took "[r]elief, slope, aspect, plan curvature, profile curvature, land use, soil, topographic wetness index, proximity to roads and proximity to lineaments" into account when preparing landslide susceptibility maps in India. CHEN et al. (2014) used topographic factors together with factors of geology and rainfall, while ANGILLIERI (2013) focused on factors regarding lithology, elevation, slope angle, slope aspect and solar radiation in his statistical analyses of debris flow occurrences in the Andes in Argentina. NANDI & SHAKOOR (2009: 13) used "slope angle, soil geology and erodibility, proximity to streams, precipitation, landcover patterns, soil properties" as independent variables in a statistical analysis of landslide occurrence in Ohio, U.S.

A study on landslides and their impacts on the Scottish road network investigates factors which can pose a hazard and influence the occurrence of landslides and debris flows in general. McMillan et al. (2005: 30) describe several "Hazard factors", which are either "conditions from the past (e.g. geology), present (e.g. slope angle) and future (e.g. forecast rainfall)". Those considerations accord with most of the variables used in the studies discussed so far. Xu et al. (2013: 45) divide important triggering factors and conditions into two categories, namely precipitation as a form of direct trigger and "environmental factors that are the basic conditions" for such events. The analyses conducted in the course of this thesis take enough rainfall as triggering condition for granted and focus on what Xu et al. (2013: 45) see as "environmental factors".

Taking these studies and information sources into account, my second major consideration concerning the selection of influential factors focused on the importance of these aspects for my two study areas and the availability of suitable data sets. These steps and thoughts led to the inclusion of several topographic factors (area size, area slope, area aspect, area curvature, stream length, stream slope) on various levels as well as of factors of land use/land cover and lithology.

Those influential factors, which will be described in more detail separately in the next paragraphs, have been obtained by using tools from the 'Zonal toolset' in the 'Spatial Analyst' section of ArcGIS. For all analyses the tool 'Zonal Statistics as Table' was used, which "[s]ummarizes the values of a raster within the zones of another dataset and reports the results to a table" (Esri 2012f). Regarding land use and lithology, an additional tool, 'Zonal Histogram', was used, which "[c]reates a table and a histogram graph that show the frequency distribution of cell values on the Value input for each unique Zone (Esri 2012g)."

The following table (Table 3) provides an overview of influential factors from the three main categories of topography, land use/cover and lithology that have been obtained for both study areas and have been used in the analyses. These categories will be discussed in more detail subsequent to this table.

Table 3 Influential factors and individual variables used in the analyses

Influential Factors regarding….	*Unit of reference*	*Individual factors in each category*
….Topography	Area	• Area size (m²) • Aspect • Slope (°) • Curvature
	Channel	• Slope (°) and length (m) of the whole channel • Slope (°) and length (m) of channel parts (see Figure 18 & 19) • Percentages of lengths of channel parts of whole channel length (%)
…Land use/cover	Area	• Land use/cover class with biggest share • Proportion of each class (%)
….Lithology	Area	• Rock formation with biggest share • Proportion of each rock formation (%)

Topographic factors

Several studies with similar approaches to the chosen methodology focused on several topographic factors in their analyses (e.g. RUPERT et al. 2008; TUNUSLUOGLU et al. 2008; NANDI & SHAKOOR 2009; RAMANI et al. 2011; ANGILLIERI 2013; DEVKOTA et al. 2013; CARRARA et al. 2014; ELKADIRI et al. 2014; REGMI et al. 2014; ZHUANG et al. 2015) and explained the significance of those factors regarding the occurrence and initiation of events like debris flows (e.g. CHEN et al. 2014: 547).

ZEPP (2014: 290) sees the importance of factors like slope and curvature for mass movement events in the fact that those aspects of topography regulate flows of water and material. Coming back to the "hazard factors" mentioned by MCMILLAN et al. (2005: 30), several topographic factors belong to the category "Geomorphic", e.g. "slope angle", "slope aspect" and "slope height" amongst several others. The same factors are also included in the category "Topographic", together with "stream angle" (ibd. 2005: 31). Other factors included in the category

“Hydrological”, namely “channel width and depth” and “catchment area”, (ibd. 2005: 30) are also topographic and have been included in my analyses.

Since several aspects of area topography can influence mass movements and especially debris flow events, various topographic factors have been used in the statistical analyses presented in the next sections of this thesis. With the help of the ‘Surface toolset’ in ArcGIS, which helps to “quantify and visualize a terrain landform represented by a digital elevation model“ (ESRI 2012h), values for area aspect, area curvature and area slope for the various sub-parts of the watershed areas were computed based on the 1m-Digital Elevation Models. Aspect is described as “[identifying] the downslope direction of the maximum rate of change in value from each cell to its neighbors“ (ESRI 2012h). It is the equivalent to slope direction and „[t]he values of the output raster will be the compass direction of the aspect” (ESRI 2012i). The tool ‘Curvature’ “[c]alculates the curvature of a raster surface, optionally including profile and plan curvature“ (ESRI 2012j) and the tool ‘Slope’ “[i]dentifies the slope (gradient, or rate of maximum change in z-value) from each cell of a raster surface“ (ESRI 2012k).

However, not only topographic factors concerning the setting and conditions of an area are important when it comes to debris flow events but also factors related to channel topography. MCMILLAN et al. (2005: 28) define “[c]hannel/slope geometry [as] an important control on the nature of debris flows”. Therefore, several topographic parameters, which describe the peculiarities of the channel in which a debris flow occurred, have been included in my investigations.

In order to extract channel parameters, channels had to be divided into several parts. In catchments with traces of past debris flows the channel was examined and subdivided in order to detect significant differences regarding characteristics of debris flows. The channels computed by ArcGIS were divided into several sub-parts, depending on the location of the debris flow and significant parts (transition zone, debris deposit zone) within the channel. The classification into these different parts is illustrated in the following figures (Fig. 18 & 19). Figure 18a depicts a sketch of a channel in which a debris flow is connected to the main river. In this visualization, the debris flow (the last part = the debris deposit labeled as part 3) reaches the river and debris flows into the river. Part 2 visualizes the transition zone of a debris flow. The aerial photograph in Figure 18b provides an example of a connected debris flow in a catchment area in the Kleinsölk valley.

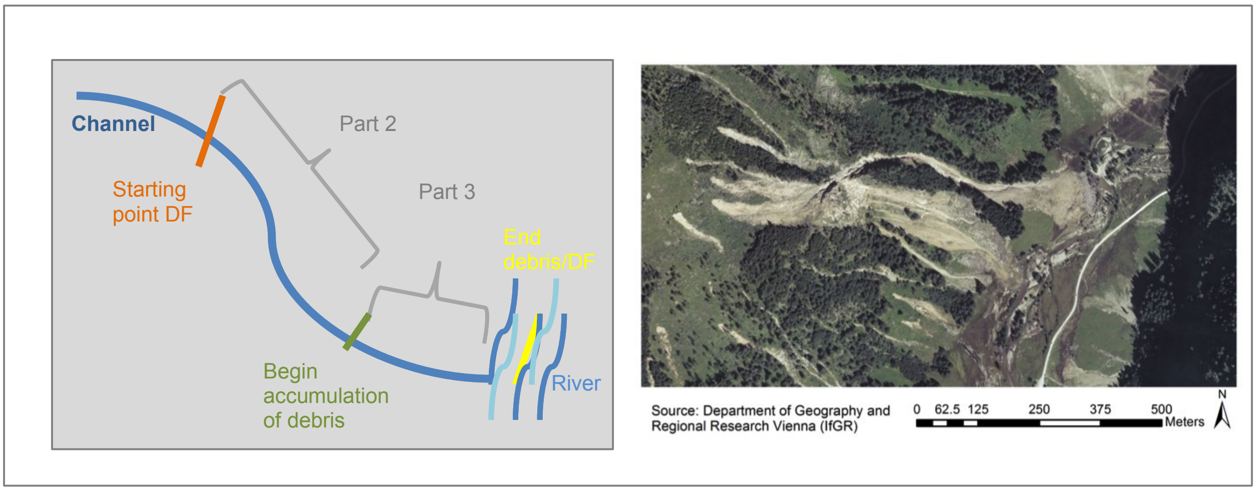


Figure 18 Debris flow with connectivity a) Depiction of a connected debris flow and sub-parts; b) Detail of the aerial image, showing the connection of a debris flow tot he main channel in the Kleinsölk valley

The next figure (Fig. 19a) depicts a situation in which a debris flow ends before reaching the river. In this sketch the area labeled as part 3 (the debris deposition zone) ends before flowing into the main river in the valley. Similar to the previous example, a catchment located in the Kleinsölk valley has been chosen to illustrate the situation (Fig. 19b).

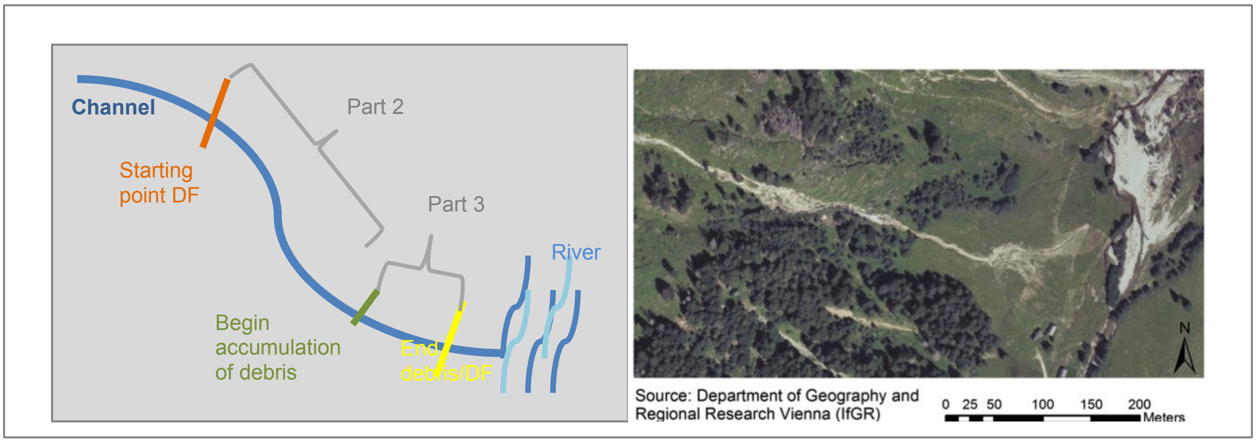


Figure 19 Debris flow without connectivity a) Depiction of a debris flow that is not connected; b) Detail of the aerial image, showing a debris flow that is not connected to the main channel in the Kleinsölk valley

Factors of land use and land cover

In addition to topographic factors, land use practices and land cover patterns in an area can either promote or prevent mass movement actions or debris flow events and are therefore included as factors of influence in several studies on the occurrence of debris flows and landslides (e.g. CARRARA et al. 2008; NANDI & SHAKOOR 2009; RAMANI et al. 2011; DEVKOTA et al. 2013; REGMI et al. 2014).

MCMILLAN et al. (2005: 30) list several factors of land use/cover as "hazard factors" in their study. For example, the aspects of "Afforestation" or "Deforestation" regarding the vegetation patterns of an area or "Agriculture" and "Forestry" are mentioned. According to their investigations "[p]lant roots play a critical role in stabili[z]ing colluvium" (ibd. 2005: 28), which makes an investigation of different land cover classes (e.g. forest and grassland) interesting with regard to the occurrence and characteristics of debris flow events.

The data regarding land use and land cover patterns in the Kleinsölk valley was mapped by Pablo Rigual 2015 and edited by Florian Stender 2016, based on aerial photography of the study area of the year 2011. Five classes of land use/cover are distinguishable based on this data set: forest, grassland, arable land, rock/debris and construction. For the Johnsbach valley no data set including classes of land use/cover was available and a comparable data set had to be complied. Florian Stender mapped the area around the Johnsbach 2016 by using the same classes as in the Kleinsölk valley and adapting the version by Hapitalp. The final maps showing the land use and land cover in both regions are illustrated in the following (Fig. 20 and 21).

The Kleinsölk valley is largely composed of forested areas, with rock/debris zones only in the higher elevation parts of the catchment. Features of construction are mostly roads and forest paths (see Fig. 20). Fig. 21 illustrates the patterns of land use/cover in the Johnsbach valley. Similar to the Kleinsölk valley, large parts of the region are composed of forest. In contrast, however, zones composed of rock/debris can be found in lower elevations too.

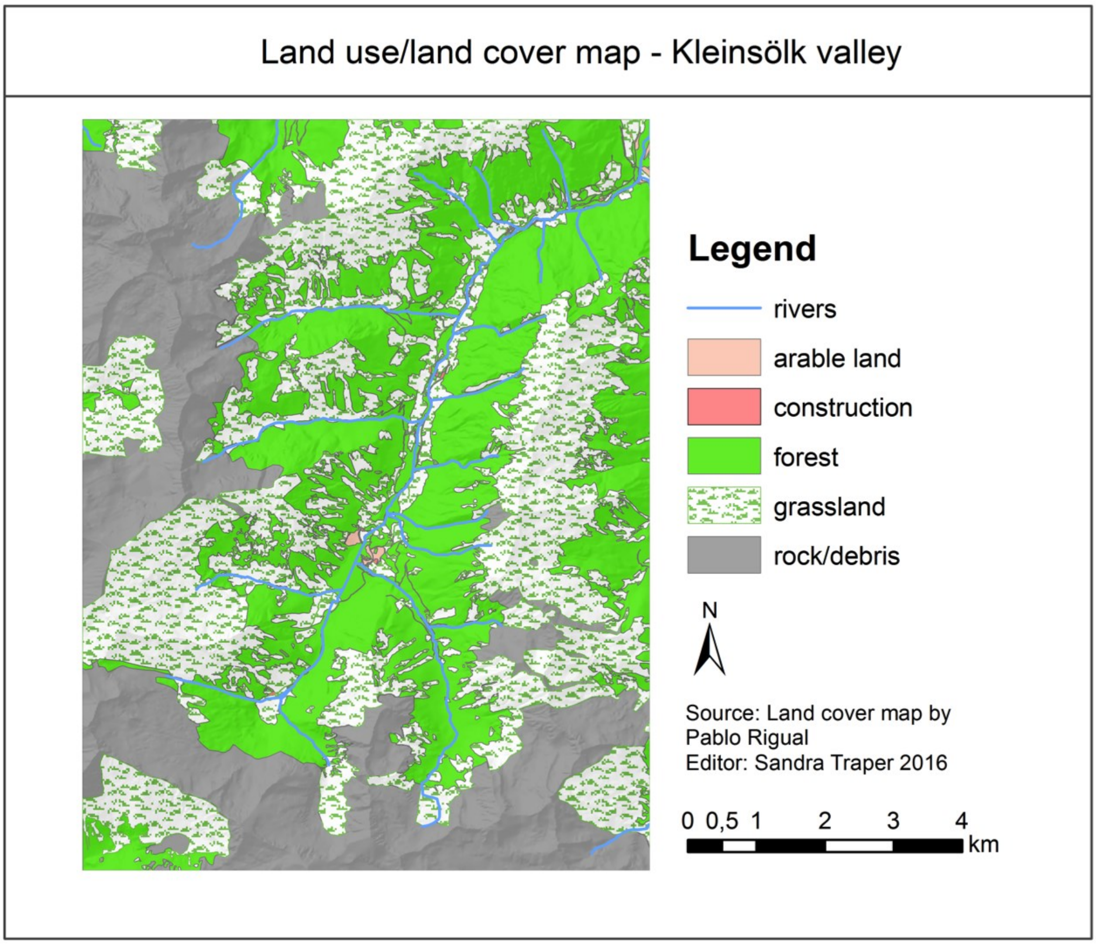


Figure 20 Land use/cover – Kleinsölk valley

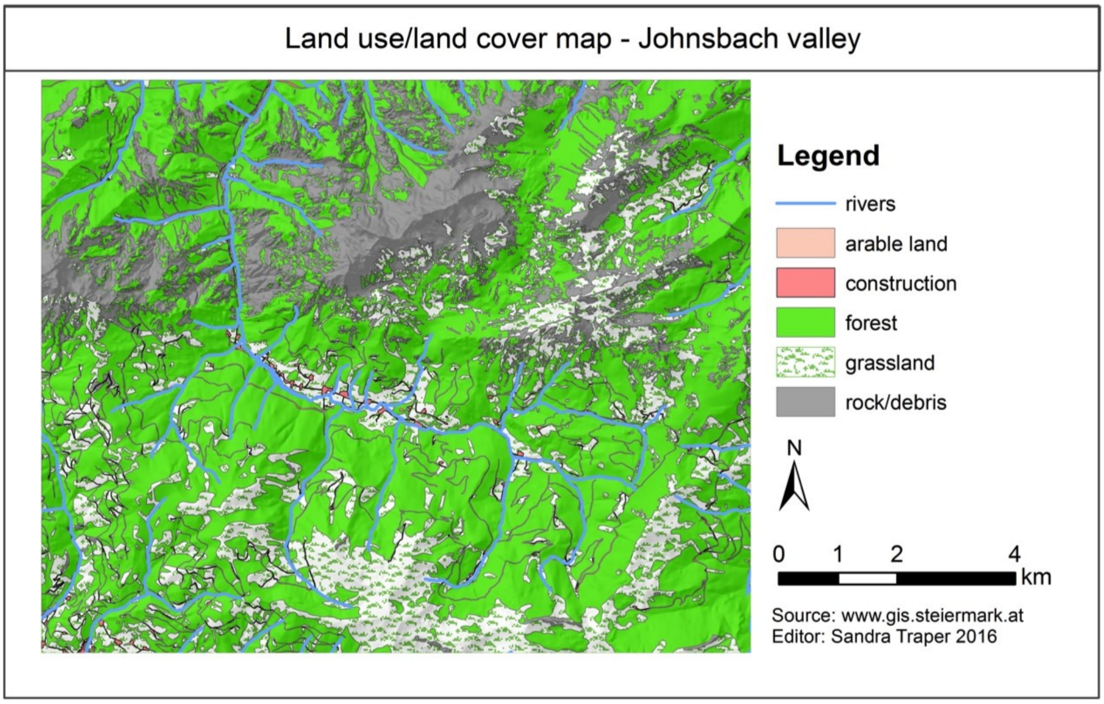


Figure 21 Land use/cover - Johnsbach valley

For both study areas the land use/cover class with the biggest share in each drainage basin, the proportion of each class in a catchment as well as the number of different classes present were computed and included in the following analyses.

Factors regarding the lithology of the study areas

In addition to factors of topography and land use/cover, a category that likewise influences the occurrence and characteristics of debris flows was considered in my analyses, namely lithology of the regions. The influence of factors concerned with geology on mass movement events has been included in several studies using logistic regression (CARRARA et al. 2008; TUNUSLUOGLU et al. 2008; NANDI & SHAKOOR 2009; ANGILLIERI 2013; DEVKOTA et al. 2013; CHEN et al. 2014; REGMI et al. 2014). Since both study areas are located in geologically different regions in Austria, it seemed to be of importance to include the predominant lithological setting as a further influential factor in addition to topography and land use/cover. Furthermore, MCMILLAN et al. (2005: 28) discuss the influence of lithology together with soil types on debris flow events and landslides in Scotland and examine particularly "sand-rich soils" as well as "granites" and "schist, shale or greywacke", which are also important lithological factors in my two study areas.

The data sets on the geological setting of both areas had to be mapped as no available layers already existed. Different lithological classes were mapped on the basis of the Digital Atlas of Styria provided by the PROVINCIAL GOVERNMENT OF STYRIA (2016) for the Kleinsölk and the Johnsbach valley in cooperation between TRAPER and STENDER 2016. The resulting lithological map for the Kleinsölk valley distinguishes between 14 different rock formations, the one for the Johnsbach valley between 19 classes. Similar to the preparation of the land use data, the lithological class with the biggest share in a catchment area as well as the proportion of each class and the variety of formations was computed.

The following figures (Fig. 22 & 23) illustrate the lithological maps that served as the basis for the extraction of influential factors.

While the Kleinsölk valley is mostly composed of crystalline rocks, the dominant rock formation in the Johnsbach valley is limestone. Figure 22 illustrates the dominance of several types of gneissic rocks in the Kleinsölk valley as discussed in section 3.1.2 of this thesis. Further significant rock formations include debris material on weathered slopes in several tributary valleys and colluvial sediments on the valley floors.

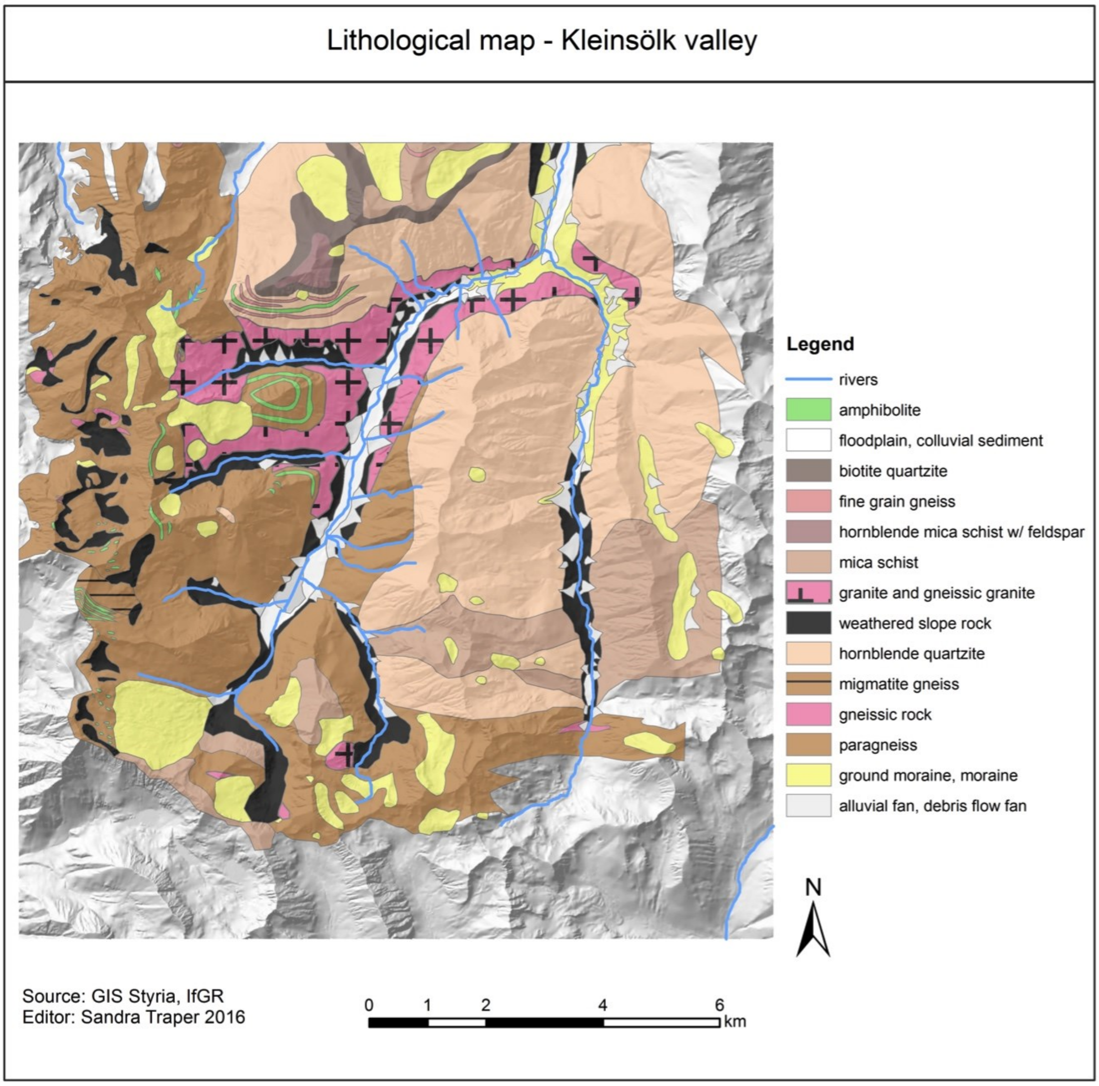


Figure 22 Lithology – Kleinsölk valley

The Johnsbach valley is largely composed of several types of limestone and dolomite in the northern part, which is particularly prone to debris flow events (see Fig. 23).

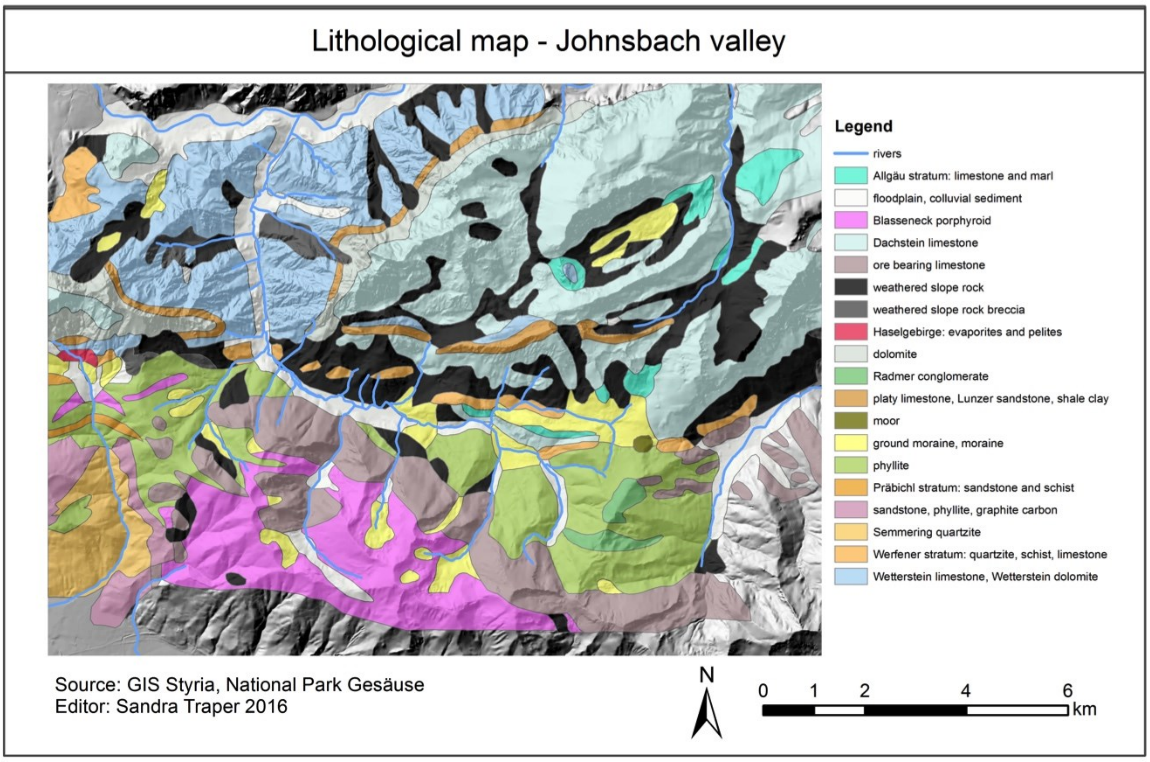


Figure 23 Lithology – Johnsbach valley

4.3. Statistical Analyses

In order to estimate probabilities of occurrence based on the influential factors presented in the previous section, logistic regression was applied. Furthermore, comparing means and computing frequencies was used as additional methods to analyze the data derived from the DEM-based GIS-analyses. The following sections of this thesis serve to introduce the functioning and important characteristics of logistic regression in general and explain data preparation processes in this study. The variety of models that were computed for both research questions and the variables used in each model will be presented.

4.3.1. Logistic regression

Logistic regression is a statistical method of analysis that is often computed in natural sciences and several studies investigating debris flows and landslides have made use of this technique in the past (e.g. ANGILLIERI 2003; RUPERT et al. 2008; RAMANI et al. 2011; ELKADIRI et al. 2014). The main purpose of this method is to "[predict] the probability of an event occurring" (RUPERT et al. 2008: 3). POEPPL et al. (2012: 520) provide a similar overall aim of the method used in natural sciences and further describe the function of such a regression "to examine the explanatory power of the potential factors of influence" on an event. According to ECKSTEIN (2012: 210), logistic regression is part of discrete decision models in statistics. KLEINBAUM (1996: 5) summarizes the core of the logistic regression in the following definition:

> **Logistic** regression is a mathematical modeling approach that can be used to describe the relationship of several *X*'s [independent variables] to a **dichotomous** dependent variable, such as *D*.

In addition to defining the concept of this statistical method, KLEINBAUM (1996: 6-7) furthermore explains the popularity of such models when it comes to predicting probabilities among other advantages in "[t]he fact that the logistic function *f*(z) **ranges between 0 and 1**"(KLEINBAUM 1996: 6).

Several researchers explain the popularity of logistic regression in connection to the functioning of linear regression models. Amongst those, RUPERT et al. (2008: 3) see the functioning of logistic regression "conceptually similar to multiple linear regression, because relations between one dependent variable and several independent variables are evaluated". The differences between both methods mainly focus on the resulting values. While the often used multiple linear regression results in "a continuous value for the dependent variable", the logistic regression provides values that have to be treated as probabilities (RUPERT et al. 2008: 3). Besides similarities to other approaches, CARRARA et al. (2008: 358) identify an advantage of the logistic regression model in analyzing data sets in that it is "less sensitive to deviances from normality of the input variables" compared to other statistical measures. RAMANI et al. (2011: 509) discuss similar considerations on the advantages of logistic regression and identify a major benefit in the fact that it can "handle both continuous and categorical variables" and that it is not necessary that all data sets show a normal distribution.

HOSMER & LEMESHOW (2000: 1) regard logistic regression as the "standard method of analysis" if "[an] outcome variable is discrete, taking on two or more possible values". In the analyses in this study the variables that are being investigated are dichotomous and can take on two different values. On the one hand the occurrence of debris flow (either a debris flow occurs or not) and on the other hand the possibility of debris flows to reach the main channel (either a debris flow reaches the channel or not) is at the core of the statistical analyses. The task of the logistic regression in this study was therefore to determine the variables with the highest explanatory power to describe debris flow occurrence as well as connectivity.

According to HOSMER & LEMESHOW (2000: 116), "[s]tepwise selection of variables" is a prominent form of several forms of regression models. The logistic regressions computed in the course of this study have also been based on stepwise picking additional variables or deleting them. SPSS offers several options of stepwise adding data. The concept behind a stepwise inclusion or exclusion is that the program itself "checks for the 'importance' of variables" and decides if variables will be integrated (HOSMER & LEMESHOW 2000: 116). Detailed descriptions on these processes and formula that explain how variables are either included or excluded based on algorithms can be found in HOSMER & LEMESHOW (2000: 116ff.).

In the models computed in the course of this thesis the option of 'backward: conditional' regression as offered by SPSS was applied and all explanatory variables were initially included and eliminated by an algorithm in order to find the most suitable composition of variables. The classification cut-off that determined the group membership of variables was predefined at 0.5 for all analyses.

BÜHL (2014: 458f.) presents the following formula for calculating the probability *p* of an event to occur:

$$p = \frac{1}{1 + e^{-z}}$$

The z-value can be computed the following way:

$$z = b_1 * x_1 + b_2 * x_2 + \ldots + b_n * x_n + a$$

In the formula above x_i are the values of the various independent variables (e.g. area size or slope angel in this study). The values for b_i are computed by the logistic regression and are regarded as coefficients, while a is a constant which is also computed by the program. If p has a value below 0.5 after inserting all values, the event under discussion is not likely to occur, whereas values above 0.5 indicate an increased probability that it will occur. (see BÜHL 2014: 458f.)

The two dependent variables that were used for the different parts (occurrence and connectivity) of the research question in this thesis were coded the following way (see Table 4) as preparation for the logistic regression:

Table 4 Coding of the two dependent variables

Dependent variable	Value	***Dependent variable***	Value
Debris flow YES	1	Connectivity YES	1
Debris flow NO	0	Connectivity NO	0

The factors regarding topography, land use/cover and lithology described in the previous sections of this thesis were used as independent variables. If an independent variable was categorical, it had to be prepared for the analysis by determining one category as category of reference for the other categories. The only categorical variable used in the analyses was the factor area aspect, which was grouped and classified the following way (see Table 5):

Table 5 Classification of the variable aspect

Category	*Category 1*	*Category 2*	*Category 3*	*Category 4*
Aspect/Directions	W	E	N, NE, NW	S, SE, SW

The last category, which included the orientations S, SE and SW, was used as category of reference as it was the most prevalent category in both regions. All other categories are then indicated with reference to this category in the logistic regression models.

4.3.2. Logistic regression models

Several different models were computed in order to find the most suitable ones with the highest explanatory power as well as best composition of explanatory variables for the two different dependent variables. Models computed in the course of this study differed either in sample size, in the use of the dependent variable or in the number and composition of independent variables. To provide an overview of the models that were computed, the following paragraphs summarize the differences and similarities between the models and group them into three different categories.

Differences in sample size can be attributed to the fact that not all catchment areas had observable channels in the aerial images. Therefore, models concerned with the occurrence of debris flows either used the bigger sample size (category 1) or focused only on those samples in which channels could be verified (category 2). The models of category 3 were concerned with the connectivity of debris flows and only included those catchments in which debris flows had occurred, leading to a different sample size.

The three different categories of models show the following characteristics:

1) ***Models of category 1***: deal with the occurrence of debris flows; include all catchment areas that were computed by ArcGIS; focus on different parts of the catchments and different lithological variables
2) ***Models of category 2***: deal with the occurrence of debris flows; only those catchment areas included in which channels could be detected in the aerial photos; focus on different parts of the catchments and different lithological variables

3) ***Models of category 3***: deal with the characteristics (connectivity) of debris flows; focus on different parts of the catchments; study areas are investigated separately and in combination; differences regarding independent variables

For the models of category 1 and 2, four different models were computed for each of the two study areas. In category 1, the first two of those four models took the whole catchment area into account, whereas the second two focused only on the upper area of the catchment. The first and second two models were further subdivided based on a different inclusion of the factors lithology (either grouped in classes according to similar characteristics or included as separate variables). The four models of category 2 followed the same approach, with a focus on those catchment areas that displayed observable channels in the aerial photographs.

Models of category 3 focused on a different part of the research question (connectivity of a debris flow to the main channel). This question was investigated in one of the study areas separately (the Kleinsölk valley) and in both areas in combination. An examination in the Johnsbach valley alone was not yielding constructive results due to the rather small sample size of 29 debris flows in this study area.

The following table (Table 6) provides an overview of the various models in the different categories computed in the course of the analyses:

Table 6 Overview of the models computed for both parts of the research question (three categories)

Study area	Model Name (abbreviated)	No. (M)	Description of model	Sample size	Number of independent variables	Variables (see Table 7 for explanations)
Category 1						
Kleinsölk	KS-C1-wa-geo-cl	M1	Kleinsölk, category 1, whole watershed area, Lithology classes	246	16	1-6, 26-30, 35-39
Kleinsölk	KS-C1-wa-geo-sep	M2	Kleinsölk, category 1, whole watershed area, Lithology separate	246	25	1-20, 35-39

Continuation Table 6

Kleinsölk	KS-C1-ua-geo-cl	M3	Kleinsölk, category 1, upper area, Lithology classes	246	16	1-6, 26-30, 35-39
Kleinsölk	KS-C1-ua-geo-sep	M4	Kleinsölk, category 1, upper area, Lithology separate	246	25	1-20, 35-39
Johnsbach	JB-C1-wa-geo-cl	M5	Johnsbach, category 1, whole watershed area, Lithology classes	384	16*	1-6, 26, 29, 31-34, 35, 36, 38, 39
Johnsbach	JB-C1-wa-geo-sep	M6	Johnsbach, category 1, whole watershed area, Lithology separate	384	29*	1-25, 35, 36, 38, 39
Johnsbach	JB-C1-ua-geo-cl	M7	Johnsbach, category 1, upper area, Lithology classes	384	16*	1-6, 26, 29, 31-34, 35, 36, 38, 39
Johnsbach	JB-C1-ua-geo-sep	M8	Johnsbach, category 1, upper area, Lithology separate	384	29*	1-25, 35, 36, 38, 39
Category 2						
Kleinsölk	KS-C2-wa-geo-cl	M9	Kleinsölk, category 2, whole watershed area, Lithology classes	161	16	1-6, 26-30, 35-39
Kleinsölk	KS-C2-wa-geo-sep	M10	Kleinsölk, category 2, whole watershed area, Lithology separate	161	25	1-20, 35-39
Kleinsölk	KS-C2-ua-geo-cl	M11	Kleinsölk, category 2, upper area, Lithology classes	161	16	1-6, 26-30, 35-39
Kleinsölk	KS-C2-ua-geo-sep	M12	Kleinsölk, category 2, upper area, Lithology separate	161	25	1-20, 35-39
Johnsbach	JB-C2-wa-geo-cl	M13	Johnsbach, category 2, whole watershed area, Lithology classes	96	16*	1-6, 26, 29, 31-34, 35, 36, 38, 39
Johnsbach	JB-C2-wa-geo-sep	M14	Johnsbach, category 2, whole watershed area, Lithology separate	96	29*	1-25, 35, 36, 38, 39
Johnsbach	JB-C2-ua-geo-cl	M15	Johnsbach, category 2, upper area, Lithology classes	96	16*	1-6, 26, 29, 31-34, 35, 36, 38, 39
Johnsbach	JB-C2-ua-geo-sep	M16	Johnsbach, category 2, upper area, Lithology separate	96	29*	1-25, 35, 36, 38, 39
Category 3						
Kleinsölk	KS-C3-wa-ch,lu	M17	Kleinsölk, category 3, whole area, channel/parts, land use	80	11	1, 4, 35-39, 40, 41, 43, 46

Continuation Table 6

Kleinsölk	KS-C3-wa-ch,lu2+4	M18	Kleinsölk, category 3, whole area, with channel + parts, landuse 2,4 only	80	8	1, 4, 36, 38, 40, 41, 43, 46
Kleinsölk & Johnsbach	KSJB-C3-wa-ch,lu	M19	Kleinsölk, category 3, whole area, with channel + parts, land use	109	10**	1, 4, 35-39, 40, 41, 43, 46
Kleinsölk & Johnsbach	KSJB-C3-wa-ch,lu2+4	M20	Kleinsölk, category 3, whole area, with channel + parts, landuse 2,4 only	109	8	1, 4, 36, 38, 40, 41, 43, 46

* data for one land use class is missing, compared to the Kleinsölk valley (no data available for 'arable land')

** land use classes are included, but arable land had to be excluded from the analysis since one region (Johnsbach) is missing this class

The independent variables used in the regression models according to their numbers can be identified in the next table (Table 7):

Table 7 Independent variables used in the models

Variable	***No.***	***Explanation of Variables***	
		Study area 1: Kleinsölk valley	Study area 2: Johnsbach valley
Area	1	Area size ($m^{2)}$	Area size ($m^{2)}$
Aspect	2	The mean aspect of the area	The mean aspect of the area
Curvature	3	The mean curvature of the area	The mean curvature of the area
Slope	4	The mean slope of the area (°)	The mean slope of the area (°)
Geology_variety	5	Number of different lithological classes in an area	Number of different lithological classes in an area
Landuse_variety	6	Number of different land use/cover classes in an area	Number of different land use/cover classes in an area
All Geology_class variables	→	***Percentage of the area that is covered in ....(%)***	
Geology_class1	7	Amphibolite	Allgäu stratum: limestone and marl
Geology_class2	8	Floodplain, colluvial sediment	Floodplain, colluvial sediment
Geology_class3	9	Biotite quartzite	Blasseneck porphyroid
Geology_class4	10	Fine grain gneiss	Dachstein limestone
Geology_class5	11	Hornblende mica schist w/ feldspar	Ore bearing limestone
Geology_class6	12	Mica schist	Weathered slope rock
Geology_class7	13	Granite and gneissic granite	Weathered slope rock breccia
Geology_class8	14	Weathered slope rock	Haselgebirge: evaporates and pelites
Geology_class9	15	Hornblende quartzite	Dolomite
Geology_class10	16	Migmatite gneiss	Radmer conglomerate
Geology_class11	17	Gneissic rock	Platy limestone, Lunzer sandstone, shale clay
Geology_class12	18	Paragneiss	Moor
Geology_class13	19	Ground moraine, moraine	Ground moraine, moraine
Geology_class14	20	Alluvial fan, debris flow fan	Phyllite
Geology_class15	21	-	Präbichl stratum: sandstone, schist
Geology_class16	22	-	Sandstone, phyllite, graphite carbon

Continuation Table 7

Geology_class17	23	-	Semmering quartzite
Geology_class18	24	-	Werfener stratum: quartzite, schist, lime
Geology_class19	25	-	Wetterstein limestone + dolomite
Debris_comb	26	Classes 8,13	Classes 6,7,13
Granite_comb	27	Classes 1,7,10,11	-
Schist_comb	28	Classes 3,5,6,9	-
Valley floors_comb	29	Classes 2,14	Class 2
Paragneiss_comb	30	Classes 4,12	-
Dachstein_limestone_comb	31	-	Classes 3,4,5,
Wetterstein_limestone_comb	32	-	Class 19
Dolomite_comb	33	-	Classes 9,10
Other formations_comb	34	-	Classes 1,11,14,18
Land_class1	35	Percentage of the area that is covered with **construction** (%)	Percentage of the area that is covered with **construction** (%)
Land_class2	36	Percentage of the area that is covered with **rock/debris** (%)	Percentage of the area that is covered with **rock/debris** (%)
Land_class3	37	Percentage of the area that is covered with **arable land** (%)	Percentage of the area that is covered with **arable land** (%)
Land_class4	38	Percentage of the area that is covered with **grassland** (%)	Percentage of the area that is covered with **grassland** (%)
Land_class5	39	Percentage of the area that is covered with **forest** (%)	Percentage of the area that is covered with **forest** (%)
Ch_length	40	Length of the channel in the catchment area (m)	Length of the channel in the catchment area (m)
Ch_slope	41	Slope of the channel in the catchment area (°)	Slope of the channel in the catchment area (°)
Ch_length2	42	Length of the second part of the channel (transportation distance) (m)	Length of the second part of the channel (transportation distance) (m)
%Ch_length2	43	Part 2 - percentage of total channel length (%)	Part 2 - percentage of total channel length (%)
Ch_slope2	44	Slope of the second part of the channel (transportation distance) (°)	Slope of the second part of the channel (transportation distance) (°)
Ch_length3	45	Length of the third part of the channel in the catchment area (area of debris deposit) (m)	Length of the third part of the channel in the catchment area (area of debris deposit) (m)
%Ch_length3	46	Part 3 - percentage of total channel length (%)	Part 3 - percentage of total channel length (%)
Ch_slope3	47	Slope of the third part of the channel in the catchment area (area of debris deposit) (°)	Slope of the third part of the channel in the catchment area (area of debris deposit) (°)
Appendices to the variables & abbreviations		*Those appendices can be attached to any variable that refers to an area. / Abbreviations for model names*	
wa		Variable was computed for the whole catchment area	
ua		Variable was computed for the upper area of the catchment	
df		Variable was computed for the area above the starting point of the debris flow event	
geo-cl		Geology/Lithology grouped in classes	
geo-sep		Geology/Lithology used as separate variables	
lu		Land use/cover	
ch		Channel and channel parts	
C1/2/3		Category 1/2/3	

5. Results

The following sections of this thesis will present the results from the processing and adaption of the initial data sets performing DEM-based GIS-analyses as well as the results of the logistic regression models. The first sub-section will present results that could be achieved by analyzing the aerial photos and using the 'Hydrology' as well as the 'Surface' tools in ArcGIS. The second one introduces the results obtained from the logistic regression models.

5.1. Debris flow occurrences and characteristics

The analysis of the aerial images with regard to the catchment areas computed with ArcGIS revealed that at the two points in time under investigation 80 debris flows were visible in the aerial photos of the Kleinsölk valley and 29 could be detected in the aerial photos of the Johnsbach valley. The following table (Table 8) provides and overview of the events identified on the basis of traces from past events:

Table 8 Occurrence of debris flows and their characteristics in both study areas

Study area	Debris flow events	Connected to the main channel
Kleinsölk valley	80	51
Johnsbach valley	29	13

Taking a closer look at the predominant topographic conditions in all catchment areas compared to those in areas with debris flows and/or connectivity exposed differences as well as commonalities. The following table (Table 9) provides a summary of the topographic conditions that could be obtained by computing frequencies with the help of SPSS. All values presented in the following tables are computed for the whole area of a drainage basin and not for the various sub-parts (e.g. upper area).

Table 9 Comparison of topographic conditions

		Kleinsölk valley			*Johnsbach valley*		
		All watersheds	Watersheds with DF	Watersheds with CONN	All watersheds	Watersheds with DF	Watersheds with CONN
Sample size (n)		246	80	50	384	29	13
Topographical factors *(in the whole catchment areas)* *Min (minimum value), Max (maximum value), Mean (mean value), Med (median value)*							
Aspect (Number of catchment areas in each category)	N	0	0	0	0	0	0
	NE	8	0	0	23	0	0
	E	50	11	6	65	3	0
	SE	67	35	22	67	11	4
	S	55	21	18	61	0	0
	SW	22	6	3	85	12	7
	W	41	7	2	66	2	1
	NW	3	0	0	17	1	1
	flat	0	0	0	0	0	0
Curvature (* = Number of catchment areas in each category)	0 *	0	0	0	0	0	0
	+ *	125	43	30	203	13	7
	- *	121	37	21	181	16	6
	Mean	0.000423	0.004470	0.007030	0.002277	-0.032077	-0.047849
	Med	0.000997	0.004011	0.008128	0.002129	-0.006541	0.002305
Slope (°)	Min	7.18	18.34	18.34	2.74	13.56	13.56
	Max	52.96	50.78	50.78	60.52	60.52	60.52
	Mean	36.45	39.70	39.77	30.16	42.38	46.36
	Med	37.45	39.64	39.39	29.28	45.29	46.88
Area (m²)	Min	11,862.07	34,682.57	34,682.57	7,602.95	8,201.36	8,201.36
	Max	9,680,218.28	6,066,432.74	6,066,432.74	9,353,092.3	3,301,512.60	3,301,512.60
	Mean	322,533.80	564,516.08	611,021.30	245,704.35	514,878.71	673,547.15
	Med	79,164.65	196,759.62	222,435.90	38,466.0166	254,697.99	294,791.30

Table 9 illustrates the distribution of catchment areas with regard to the different categories of area aspect and provides values for area curvature, area slope and area size in all catchment areas and in those in which debris flows occurred and debris flows reached the main channel. These figures show that most catchment areas in general have a southeast orientation (67 out of 246), the same applies to those catchments with debris flows (35 out of 80) and those with connected debris flows (22 out of 51) in the Kleinsölk valley. In the Johnsbach valley the main orientation is southwest with 85 out of all 384 catchments oriented southwest. Regarding areas with debris flows, 12 of all 29 catchments are oriented southwest; catchments with connected debris flows are also mainly southwest facing (7 out of 13). Furthermore, the table presents higher values regarding the mean area slope in catchments with debris flows and in basins with connected debris flows in comparison to all drainage basins investigated. The values for the Kleinsölk valley are 36.45° for all areas, 39.70° for those with debris flows and 39.77° for those with connectivity. The situation in the Johnsbach valley is similar with values between 30.16° for all areas and 46.36° for those that had traces of connected debris flows in the aerial images. A detailed discussion of those values will be provided in the next chapter of this thesis. While the preceding table illustrated the topographic conditions in the catchment areas, the next table (Table 10) illustrates predominant land use/cover and the distribution of classes among the different catchments.

Table 10 Comparison of land use/cover conditions

		Kleinsölk valley			***Johnsbach valley***		
		All water-sheds	Watersheds with DF	Watersheds with CONN	All watersheds	Watersheds with DF	Watersheds with CONN
Sample size (n)		246	80	51	384	29	13
Land use							
Variety *(=Average Number of different classes)*		**2 & 3** (n=110 each)	**3** (n=42)	**2 & 3** (n=24 each)	**3** (n=193)	**3 & 4** (n=11 each)	**2** (n=5)
Majority *(=Average predominant land use class)*		**Forest** (n=167)	**Forest** (n=41)	**Forest** (n=26)	**Forest** (n=300)	**Forest** (n=17)	**Rock/ debris** (n=8)
Land use classes (%) *(=Average percentage covered in…)*	Construct-ion	0.50	0.13	0.07	3.24	0.56	0.10
	Rock/ debris	7.32	10.50	9.35	5.64	38.81	56.60
	Arable land	0.19	0.067	0.00	0	0	0
	Grassland	31.88	39.25	41.12	21.32	11.28	6.15
	Forest	60.11	50.06	49.46	69.80	49.35	37.14

The average number of different land use/cover classes in all catchment areas ranges between 2 and 3 in the Kleinsölk valley and 2 and 4 in the Johnsbach valley. In the Kleinsölk valley all drainage basins in general as well as only those with debris flows and those with connected debris flows are mostly composed of forested areas. Similar conditions are present in the Johnsbach valley with the exception of basins with connected debris flows, which are mostly composed of rock/debris.

Similar to the illustration of land use/cover conditions in both areas, the following table (Table 11) presents an overview of the average lithological variety, predominant lithological classes as well as the average proportions of all lithological classes in both study areas.

Table 11 Comparison of lithological conditions

	Kleinsölk valley				***Johnsbach valley***		
Variety: Average Number of different classes, Majority: Average predominant rock formation							
	All Watersheds (n=246)	*Watersheds with DF* (n=80)	*Watersheds with CONN (n=51)*		*All Watersheds (n=384)*	*Watersheds with DF (n=29)*	*Watersheds with CONN (n=13)*
Variety	**3** (n=64)	**4** (n=21)	**4+5** (n=13)	***Variety***	**2** (n=160)	**2** (n=13)	**2** (n=5)
Majority	Class 12 Paragneiss (n=107)	Class 12 Paragneiss (n=33)	Class 12 Paragneiss (n=21)	***Majority***	Class 14 Phyllite (n=68)	Class 19 Wetterstein limestone/ dolomite (n=19)	Class 19 Wetterstein limestone/ dolomite (n=10)
Geolog-ical classes *(%) (Average percentage composed of...)*				***Geolog-ical classes*** *(%)(Average percentage composed of...)*			
1	2.22	3.09	3.55	1	1.81	0.00	0.00
2	3.29	1.03	0.89	2	15.45	11.12	14.05
3	0.47	1.35	2.05	3	6.03	5.29	6.29
4	0.40	0.95	1.40	4	9.34	5.37	0.82
5	0.19	0.53	0.80	5	14.89	4.29	0.00
6	3.21	1.05	0.51	6	10.49	4.94	0.73
7	18.15	22.13	24.05	7	0.56	3.78	7.03
8	13.93	7.45	6.77	8	0.00	0.00	0.00
9	12.37	20.85	19.91	9	0.40	3.49	4.54
10	0.37	0.57	0.74	10	0.24	0.00	0.00
11	0.00	0,00	0.00	11	1.28	4.23	3.10
12	36.74	33.37	30.38	12	0.00	0.00	0.00
13	4.90	6.19	7.48	13	11.87	0.77	1.40
14	3.74	1.43	1.46	14	15.81	2.49	0.00
				15	0.00	0.00	0.00
				16	0.00	0.00	0.00
				17	0.00	0.00	0.00
				18	2.82	0.22	0.00
				19	9.02	54.01	62.03
For an explanation of geological classes → table 7, section 4.3.2.							

The number of different rock formations in a drainage basin in the Kleinsölk valley ranges between 3 and 5, whereas in the Johnsbach valley on average 2 different formations are present. Class 12 (paragneiss) is the dominant rock formation in the Kleinsölk valley in all catchments. The Johnsbach valley has a domination of class 14 (phyllite) on average in all drainage basins, however, those basins that experienced debris flow or connectivity are mostly composed of class 19 (Wetterstein limestone/dolomite).

Channels in catchments with debris flows have been subdivided into several parts (see section 4.2.2. of this thesis). The next table (Table 12) summarizes values regarding average channel length and average channel slope.

Table 12 Channel specific parameters

	Watersheds with DF *Kleinsölk only*	***Watersheds with CONN*** *Kleinsölk only*	***Watersheds with DF*** *KS & JB*	***Watersheds with CONN*** *KS & JB*
Average channel length (m)	1,400.41	1,416.16	1,409.87	1,462.20
Average channel slope (°)	24.84	25.16	23.27	23.90
Average length part 2 (m)	353.38	426.06	355.09	427.81
Average slope part 2 (°)	23.58	21.37	21.89	19.36
Average length part 3 (m)	176.63	194.35	164.96	179.27
Average slope part 3 (°)	12.72	11.05	12.65	10.44

This table shows that channels tend to be longer and steeper in basins with connected debris flows. A more detailed discussion of those values will follow in the discussion section of this thesis.

5.2. Results of the logistic regression models

After a presentation of values obtained by frequency analyses, the following paragraphs illustrate the results from the logistic regression models. 22 different models (see section 4.3.2. of this thesis) have been computed in course of the analyses. The characteristic numbers of all 22 models are included in the appendix of this thesis. The following table (Table 13) presents values regarding Chi-square, Nagelkerke R Square, the percentages of correctly assigned cases as well as the number of independent variables that stayed in the models. Those figures served as the basis for electing the best models in each category.

Table 13 Results of the logistic regression models

No.	Model abbreviation	Chi-square	Nagel-kerke R Square	Percentage correct (%)	Correct: dep.var. = 1 (%)	Correct: dep.var. = 0 (%)	Number of variables
	Category 1						
M1	KS-Ca-wa-geo-cl	116.319	0.526	82.1	66.3	89.8	6
M2	KS-C1-wa-geo-sep	131.149	0.577	83.3	70	89.8	9
M3	KS-C1-ua-geo-cl	71.266	0.351	76.0	53.8	86.7	7
M4	KS-C1-ua-geo-sep	79.250	0.384	75.6	50.0	88.0	7
M5	JB-C1-wa-geo-cl	108.564	0.594	96.1	62.1	98.9	5
M6	JB-C1-wa-geo-sep	117.135	0.634	95.8	58.6	98.9	8
M7	JB-C1-ua-geo-cl	94.305	0.525	94.0	44.8	98.0	6
M8	JB-C1-ua-geo-sep	89.991	0.504	93.8	37.9	98.3	7
	Category 2						
M9	KS-C2-wa-geo-cl	60.332	0.417	76.4	78.8	74.1	6
M10	KS-C2-wa-geo-sep	69.927	0.470	78.3	78.8	77.8	8
M11	KS-C2-ua-geo-cl	35.419	0.263	68.3	66.3	70.4	6
M12	KS-C2-ua-geo-sep	34.900	0.260	68.3	60.0	76.5	5
M13	JB-C2-wa-geo-cl	35.523	0.438	83.3	58.6	94.0	3
M14	JB-C2-wa-geo-sep	49.294	0.569	82.3	69.0	88.1	7
M15	JB-C2-ua-geo-cl	28.139	0.360	74.0	41.4	88.1	4
M16	JB-C2-ua-geo-sep	34.865	0.431	80.2	58.6	89.6	9
	Category 3						
M17	KS-C3-wa-ch,lu	30.067	0.429	77.5	84.3	65.5	7
M18	KS-C3-wa-ch,lu2+4	25.820	0.378	77.5	84.3	65.6	4
M19	KSJB-C3-wa-ch,lu	33.242	0.354	74.3	87.5	55.6	7
M20	KSJB-C3-wa-ch,lu2+4	25.009	0.276	70.6	84.4	51.1	4

The following lines summarize the main results presented in Table 13 regarding differences and similarities of the models.

The general percentage of correctly assigned cases ranges between 68.3% and 96.1% for both study areas regarding the occurrence of debris flows (models of category 1 and 2). Looking at both study areas separately reveals percentages in a range of 68.3% to 83.3% for the Kleinsölk valley and values between 74.0% and 96.1% for the Johnsbach valley. Values regarding the models of category 1 range between 75.6% and 96.1% for both study areas (75.6% to 83.3% for the Kleinsölk valley; 93.8% to 96.1% for the Johnsbach valley). Comparing at the results from models examining the connectivity of debris flows (category 3) reveals correctly assigned cases between 70.6% and 77.5%.

The number of independent variables that stayed in the models ranges between 3 and 9 with regard to the occurrence of debris flows in both valleys (5 to 9 in the Kleinsölk valley and 3 to 9 in the Johnsbach valley). The second part of the research question (connectivity) is explained by models with 4 to 7 independent variables for both study areas; regarding the models investigating the Kleinsölk valley separately, 4 and 7 independent variables remained in the models.

All models show significant Chi-square values indicating a general acceptance of these models. Chi-square values range between 28.139 and 131.149 in models of category 1 and 2; models of category 3 exhibit Chi-square values between 25.009 and 33.242.

The Nagelkerke R-Square values range between 0.260 and 0.634 for the first part of the research question for category 1 and 2 (0.260 to 0.577 in the Kleinsölk valley and 0.360 to 0.634 the Johnsbach valley). The values for the second part of the research question (category 3) range between 0.276 and 0.429 for both study areas and 0.378 and 0.429 investigating the Kleinsölk valley separately. Nagelkerke R-Square "measure[s] the strength of association of the model" and provides values on how good the variables in the models can explain the dependent variable (RAMANI et al. 2011: 515).

Based on the percentages of correctly assigned cases in general and those regarding the occurrence of 'yes'-cases in particular as well as based on the highest diversity of variables that stayed in each model, four following models were elected to best represent the two parts of the research question. The following table (Table 14) provides an overview of variables and their regression coefficients in those models. All other values can be found in the appendix to this thesis.

Table 14 Variables in the models that have been elected on the basis of correctly assigned cases

No.	Model	Variables in the Models	Regression coefficient B
M2	KS-C1-wa-geo-sep	Area_wa	1.331
		Aspect_wa	
		Aspect (1) (W)	-2.006
		Aspect (2) (E)	-0.004
		Aspect (3) (N,NE,NW)	-19.819
		Slope_wa	0.210
		Geology_variety_wa	0.519
		Geology_class7_wa	0.057
		Geology_class9_wa	0.047
		Geology_class12_wa	0.041
		Geology_class13_wa	0.048
		Land_class4_wa	0.023
		Constant	-21.751
M6	JB-C1-wa-geo-sep	Landuse_variety_wa	2.154
		Land_class5_wa	-0.078
		Land_class1_wa	-0.769
		Land_class4_wa	-0.070
		Geology_class1_wa	-14.496
		Geology_class2_wa	-0.025
		Geology_class4_wa	-0.029
		Geology_class7_wa	0.068
		Constant	-1.045
M10	KS-C2-wa-geo-sep	Area_wa	1.096
		Aspect_wa	
		Aspect (1) (W)	-2.298
		Aspect (2) (E)	-0.379
		Aspect (3) (N,NE,NW)	-21.377
		Slope_wa	0.183
		Geology_variety_wa	0.381
		Land_class4_wa	0.016
		Geology_class6_wa	-0.067
		Geology_class7_wa	0.016
		Geology_class9_wa	0.015
		Constant	-14.865
M14	JB-C2-wa-geo-sep	Landuse_variety_wa	1.603
		Land_class5_wa	-0.051
		Land _lass1_wa	-0.735
		Geology_class4_wa	-0.040
		Geology_class6_wa	-0.043
		Geology_class7_wa	0.221
		Geology_class13_wa	-0.125
		Constant	-1.273
M17	KS-C3-wa-ch,lu	Area_wa	2.421
		Ch_slope	0.142
		%Ch_length2	0.061
		%Ch_length 3	0.115
		Land_class2_wa	2.110
		Land_class4_wa	2.117
		Land_class5_wa	2.111
		Constant	-230.327
M19	KSJB-C3-wa-ch,lu	Area_wa	1.972
		Ch_slope	0.113
		%Ch_length2	0.030
		%Ch_length 3	0.092
		Land_class2_wa	1.431
		Land_class5_wa	1.423
		Land_class4_wa	1.429
		Constant	-157.441

6. Discussion

The following sections of this paper will discuss the data and results that have been presented in the previous chapter. Conclusions shall be drawn with regard to the two parts of the research question that have guided the analyses in this thesis. On the one hand the results from the data preparation and DEM-based GIS-analyses will be discussed, on the other hand results, differences and usability of the logistic regression models will be examined.

6.1. Discussion of debris flow occurrences and characteristics

A comparison of topographic conditions in all catchment areas with regard to debris flow occurrences and cases of connectivity reveals some peculiarities and first insights regarding the influence of area as well as channel topography. Interpretations and conclusions in the following are based on the results illustrated in Table 9, section 5.1., in this thesis.

Regarding the mean aspect, most drainage basins in the Kleinsölk valley are oriented southeast, whereas most areas in the Johnsbach valley are facing southwest. HEALD & PARSONS (2005: 70) regard "[s]lope aspect relative to the key elements of bedrock structure" as significant in a hazard analysis. In their study conducted in Scotland this factors is most important in triggering mass movements "when the slope aspect and the direction of dip of a relatively smooth rockhead profile coincide" (ibd. 2005: 70). However, despite the relative importance of the factor aspect in combination with other factors, they also see "limited evidence that slope aspect alone is a reliable predictor of debris flows" (ibd. 2005: 70) and recommend a rather precautious interpretation of this factor without further data.

Coming back to the direction of slopes in both study areas, one recognizes that the dominant orientation of basins in which debris flows occurred or debris flows showed connectivity is also the overall prevailing aspect of slopes in these regions.

It therefore appears that this characteristic of slopes is controlled by the general setting of slopes and valleys in these regions. The proposition that the direction of slope shows a causal connection to debris flows and connectivity should therefore be considered carefully. However, according to ELKADIRI et al. (2014: 4822), it can be assumed "that the aspect is an indicator of exposition to preferential wind directions, precipitation regimes, sunlight impact, and discontinuity orientations". Southeast and southwest oriented slopes are exposed to more sunlight than slopes facing other directions. The combination of heat in summer and cold in winter could possibly lead to intense weathering of slopes and rocks and, thus, promote the occurrence of debris flows.

In contrast to the average slope aspect of the watersheds, which does not differ between different types of watersheds, the average slope angles reveal interesting insights. Slope angle in general is seen as a very significant factor when it comes to natural process that can turn into natural hazards. While several factors are believed to affect the possible development of debris flows, some are regarded as more important than others. This is particularly true for a steep slope angle of an area, which is "considered fundamental and must be in place" for a debris flow to occur according to HEALD & PARSONS (2005: 68). They identify a value of 30° as the threshold above which a debris flow can be triggered by several other factors (ibd. 2005: 68). Comparing the mean values of average slope angles in both regions reveals a transgression of this threshold in all catchment areas (regardless of past debris flow occurrences/connectivity). However, the mean values for all watersheds in both study areas are lower than the mean values for only those basins in which debris flows had happened. The values for catchment areas in which debris flows had reached the main channel are even higher. For the Kleinsölk valley the mean values is 36.45° for all watersheds, 39.70° for the areas with debris flows, and 39.77° for those with connectivity to the main channel. The Johnsbach valley shows a similar distribution with 30.16°, 42.38° and 46.36°. These values suggest that debris flows are more likely to occur in steeper areas and possible connectivity of material to rivers in the valley requires an even steeper slope.

The mean area sizes measured in m^2 expose similar patterns in both regions. An investigation of the mean values reveals a tendency for debris flows to occur in bigger areas. A further division of debris flow occurrences with regard to the factor connectivity reveals an additional increase in area size when debris flows reached the river in both study areas. For the Kleinsölk valley the mean value of area size for all watersheds is 322,533.80 m^2, while the mean value for those catchments in which debris flows occurred is 564,516.08 m^2 and 611,021.30m^2 for those with connected debris flows. In the Johnsbach valley 245,704.35 m^2, 514,878.71 m^2 and 611,021.30 m^2 could be observed.

Not only factors regarding topographic conditions of drainage basins in general reveal interesting insights but also channel-specific topographic parameters show significant differences. An investigation of average slope angles highlights the significance of this factor when it comes to hillslope-channel connectivity (see values in Table 12 in section 5.1.). In both regions the average channel appears to be steeper in those catchments in which debris flows connected to the rivers on the valley floors. In the Kleinsölk valley the average channel slope for connected debris flows is 25.16°, compared to an average value of 24.84° in all catchments with debris flows. In the Johnsbach valley the same tendency can be observed with an even bigger difference between those values (32.90° compared to 23.27°). Regarding differences in channel length, in both regions the average channel is longer in those basins, in which debris flows reached the channel. Not only the average channel is longer in those drainage basins, but also the part that has been identified as the transportation distance of a debris flow. This accords with findings by HEALD and PARSONS (2005: 75), who reported that "of debris flows origination at a similar height, 'smaller' flows did not tend to reach the A83 [a certain road in Scotland]". They conclude "that there is a certain volume of material required to gain sufficient momentum to reach the road", but end their considerations with a need for "more detailed investigation[s]" (ibd. 2005: 75f.). The same tendency can be detected in both regions under investigation in this thesis, with longer transportation distances in those catchments in which the flows were able to reach the main channel. In other words, more material was probably involved to keep the flow in motion in those basins.

Analyzing the factors of land use/land cover in more detail (see Table 10, section 5.1. for exact values) reveals a domination of forest areas in the drainage basins (regardless of the occurrence of debris flows or of the factor connectivity). In the second study area, the Johnsbach valley, the majority of areas are covered in forest. However, regarding connected debris flows, the dominant land cover class in those basins is rock/debris.

Further analyses regarding differences and influences of factors of area topography, channel topography as well as land use/cover and lithology on the occurrence and characteristics of debris flows will be presented in the next section in a discussion of the logistic regression models.

6.2. Discussion of logistic regression models

The following paragraphs will discuss the results obtained by logistic regressions that have been computed for the three different categories of models as described in section 5 of this thesis. First, all three categories will be discussed separately and several models will be compared in order to explain the approach to finding the best model(s) of each category or the most suitable model(s) to answer the two parts of the research question. In a next step the models that have been elected will be discussed in more detail. This step involves a separate discussion of both study areas in order to detect similarities, communalities as well as peculiarities of the regions with regard to influential factors on debris flow occurrences and characteristics.

All models have been computed with two options of including the geological setting of the area (as individual factors as well as grouped in classes according to common characteristics of rock formations). The models using the individual classes yielded better results regarding percentages of correctly assigned cases in general and will therefore be used for the remainder of the discussion section.

6.2.1. Models investigating the occurrence of debris flows

Regarding category 1, models that took the whole watershed area into account yielded higher percentages of correctly assigned cases than those that only focused on the upper area of the basins. These findings apply to both study areas, however, the differences are more dominant in study area 1. The following table (Table 15) illustrates this comparison of correctly assigned cases in both study areas. The models with higher percentages are highlighted in color.

Table 15 Results of models of category 1 (correctly assigned cases)

Models	No.	Percentage correct	Correct where dependent var. = 1	Correct where dependent var. = 0
Kleinsölk valley whole area *KS-C1-wa-geo-sep*	M2	83.3	70.0	89.8
Kleinsölk valley upper area *KS-C1-ua-geo-sep*	M4	75.6	50.0	88.0
Johnsbach valley whole area *JB-C1-wa-geo-sep*	M6	95.8	58.6	98.9
Johnsbach valley upper area *JB-C1-ua-geo-cl*	M8	93.8	37.9	98.3

As this table shows, in both study areas the models that took the whole catchment area into account yielded higher proportions of correctly assigned cases in total as well as regarding the percentage of 'yes' and 'no' cases. Therefore, models *KS-C1-wa-geo-sep* (for study area 1) and *JB-C1-ua-geo-sep* (for study area 2) should be preferred for category 1. All models in this category are better at predicting cases in which the dependent variable is coded as '0' ('no debris flow'); the values for the percentages of debris flow occurrences are smaller.

The models computed for category 2 are similar regarding the observations presented in the previous paragraph. As discussed before, the percentages of correctly assigned cases in general as well as those for both characteristics of the dependent variable are smaller when using the variables for the upper areas of the catchments (Table 16).

Table 16 Results of models of category 2 (correctly assigned cases)

Chose part of the study areas	No.	Percentage correct	Correct where dependent var. = 1	Correct where dependent var. = 0
Kleinsölk valley whole area *KS-C2-wa-geo-sep*	10	78.3	78.8	77.8
Kleinsölk valley upper area *KS-C2-ua-geo-sep*	12	68.3	60.0	76.5
Johnsbach valley whole area *JB-C2-wa-geo-sep*	14	82.3	69.0	88.1
Johnsbach valley upper area *JB-C2-ua-geo-sep*	16	80.2	58.6	89.6

As this table illustrates, similar to the models of category 1, models that took the whole area into account should be preferred for both study areas (marked in blue). It seems that the area above a debris flow does not have that much influence as the whole drainage basin does.

Both categories (1 and 2) investigated influential factors on the occurrence of debris flow events (first part of the research question), differing only in sample size. While category 1 took all catchment areas into account, category 2 only included those basins in which channels could be verified in the aerial images. Comparing the models of category 1 and 2 leads to the preference of models belonging to the first category to answer the first part of the research question (influential factors on the occurrence of debris flow events) with higher values of correctly assigned cases in general. Those models will be discussed in more detail in the following (models presented in Table 15).

Interestingly, the models of category 2 achieved higher percentages of correctly assigned cases of debris flow occurrences (dependent variable = 1) than those of category 1. This may be caused by a better distribution of 'yes' and 'no'-cases in the models of category 2. However, du to the higher percentages of correctly assigned cases in general, models of category 1 were elected to best explain the occurrence of debris flows.

In order to reveal and discuss the factors that influence debris flow occurrences and lead to those percentages, the following table (Table 17) presents the variables and their regression coefficient values that stayed in the models after using the technique of backward logistic regression. The significance of each independent variable that stays in the model is reflected in the values and directions of the regression coefficients, which determine the relationships between the independent and the dependent variable (ZHUANG 2015: 458).

Table 17 Results category 1 – variables and regression coefficients of chosen models

Kleinsölk *KS-C1-wa-geo-sep* **valley**		**Johnsbach valley** *JB-C1-wa-geo-sep*	
Variables	***Regression coefficient B***	***Variables***	***Regression coefficient B***
Area size (m^2)	1.331	Land use variety	2.154
Area Aspect (category of reference)		% covered in forest	-0.078
Area Aspect (W)	-2.006	% covered in construction	-0.769
Area aspect (E)	-0.004	% covered in grassland	-0.070
Area aspect (N, NE, NW)	-19.819	% covered in Allgäu stratum: limestone and marl	-14.496
Area slope	0.210		
% covered in grassland	0.023	% covered in colluvial sediment	-0.025
% covered in granite/gneissic granite	0.057	% covered in Dachstein limestone	-0.029
% covered in hornblende quartzite (schist)	0.047	% covered in weathered slope rock breccia	0.068
% covered in paragneiss	0.041	Constant	-1.045
% covered in ground moraine/moraine debris	0.048		
Geological variety	0.519		
Constant	-21.751		

Illustrated in this table (Table 17), the models in the two study areas retained different factors in the end-models. Implications from those values will now be presented and discussed for both study areas separately.

6.2.1.1. Implications for study area 1

As expected from readings and an investigation of similar studies, topographic factors showed great significance in explaining the occurrence of debris flows in the Kleinsölk valley (study area 1). The best model for this study area (*KS-C2-wa-geo-sep)* includes the size of the area as well as area slope and area aspect as influential variables, with all three showing a positive regression coefficient. In other words, the steeper an area is on average, the higher is the probability that a debris flow occurs; the bigger an area is, the higher is the chance of occurrence. Similar results focusing on a positive regression coefficient of the factor area size have been obtained by CHEN et al. (2014: 551).

The factor aspect in the model reveals a tendency for debris flows to occur on slopes facing south, southeast or southwest. If slopes face either one of these directions (which were used as category of reference in the logistic regression), the probability of a debris flow to occur is higher than with all other orientations (N,NE,NW,E,W). Those directions lead to a reduction of probability values. The predominance of mass movement events on mainly "south-facing slopes" has also been discovered in the study by REGMI et al. (2014: 259).

Looking at those topographic factors in more detail can help to reveal interesting insights. Similar to the study by ELKADIRI et al. (2014: 4822), I assumed that "an increase of debris-flow occurrences with increase in slope angle" would result from my analyses, which proved to be true in study area 1 (Kleinsölk valley). In fact, slope has been an important factor in the results of several other studies investigating debris flows or landslides with the help of logistic regression models (e.g. TUNUSLUOGLU et al. 2008; RAMANI et al. 2011; DEVKOTA et al. 2013; REGMI et al. 2014; ZHUANG et al. 2015). RAMANI et al. (2011: 515f.), for example, have proved "that slope plays a vital role in causing slope instability in [their] study area". Further similar results regarding a positive regression coefficient of the factor slope angle have been obtained by NANDI & SHAKOOR (2009: 18) and CARRARA et al. (2008: 368). Therefore, with regard to the factor slope angle, a significant influence of slope steepness on the initiation of debris flow events can be assumed.

Regarding the mean aspect of watershed areas in the Kleinsölk valley it has been shown that most debris flows occur on slopes facing S, SE or SW. These directions were grouped and used as the category of reference in the logistic regression due to the high number of cases in those categories. If slopes are facing other directions, the chances of debris flows to occur are smaller, represented in the negative coefficients of those categories. Other studies on debris flow or landslide occurrences also included slope aspect in their analyses (e.g. ELKADIRI et al. 2014) due to correlations with wind, sun and rainfall in a region (see section 6.1. of this thesis). More impact of rainfall as well as more direct exposure to sunlight can contribute to faster and more intensive weathering of soil as well as underlying rock formations.

Concerning the various aspects of lithology that have been included as influential factors in the statistical analysis, several variables stayed in the Kleinsölk valley model. First of all, the results show that geological variety promotes debris flow events in this region. In other words, the chance of a debris flow to occur is higher if there is a higher variety of different rock types and rock formations in one catchment area. This accords with findings from literature. RAMANI et al. (2011: 506), for example, note that "[s]tudies on landslide susceptibility analysis show that variation in lithology is an important parameter causing slope instability". Since slope instability is significant for the occurrence of all landslides, a similar importance for debris flow events may be inferred. The study by RAMANI et al. (2011: 506), however, did not include geological variation in their analysis due to a lack of various rock types in their region under investigation. The results from my analysis, nevertheless, reveal an importance of this factor.

Further variables regarding the lithological setting that stayed in the model, proposing a possible influence on the occurrence of debris flows, are granite/gneissic granite, hornblende quartzite of the hornblende-schist stratum, paragneiss and ground moraine/moraine debris. The variables included in the analyses all focused on the percentages of an area that are composed of those geological rock formations. All lithological variables show a positive regression coefficient. Therefore, the bigger the parts in a drainage basin that are composed of each of those geological formations, the bigger the chance that debris flows occur in the Kleinsölk valley. Examining several qualities of those rock formations in literature let me expect some of those features, however, some seemed to be peculiar at first. Especially granite and gneissic granite, which are rather hard rock formations and not always connected with mass events immediately, were not expected to lead to debris flows in the same way that moraine debris does.

The influence that geology has on debris flows has to be analyzed carefully due to considerations by HEALD & PARSONS (2005: 71). They discuss that "[s]ince [...] flows largely mobili[z]e unconsolidated deposits, the influence of bedrock geology may at first be considered to be limited" (ibd. 2005: 71). According to their investigations of debris flow events in Scotland, schist is "a rock type often associated with a relatively low debris flow activity" (ibd. 2005: 71). However, similar to my results, in their study area many regions that experienced debris flows were composed of schist. They further discuss the importance of schist and metamorphic rocks (which would include paragneiss and the hornblende quartzite in the Kleinsölk valley) in their importance for debris flow events. According to HEALD & PARSONS (2005: 71), there is a "tendency for schists and similar metamorphic rocks to weather to produce fine soils", even though connections between debris flow events and rock formations still have to be investigated. Moreover, HEALD & PARSONS (2005: 71) also regard the "low permeability of these rock types [as] likely to limit dissipation of pore water pressures by under drainage".

However, conclusions drawn from the variables regarding the lithological setting of the areas that stayed in the models should be treated carefully. Similar to the situation investigated in Scotland, where the rock formations that were connected with debris flow events were also the predominant rock formation in the entire region, those formations that stayed in the model in the Kleinsölk valley are also dominant regarding the lithology of the whole area.

It can be concluded that, "while the solid geological formation is not in itself considered significant, the lithology of the underlying bedrock is likely to be a secondary influence" (HEALD & PARSONS 2005: 71). Therefore, results regarding the lithology should be investigated in combinations with other factors (factors of topography and soil properties). CARRARA et al. (2008: 370) come to similar conclusions and see "bedrock geology" as an important factor "control[ing] debris-flow occurrence" together with other factors in their analysis.

In an examination of all factors that have remained in the model, the point in time of the analysis also needs to be taken into account. This applies for the geological results as well as all other results when it comes to explaining possible peculiarities. The aerial photos, which were taken as a basis to determine which watersheds experienced debris flows and which did not, depict the situation of the region after the severe rainfall event in 2010 (see section 3.1.4. of this thesis). In course of this weather event, especially one valley in the Kleinsölk valley was most affected because of the location of the thunderstorm, namely the area around the Breitlahnalm (ENNSTALWIKI 2016).

Comparing the geological map of the area with my results reveals that especially those parts that were most affected by the thunderstorm cell are composed of those rock formations that were retained in the model. Therefore, it cannot be directly concluded that those rock types lead to or promote debris flow events since only this one point in time could be evaluated in the course of this study. To further analyze the factor lithology, it would be necessary to conduct similar analyses at different points in time in the same valley, when thunderstorm cells are more evenly distributed.

From the variables belonging to the category of land use/land cover only one variable (the percentage of an area covered in grassland) remained in the model, exhibiting a positive regression coefficient. It appears that areas that are largely covered in grassland are particularly prone to debris flow events. These findings correlate with information provided by HEALD & PARSONS (2005: 74), who analyze the influence of several factors regarding vegetation and land use on the occurrence of debris flows. According to their investigations, "[d]ifferent types and densities of vegetation may be more or less retardant to debris flows depending upon how they affect soil infiltration rates and upon how their root systems serve to hold the soil in place" (ibd. 2005: 74). In their study they refer to landslide events in Hong Kong in the years of 1992-1993, when landslides rather affected areas "with low scrub and grass", instead of regions which were covered with "the dense tropical vegetation typical of the region" (ibd. 2005: 74). HEALD & PARSONS (2005: 74) conclude that "[f]orestry in particular" can help to minimize the harmful effects of debris flows. DEVKOTA et al. (2013: 155) obtained similar results regarding the influence of grassland. In their study on landslides in the Himalaya, forest led to a reduction of landslide occurrences while grassland seemed to promote events. Moreover, CARRARA et al. (2008: 370), who investigated the influence of "pasture" and "non-vegetated land", came to the conclusion that those types of land cover promote debris flow occurrence.

Similar conclusions can be drawn from the results regarding land use/cover in the Kleinsölk valley. Based on the positive regression coefficient it can be concluded that areas that are mostly composed of grassland are more likely to experience debris flow events.

Having discussed the effects and results of the regression coefficients, the variables and their values can be inserted in the formula presented in chapter 4.3.1. of this thesis in order to compute values for the probability of debris flow occurence:

$$\boldsymbol{p} = \frac{1}{1 + e^{-z}}$$

The calculation for the z-value in the Kleinsölk valley can be computed the following way (Table 18):

Table 18 Formula for computing the z-value for the Kleinsölk valley

z =	1.331 * area size	+	0 * aspect (S,SE,SW) / or / (-2.006) * aspect (W) / or / (-0.004) * aspect (E) / or / (-19.819) * aspect (N,NE,NW)					+
	+ 0.210 * area slope	+	0.519 * geological variety	+	0.057 * area covered in granite	+	0.047 * area covered in schist	+
	0.041 * area covered in paragneiss	+	0.048 * area covered in moraine debris	+	0.023 * area covered in grassland	+	(-21.751) (constant)	+

The following map (Figure 24) visualizes the values regarding the probability of debris flow occurrences in each catchment area of study area 1. Drainage basins that display a probability value above 0.5 are likely to experience debris flows, whereas those with values below that threshold are not that susceptible.

The visualization of those values shows a rather even distribution of catchments that are vulnerable to experience debris flow events and those that are not at risk. What immediately stands out in this figure is the influence of the factor area size as discussed in the previous paragraphs with numerous rather big areas highlighte in red.

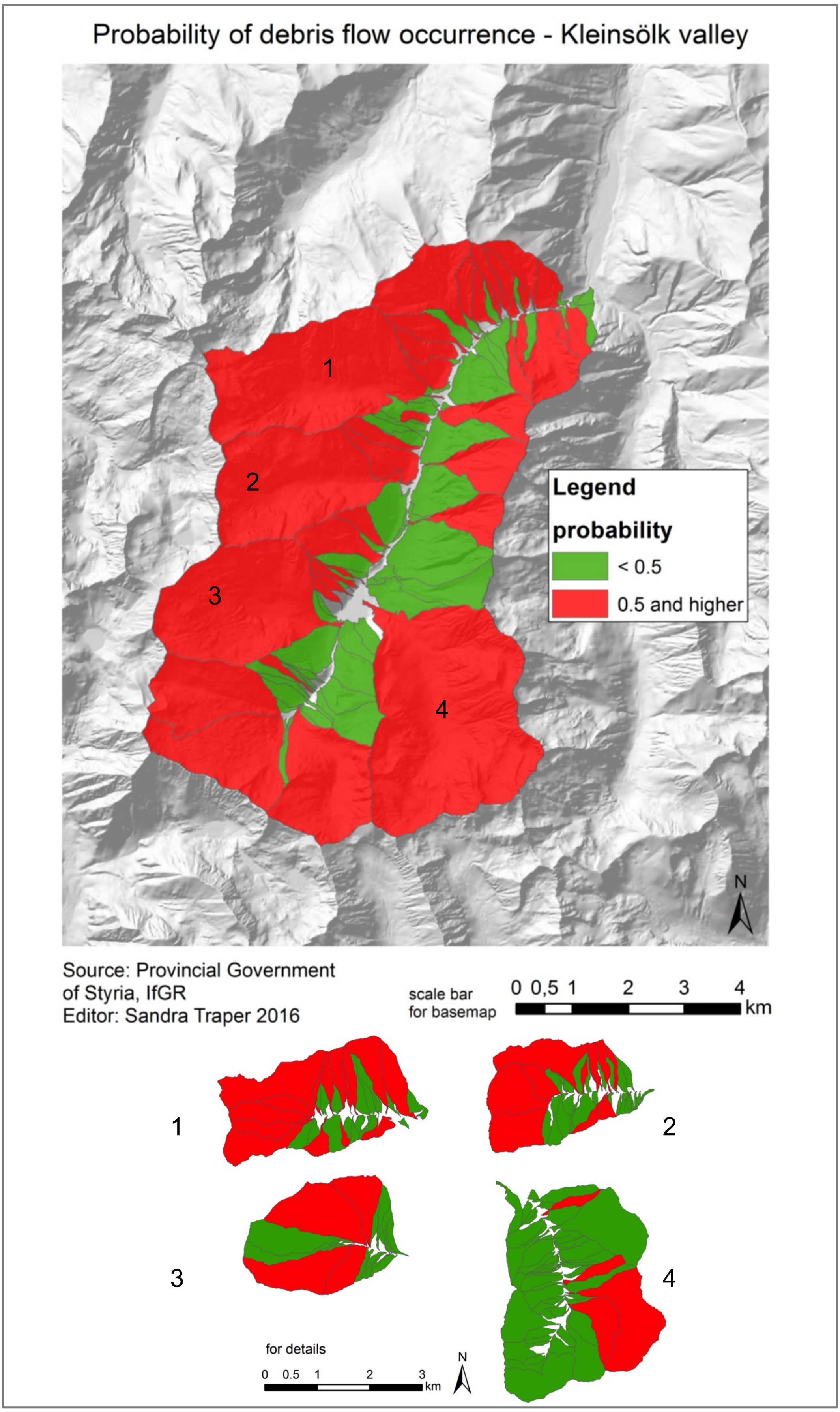


Figure 24 Probability of debris flow occurrence - Kleinsölk valley

6.2.1.2. Implications for study area 2

Having discussed the results of the best model to answer part one of the research question for study area 1 (Kleinsölk valley), the next paragraphs focus on study area 2 and discuss similarities and differences. Looking at the results for the Johnsbach valley and comparing it with the Kleinsölk valley surprisingly shows that topographic factors do not seem to influence the occurrence of debris flows in this region. Using the same technique (backward conditional logistic regression) did not result in the same variables in the end-model. While the logistic regression for the Kleinsölk valley resulted in a significance of several topographic factors, no variable describing area topography was retained in the model in the Johnsbach valley.

In the Johnsbach valley the model with the best explanatory power retained the following variables: Variety of land use/cover, the percentage of an area covered in forest, construction, grassland as well as several variables regarding the lithology of the area (area composed of Allgäu stratum (limestone and marl), colluvial sediment, Dachstein limestone, weathered slope rock breccia).

Before analyzing these results in more detail, some explanatory remarks shall be provided. The Johnsbach valley was investigated based on aerial images depicting the situation in 2010 (similar to the Kleinsölk valley). However, while in study area 1 a severe thunderstorm had led to numerous debris flows and those effects were still visible in the photographs, in the Johnsbach valley no weather event of a similar magnitude and extent had happened in that time frame. Therefore, fewer catchment areas with debris flow events could be detected in the aerial images compared to the Kleinsölk valley. Compared to the overall number of catchments in the Johnsbach valley, the number of drainage basins that had experienced debris flow events was rather small. This is not the best precondition for a logistic regression since the dependent variable in such an analysis should be distributed independently (see BACKHAUS et al. 2016: 346). An even distribution of both characteristics of the dependent variable could not be achieved in the Kleinsölk valley either, however, the difference between catchments with debris flows and those without events was more prominent in the Johnsbach valley with only 29 catchments with debris flows from an overall number of 384 catchments. In comparison, in the Kleinsölk valley 80 debris flow events were distributed in an overall number of 246 catchments. In general, BACKHAUS et al. (2016: 346) recommend a number of at least 25 cases of each characteristic of the dependent variable for significant results.

Despite these more difficult original conditions in study area 2, the percentages of correctly assigned cases were rather high and implications and details regarding the independent variables will be presented. While in the model for the Kleinsölk valley the percentage of an area covered in grassland showed a positive coefficient, meaning that areas with more grassland experience more debris flows, the opposite resulted from the analysis in the Johnsbach valley. Three factors of land use/cover were retained by the logistic regression in the end-model (percentage of an area covered in grassland, construction and forest) and all three show a negative regression coefficient. Regarding the area covered with forest I expected these results, based on the considerations by HEALD & PARSONS (2005: 74) on the importance of wood and forest areas for the prevention of debris flows. Areas with dense forests are less likely to experience debris flows because of their "root systems [which] serve to hold the soil in place" and the effect that forests have on "soil infiltration rates" (ibd. 2005: 74). Similar information on the role of forests to prevent debris flows is provided by ISHIKAWA et al. (2003: 37), who discuss the role that forest areas play in avoiding the initiation of debris flows "by reinforcing soil through root strength" as well as hindering the flow of debris. Similar to the results regarding forested area in this study, DEVKOTA et al. (2013: 155) obtained a negative regression coefficient of the factor forest in their study.

The influence of construction does not seem to be that straightforward to explain as the role of forest. In study area 2 mainly forest roads are the dominant forms of construction in the region. HEALD & PARSONS (2005: 74f.) in their investigation on tracks, pathways and similar features come to the conclusion that "these features are of local significance and would be difficult to incorporate into a national model" (HEALD & PARSONS 2005: 75). However, they agree that those features may have an influence on debris flow occurrence (ibd. 2005: 74). The direction of influence is not always easy to determine since "[t]erraces, ditches (natural or otherwise), and breaks in slope may have a positive or negative influence on the formation of debris flows depending upon their form or location" (ibd. 2005: 70). They further discuss "natural or artificial barriers in the source, transportation or deposition zones [which either] may retard the formation or impact of a flow" (ibd. 2005: 70). The same considerations shall be given to roads and forest paths in the study area. Depending on their location and orientation within a catchment area, positive or negative influences can be achieved. Overall, the factor construction shows a negative influence in the Johnsbach valley, meaning that more construction leads to less debris flows.

The influence of grassland areas on debris flow occurrences resulted in the opposite information as in the Kleinsölk valley. In the Johnsbach valley the results indicate that less grassland results in less debris flows in this study area. However, the nature of the Johnsbach valley and its setting is different to the Kleinsölk valley. In this region in the Gesäuse more areas are covered in rock/debris in the steeper regions of the study area. Therefore, areas with grassland are mostly located in flatter areas that are not affected by debris flow events. While those catchment areas that are covered with more than 50% grassland show an average slope angle of only 23.34°, those areas that are more than half composed of rock/debris have an average slope angle of 48.70° (the average slope angle of all areas, regardless of land cover patterns, is 30.17°). These values suggest that the factor grassland has been included in the model with a negative coefficient due to the location of grass areas in flatter areas of the valley.

One further factor of the category land use/cover stayed in the model, namely the variety of land use/cover. This variable shows a positive coefficient, meaning that the more different land use classes are present in one catchment area, the higher the probability that debris flows might occur.

The remaining variables in the model belong to the category lithology. Three lithological classes (Allgäu stratum (limestone and marl), colluvial sediment and valley floors, Dachstein limestone) have a negative coefficient, the existence of weathered slope rock breccia in a catchment area, however, shows a positive coefficient. Several researchers mention the importance of debris material and breccia on slopes for the occurrence of mass movements. For example, HEALD & PARSONS (2005: 71) discuss "[t]he presence of a mantle of superficial deposits" which is necessary to initiate debris flows. Colluvium and valley floors, which are also characterized by loose material, however, are mostly located in rather flat areas and are therefore marked with a negative coefficient.

Similar to study area 1, the factors obtained by computing the regression models have been inserted in the formula presented earlier, resulting in the following calculation for values regarding the probability of debris flow occurrence:

$$\boldsymbol{p} = \frac{1}{1 + e^{-z}}$$

Table 19 Formula for computing the z-value for the Johnsbach valley

$z =$

*2.154 * land use variety*	+	*(-0.078) * area covered in forest*	+	*(-0.769) * area covered in construction*	+	*(-0.070) * area covered in grassland*	+
*(-14.496) * area covered in Allgäu limestone*	+	*(-0.025) * area covered in colluvium*	+	*(-0.029) * area covered in Dachstein limestone*	+	*0.068 * area covered in debris*	+
(-1.045) (constant)							

The following map (Figure 25) visualizes the probabilities in the Johnsbach valley. Again, those drainage basins that received a value above 0.5 (a debris flow is likely to occur) are marked in red, whereas those that are unlikely to experience a debris flow with values below 0.5 are marked in green.

Vulnerable areas are mostly located in the northern part of the valley, where the Johnsbach flows in a south-north direction. Steep slopes and an abundance of debris material characterize this part of the region, which provide the prefect conditions for debris flow events.

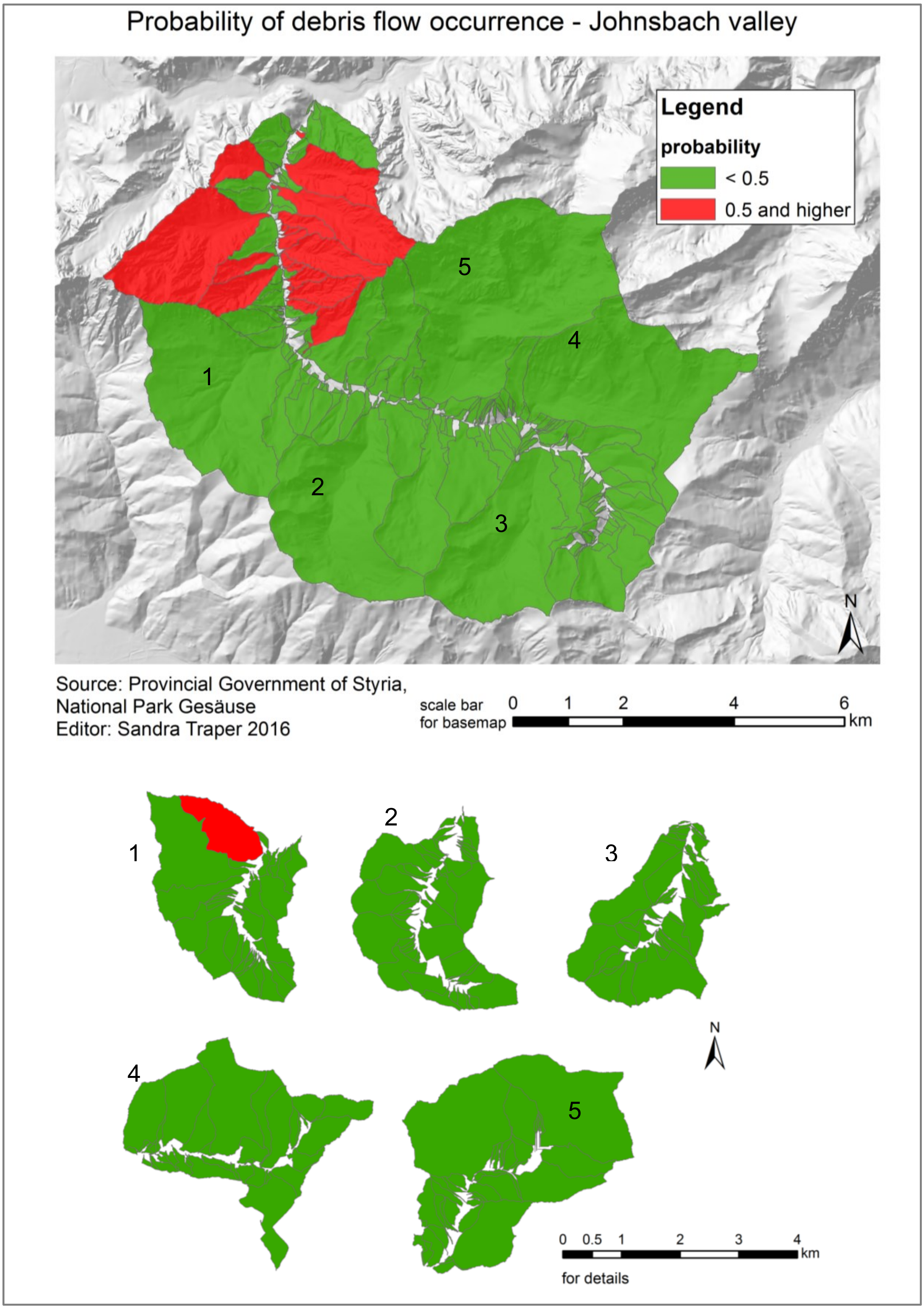


Figure 25 Probability of debris flow occurrence - Johnsbach valley

6.2.2. Models investigating the characteristics (connectivity) of debris flows

In contrast to the models discussed in the previous sub-sections of this thesis, the models of category 3 did not investigate the occurrence but the characteristics of a debris flow, more precisely the possibility of a debris flow to reach the main channel (connectivity). This problem was investigated by analyzing data from the Kleinsölk valley separately as well as by combining the data sets (without the factors regarding lithology due to different and not comparable geological settings). An investigation of the question in the Johnsbach valley alone would not have led to significant results because of a rather small sample size of only 29 debris flow events. In the course of this section, the following sub-question of the main research question presented in the introduction to this thesis shall be answered:

- ***(2) Which debris flows showed signs of connectivity and managed to reach the channel system of both valleys, which did not and why?***

In the models of category 3 channel specific parameters (length and slope of the whole channel as well as of channel parts) were included in the regression models. In order to find the model with the best explanatory power, several combinations of channel parameters were tested in combination with factors of land use/cover and area topography. The explanatory power of the best models for the Kleinsölk valley as well as for both valleys are illustrated in the following table (Table 20):

Table 20 Results of models of category 3 (correctly assigned cases)

Study area with differences regarding variables	No.	Percentage correct	Correct where dependent var. = 1	Correct where dependent var. = 0
Kleinsölk valley whole area *KS-C3-wa-ch,lu*	17	77.5	84.3	65.5
KS + JB valley whole area *KS-C3-wa-ch,lu*	19	74.3	87.5	55.6

Both models include factors of area topography as well as factors of channel topography and variables regarding land use/cover in the regressions. In both cases slope of the channel, area size, the percentage of an area covered in grassland, rock/ debris and forest as well as the percentage of the total length that is part of the debris flow transition distance (part 2) and the debris deposit distance (part 3) stayed in the model. The next table (Table 21) presents the regression coefficients of those variables.

Table 21 Results category 3 – variables and regression coefficients of chosen models

	KS-C3-wa-ch,lu	*KSJB-C3-wa-ch,lu*
Variables	Regression coefficient B	Regression coefficient B
Channel slope (°)	0.142	0.113
Area Size (m^2)	2.421	1.972
% covered in rock/debris	2.110	1.431
% covered in grassland	2.117	1.429
% covered in forest	2.111	1.423
Channel part 2 - % of length of total channel length	0.061	0.030
Channel part 3 - % of length of total channel length	0.115	0.092
Constant	-230.327	-157.441

In both models channel slope shows a positive coefficient, meaning that steeper channels promote hillslope-channel connectivity. The effects of slope values on characteristics of a debris flow have been discussed by HEALD & PARSONS (2005: 68), who identify a universal understanding "that slope angle is a fundamentally important factor influencing the occurrence of debris flows". However, not only the occurrence itself is influenced by the slope angle but also different values are regarded as important to trigger the event and "to maintain the mobility of the flow in its run-out zone" (HEALD & PARSONS 2005: 68). It can be concluded that the factor slope angle influences the mobility of a flow and determines if a debris flow reaches the river.

The size of a catchment area also shows a positive correlation with the probability of connectivity to occur. The bigger an area is in size, the higher the probability that a debris flow in a catchment area reaches the river. These findings can be explained with the availability of debris material as well as discharge. Bigger areas experience more discharge and more material is available to be set in motion and initiate a debris flow as well as to keep the flow moving.

The three factors of land use/cover that stayed in the model are not that straightforward to interpret since, according to the models, areas with rock/debris, grassland as well as forest all promote connectivity with rather similar values. Disregarding the algebraic signs of the coefficients for a first interpretation leads to the conclusion that variables concerned with land use/cover in fact can have an influence on possible connectivity of a debris flow. These findings should be seen in the context of channel-specific topographic parameters. HEALD & PARSON (2005: 76) discuss effects on the "run-out zone" of a debris flow and, thus, on the possibility of a debris flow to connect to the channel network and conclude that "surface conditions [...] may permit or impede the run-out of the flow". Their further explanations focus on the contradictory appearing influence of forest. While "[a]fforestation may be [...] important in retarding flows", areas with forest can also have the opposite effect if a lot of trees are uprooted, which may then "contribute to the power of debris flows" (ibd. 2005: 76). According to their study "hard surfacing or pasture land may be much more permissive to flows" (ibd. 2005: 76), which is true for the other two factors of land use/cover with positive algebraic signs in the model (grassland and rock/debris).

ISHIKAWA et al. (2003: 44), in their study on the role of forest on several parameters of debris flows, investigated the impact of forested areas on the length of the zone in which debris is deposited. According to their findings, "forest is considered to be effective in suppressing sediment movement", because forested areas show shorter zones of deposition than areas with grassland (ibd. 2003: 44). Findings in this study are similar. Investigating the factor forest with regard to the length of the debris deposition zones leads to mean length of debris deposition zones of 159.87 m if more than 50% of the area is covered in forest and 191.79 m if less than half of the catchment is composed of forest (see Table 22).

Table 22 Comparison of lengths of mean debris deposition zones

Forest coverage	*Length of debris deposition zone*
Areas with more than 50% of the total area covered in forest	159.87
Areas with less than 50% of the total area covered in forest	191.79

The last two variables that stayed in the models are concerned with channel topography. According to these findings, the bigger the share of the length of part 2 and part 3 of the total channel length, the higher the probability that a debris flow will reach the river in both the Kleinsölk valley and in both study areas together. These results propose that a longer transportation distance as well as a longer debris deposit distance leads to more cases of connectivity. Those findings should be seen in context of material availability, meaning that longer channels may provide more debris material and may therefore keep the flow in motion.

Coming back to sub-question (2) of the main research question,....

- ***(2) Which debris flows showed signs of connectivity and managed to reach the channel system of both valleys, which did not and why?***

...the following statements shall summarize the findings and answer this question. In both areas under investigation steep channels and large watershed areas promoted hillslope-channel connectivity (positive regression coefficient of both variables). Regarding land use/cover, particularly areas with high percentages of grassland, of rock/debris as well as of forest increased the chance of connectivity. Further factors that played a decisive role in promoting connectivity in both regions included longer debris flow transportation distances as well as longer debris deposit distances. It can therefore be summarized that particularly those factors influenced connectivity of debris flows in both areas under investigation at that point in time.

According to the formula presented by BÜHL (2014: 458f.) probabilities of the occurrence of connectivity can be computed.

$$p = \frac{1}{1+e^{-z}}$$

The formula for computing the z-value in the Kleinsölk valley is:

Table 23 Formula for computing the z-value for the Kleinsölk valley

z =

*0.142 * channel slope*	+	*2.421 * area size*	+	*2.110 * area covered in rock/debris*	+	*2.117 * area covered in grassland*	+
*2.111 * area covered in forest*	+	*0.061 * percentage of length of part 2 of total channel length*	+	*0.115 * percentage of length of part 3 of total channel length*	+	*(-230.327)*	

The z-value for both study areas together can be obtained by the following calculation:

Table 24 Formula for computing the z-value for both regions

z =

*0.113 * channel slope*	+	*1.972 * area size*	+	*1.431 * area covered in rock/debris*	+	*1.429 * area covered in grassland*	+
*1.423 * area covered in forest*	+	*0.030 * percentage of length of part 2 of total channel length*	+	*0.092 * percentage of length of part 3 of total channel length*	+	*(-157.441)*	

6.2.3. Similarities and differences between the two study areas

As a final conclusion and closure to the results discussed in the previous chapters some general remarks on debris flow occurrences and characteristics shall summarize the findings and answer the following sub-question, presented in the introduction to this thesis:

- ***(3) What differences concerning debris flows can be observed in the two geologically different regions regarding influential factors?***

While some aspects regarding influential factors on debris flow occurrence and characteristics are similar and resulted in related outcomes in both regions, several factors highlight the differences between those regions. Connectivity in both study areas can be explained by a combination of the same factors (see Table 21), namely steep channels with long debris flow transportations distances as well as long debris deposit distances in big drainage basins as well as a domination of several land use/cover classes. The general occurrence of debris flows, however, is influenced by different aspects in the two study areas, according to the results obtained in this study (see Table 17). Particularly the factor grassland resulted in different regression coefficients in both areas. However, those peculiarities have to be considered with regard to the general settings and landscape conditions of both areas (locations of grassland areas), as discussed in section 6.2.1.2. While in the Kleinsölk valley several topographic factors are included in the best model, the model for the Johnsbach valley only includes factors of land use/cover and no variables of area topography. The existence of debris material and weathered slopes has been proven to promote debris flows in both regions.

Taking the illustrations of probability-values above 0.5 (a debris flow is likely to occur according to the results) into account (Fig. 24 & 25), reveals a rather even distribution of susceptible basins in the entire region in the Kleinsölk valley, while most susceptible drainage basins are located in the northern part in the Johnsbach valley.

6.3. Use and limitations of these methods/models

Subsequent to the discussion of the results and implications of the logistic regression models, some statements will focus on the suitability as well as on possible limitations of these methods and models. The following sub-question, presented in the introduction to this thesis, shall be answered:

- (1) I***n how far can the methods proposed in the thesis be relevant and help to bring new insights into this field of research?***

In general, significant and meaningful results could be obtained by the combination of a theoretical literature review and DEM-based GIS-analyses as well as statistical analyses. The categories of influential factors investigated in this thesis (factors of area and channel topography, land use/cover and lithology) have been proven to influence the occurrence as well as the connectivity of debris flows in different intensities and directions. Results obtained in the empirical part of this paper accorded with findings from previous studies and literature on the phenomenon of debris flow to a large extent (particularly regarding the influence of land use/cover and topography). New insights could be gained regarding several aspects of area lithology and aspects of land use/cover (e.g. the influence of forest areas). Therefore, the combination of methods applied in this thesis can be regarded as useful for an investigation of natural processes like debris flows.

However, like most methods used to predict occurrences, the models computed in the course of the empirical part of this thesis cannot be seen as absolute. In both study areas only one particular point in time had been selected and was investigated thoroughly. Therefore, the models generated in this study are only applicable to exactly that point in time; thus, a transfer to other time scales and other areas that have experienced different weather conditions may be problematic. As also discussed by RUPERT et al. (2008: 8), who specify that their models are generally applicable for the study area in which they were developed (in their case southern California), the models in this thesis are primarily applicable in the two study areas in Styria for which they were generated. However, even in those catchment areas no "absolute certainty" (RUPERT at al. 2008: 8) can be given that watersheds that exhibit the features that are mentioned in the models will lead to a debris flow event since several other factors that have not been included in this thesis (particularly hydrological features as well as factors regarding soil properties) are important as well. The considerations of RUPERT et al. (2008: 8) regarding their data and models also apply to the results in this thesis, in which instead of "absolute certainty" "rather the potential for (or likelihood of) a debris flow if a rainstorm of sufficient intensity occurs" is provided by the analyses. Taking these considerations into account, one particular statement by RUPERT et al.

(2008: 8) summarizes the core of these statistical analyses accurately, namely that "[p]robability is not the same as certainty; a high-probability basin may not experience a debris flow, and a low-probability basin may still experience a debris flow".

Despite these limitations, the models that have been developed in the course of the analyses can help to handle debris flows in those regions by providing the basis for susceptibility mapping of the areas.

6.4. Outlook

Several factors of influence have been included in the analyses in the empirical part of this thesis. While the results regarding the occurrence and characteristics of debris flows are significant and meaningful in both study areas, several steps could be taken in order to improve the explanatory power as well as to provide more depth of information in these models. Taking the time scale that was investigated into account, it has to be noted that further long-term research is necessary to verify the results obtained in this study. The results that have been obtained by an analysis of catchment areas at one particular point in time should be compared to investigations of different time scales in both areas.

Furthermore, while all factors that have been included in the analyses (several factors of topography, land use/cover and lithology) have resulted in an influence regarding the occurrence and characteristics of debris flow events, regression models that include additional variables could enhance the depth of content of these results. Coming back to the discussion of triggering and preparatory factors discussed in section 2.1.4. in this thesis, leads to the conclusion that especially factors of soil properties should be taken into account in further studies. The importance of factors regarding soil type and properties is also mentioned by MCMILLAN et al. (2005: 27), who identified "[s]oil type [as] an important factor in debris flow activity" in their investigations of landslide and debris flow hazards in Scotland. Therefore, the inclusion of the factor soil in further statistical analyses in addition to the factor lithology could lead to new insights. Furthermore, additional classes regarding the land use/cover of the area should be considered. For example, a further classification of areas belonging to the land use/cover class forest in this thesis into more sub-classes could lead to interesting results. Particularly land use/land cover classes focusing on damages or intensive uses of areas could yield significant results. Taking the discussion of results regarding the influence of forest into account leads to a particular significance of areas that have experienced damage to trees or areas that have experienced damage due to strong winds as those areas could either promote or prevent debris flows. An inclusion of these factors in further studies on the topic is recommended.

7. Conclusion

The present thesis focused on an investigation of influential factors on the occurrence and characteristics (connectivity) of debris flows in two geologically different areas in Styria, Austria. The topic was investigated using a combination of several methods. A literature review provided the basic information on debris flow occurrences, on triggering and preparatory factors as well as on hillslope-channel connectivity, while subsequent empirical investigations focused on DEM-based GIS-analyses and statistical analyses. The main aim of those analyses was the creation of models that illustrate and estimate the influences of several factors by using the technique of logistic regression. Two regions in Styria, which are both prone to debris flow events, provided the data for those analyses. In the course of this thesis it has been shown that variables from the categories of topography, land use/land cover and lithology influence the occurrence and characteristics of debris flow events in different intensities and different directions in both areas under investigation. Particularly factors regarding dominant land use/cover of an area have been shown to be important with regard to debris flow events. While the influence of forest is not persistent in its direction and intensity in both study areas, grassland and areas covered in unconsolidated debris lead to more debris flows in general and to more connected debris flows in particular. Factors regarding area as well as channel topography influence the occurrence and connectvity of debris flows in the Kleinsölk valley and in both areas in combination. Further long-term research is necessary to verify the results obtained in this study.

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9. Appendix

Results of the logistic regression models

Model & Number	Chi-square (Significance)	Nagelkerke R Square	Percentage correct (%)	Correct where dep.var. = 1 (%)	Correct where dep.var. = 0 (%)	Variables (see section 4.3.2, Table 7, for explanations)	Regression coefficient B	S.E.	Wald	df	Sign.of coeff.	Exp(B)
Category 1												
KS-C1-wa-geo-cl	116.319 (0.000)	0.526	82.1	66.3	89.8	Granite_comb_wa	0.14	0.007	3.960	1	0.047	1.014
						Area_wa	1.727	0.454	14.481	1	0.000	5.624
M1						Slope_wa	1.196	0.045	19.377	1	0.000	1.217
						Geology_variety_wa	0.316	0.154	4.191	1	0.041	1.372
						Land_class4_wa	0.21	0.007	8.011	1	0.005	1.021
						Aspect_wa			9.806	3	0.020	
						Aspect (1) (W)	-1.826	0.587	9.678	1	0.002	1.161
						Aspect (2) (E)	-0.407	0.468	0.758	1	0.384	0.666
						Aspect (3) (N,NE,NW)	-19.770	11051.446	0.000	1	0.999	0.000
						Constant	-18.963	3.251	34.029	1	0.000	0.000
KS-C1-wa-geo-sep	131.149 (0.000)	0.577	83.3	70.0	89.8	Area_wa	1.331	0.480	7.701	1	0.006	3.784
						Aspect_wa			9.050	3	0.029	
						Aspect (1) (W)	-2.006	0.669	8.994	1	0.003	0.134
M2						Aspect (2) (E)	-0.004	0.497	0.000	1	0.994	0.996
						Aspect (3) (N,NE,NW)	-19.819	10386.271	0.000	1	0.998	0.000
						Slope_wa	0.210	0.053	15.684	1	0.000	1.234
						Geology_variety_wa	0.519	0.177	8.555	1	0.003	1.680
						Geology_class7_wa	0.057	0.016	12.631	1	0.000	1.058
						Geology_class9_wa	0.047	0.014	10.572	1	0.001	1.048
						Geology_class12_wa	0.041	0.014	7.877	1	0.005	1.042
						Geology_class13_wa	0.048	0.019	6.165	1	0.013	1.050
						Land_class4_wa	0.023	0.008	7.749	1	0.005	1.023
						Constant	-21.751	3.802	32.725	1	0.000	0.000
KS-C1-ua-geo-cl	71.266 (0.000)	0.351	76.0	53.8	86.7	Aspect_ua			13.781	3	0.003	
						Aspect (1) (W)	-2.154	0.586	13.505	1	0.000	0.116
						Aspect (2) (E)	-0.128	0.413	.0961	1	0.757	0.880
M3						Aspect (3) (N,NE,NW)	-.0385	0.617	.389	1	0.533	0.681
						Slope_ua	0.070	0.028	6.263	1	0.012	1.073
						Landuse_variety_ua	-0.582	0.280	4.321	1	0.038	0.559
						Land_class2_ua	0.023	0.005	17.630	1	0.000	1.023

						Land_class4_ua	0.023	0.005	20.187	1	0.000	1.023
						Debris_comb_ua	-0.017	0.010	2.769	1	0.096	0.983
						Schist_comb_ua	0.008	0.004	3.727	1	0.054	1.008
						Constant	-3.640	1.455	6.256	1	0.012	0.026
KS-C1-ua-geo-sep M4	79.250 (0.000)	0.384	75.6	50.0	88.0	Aspect_ua			10.372	3	0.016	
						Aspect (1)	-1.891	0.593	10.160	1	0.001	0.151
						Aspect (2)	-0.129	0.416	.097	1	0.756	0.879
						Aspect (3)	-0.003	0.606	.000	1	0.996	0.997
						Slope_ua	0.082	0.027	9.083	1	0.003	1.086
						Land_ class2_ua	0.025	0.005	20.129	1	0.000	1.025
						Land_class4_ua	0.024	0.005	21.558	1	0.000	1.024
						Geology_class1_ua	0.048	0.019	6.130	1	0.013	1.049
						Geology_class3_ua	0.042	0.025	2.834	1	0.092	1.043
						Geology_class9_ua	0.017	0.005	11.637	1	0.001	1.017
						Constant	-5.694	1.271	20.057	1	0.000	0.003
JB-C1-wa-geo-cl M5	108.564 (0.000)	0.594	96.1	62.1	98.9	Landuse_variety_wa	1.864	0.462	16.262	1	0.000	6.449
						Land_class5_wa	-0.053	0.014	14.890	1	0.000	0.948
						Land_class1_wa	-0.513	0.234	4.809	1	0.028	0.599
						Land_class4_wa	-0.035	0.018	3.846	1	0.050	0.966
						Wetterstein_limestone_comb_wa	0.030	0.011	7.742	1	0.005	1.031
						Constant	-4.175	1.791	5.435	1	0.020	0.015
JB-C1-wa-geo-sep M6	117.135 (0.000)	0.634	95.8	58.6	98.9	Landuse_variety_wa	2.154	0.510	17.813	1	0.000	8.620
						Land_class5_wa	-0.078	0.016	25.188	1	0.000	0.925
						Land_class1_wa	-0.769	0.285	7.257	1	0.007	0.464
						Land_class4_wa	-0.070	0.015	21.343	1	0.000	0.933
						Geology_class1_wa	-14.496	606.122	0.001	1	0.981	0.000
						Geology_class2_wa	-0.025	0.015	2.672	1	0.102	0.976
						Geology_class4_wa	-0.029	0.014	4.403	1	0.036	0.972
						Geology_class7_wa	0.068	0.033	4.117	1	0.042	1.070
						Constant	-1.045	1.507	0.481	1	0.488	0.352
JB-C1-ua-geo-cl M7	94.305 (0.000)	.525	94.0	44.8	98.0	Landuse_variety_ua	0.849	0.427	3.963	1	0.047	2.338
						Land_class5_ua	-0.037	0.008	20.913	1	0.000	0.964
						Land_class1_ua	-236.580	1817.229	0.017	1	0.896	0.000
						Land_class4_ua	-0.026	0.010	7.310	1	0.007	0.974
						Wetterstein_limestone	0.021	0.006	10.629	1	0.001	1.021

						_comb_ua						
						Dolomite_comb_ua	0.025	0.010	6.852	1	0.009	1.025
						Constant	-1.705	1.009	2.853	1	0.091	0.182
JB-C1-ua-geo-sep M8	89.991 (0.000)	.504	93.8	37.9	98.3	Landuse_variety_ua	1.108	0.462	5.756	1	0.016	3.027
						Land_class5_ua	-0.044	0.008	29.175	1	0.000	0.957
						Land_class1_ua	-242.761	1557.447	0.024	1	0.876	0.000
						Land_class4_ua	-0.044	0.009	24.915	1	0.000	0.957
						Geology_class4_ua	-0.016	0.007	4.847	1	0.028	0.984
						Geology_class6_ua	-0.025	0.019	1.693	1	0.193	0.975
						Geology_class14_ua	-22.837	222.512	0.011	1	0.918	0.000
						Constant	-0.162	0.960	0.029	1	0.866	0.850
Category 2												
KS-C2-wa-geo-cl M9	60.332 (0.000)	0.417	76.4	78.8	74.1	Area_wa	0.879	0.509	2.982	1	0.084	2.407
						Aspect_wa			9.951	3	0.019	
						Aspect (1) (W)	-1.805	0.595	9.208	1	0.002	0.164
						Aspect (2) (E)	-0.661	0.482	1.881	1	0.170	0.516
						Aspect (3) (N,NE,NW)	-21.779	22390.575	0.000	1	0.999	0.000
						Slope_wa	0.179	0.050	12.554	1	0.000	1.196
						Geology_variety_wa	0.394	0.176	4.986	1	0.026	1.482
						Land_class4_wa	0.016	0.008	4.026	1	0.045	1.016
						Granite_comb_wa	0.017	0.008	4.654	1	0.031	1.018
						Constant	-13.619	3.523	14.941	1	0.000	0.000
KS-C2-wa-geo-sep M10	69.927 (0.000)	0.470		78.8	77.8	Area_wa	1.096	0.525	4.358	1	0.037	2.992
						Aspect_wa			10.356	3	0.016	
						Aspect (1) (W)	-2.298	0.724	10.067	1	0.002	0.100
						Aspect (2) (E)	-0.379	0.500	0.577	1	0.448	0.684
						Aspect (3) (N,NE,NW)	-21.377	19690.657	0.000	1	0.999	0.000
						Slope_wa	0.183	0.054	11.691	1	0.001	1.201
			78.3			Geology_variety_wa	0.381	0.184	4.317	1	0.038	1.464
						Land_class4_wa	0.016	0.008	3.690	1	0.055	1.016
						Geology_class6_wa	-0.067	0.034	3.804	1	0.051	0.935
						Geology_class7_wa	0.016	0.008	3.690	1	0.055	1.016
						Geology_class9_wa	0.015	0.009	2.840	1	0.092	1.016
						Constant	-14.865	3.773	15.521	1	0.000	0.000

KS-C2-ua-geo-cl M11	35.419 (0.000)	0.263	68.3	66.3	70.4	Aspect_ua Aspect (1) (W) Aspect (2) (E) Aspect (3) (N,NE,NW) Curvature_ua Geology_variety_ua Landuse_variety_ua Schist_comb_ua Valley floors_comb_ua Constant	 -1.612 -0.777 -0.615 -3.217 0.600 -0.689 0.010 -4.621 0.288	 0.626 0.449 0.698 1.307 0.263 0.307 0.005 700.485 0.689	8.725 6.620 2.996 0.778 6.062 5.228 5.034 4.506 0.000 0.175	3 1 1 1 1 1 1 1 1 1	0.033 0.010 0.083 0.378 0.014 0.022 0.025 0.034 0.995 0.676	 0.200 0.460 0.541 0.040 1.823 0.502 1.010 0.010 1.334
KS-C2-ua-geo-sep M12	34.900 (0.000)	0.260	68.3	60.0	76.5	Aspect_ua Aspect (1) (W) Aspect (2) (E) Aspect (3) (N,NE,NW) Curvature_ua Geology_class1_ua Geology_class3_ua Geology_class9_ua Constant	 -1.552 -0.464 0.030 -3.165 0.058 0.041 0.017 -0.292	 0.657 0.445 0.679 1.326 0.025 0.024 0.006 0.268	6.570 5.579 1.089 0.002 5.699 5.397 2.802 8.246 1.187	3 1 1 1 1 1 1 1 1	0.087 0.018 0.297 0.965 0.017 0.020 0.094 0.004 0.276	 0.212 0.628 1.030 0.042 1.059 1.042 1.017 0.747
JB-C2-wa-geo-cl M13	35.523 (0.000)	.438	83.3	58.6	94.0	Landuse_variety_wa Land_class5_wa Wetterstein_limestone_comb_wa Constant	1.165 -0.041 0.035 -3.315	0.457 0.013 0.009 1.532	6.497 9.507 16.577 4.684	1 1 1 1	0.011 0.002 0.000 0.030	3.206 0.960 1.036 0.036
JB-C2-wa-geo-sep M14	49.294 (0.000)	.569	82.3	69.0	88.1	Landuse_variety_wa Land_class5_wa Land _lass1_wa Geology_class4_wa Geology_class6_wa Geology_class7_wa Geology_class13_wa Constant	1.603 -0.051 -0.735 -0.040 -0.043 0.221 -0.125 -1.273	0.574 0.018 0.341 0.016 0.029 0.149 0.064 1.495	7.799 8.263 4.657 6.096 2.202 2.197 3.836 .725	1 1 1 1 1 1 1 1	0.005 0.004 0.031 0.014 0.138 0.138 0.050 0.395	4.969 0.950 0.480 0.961 0.958 1.248 0.883 0.280
JB-C2-ua-geo-cl M15	28.139 (0.000)	.360	74.0	41.4	88.1	Land_class5_ua Land_class1_ua Dachstein_limestone_comb_ua	-.020 -120.488 -0.019	0.007 3780.130 0.006	7.264 0.001 9.198	1 1 1	0.007 0.975 0.002	0.980 0.000 0.982

						Other formations_ comb_ua	-0.029	0.12	5.979	1	0.014	0.972
						Constant	1.158	0.526	4.851	1	0.028	3.184
JB-C2-ua-geo-sep M16	34.865 (0.000)	.431	80.2	58.6	89.6	Landuse_variety_ua	0.794	0.492	2.609	1	0.106	2.212
						Land_class5_ua	-0.021	0.008	6.738	1	0.009	0.979
						Land_class1_ua	-138.706	3632.414	0.001	1	0.970	0.000
						Geology_class3_ua	-0.026	0.012	4.592	1	0.032	0.975
						Geology_class4_ua	-0.021	0.008	6.749	1	0.009	0.979
						Geology_class5_ua	-0.014	0.009	2.366	1	0.124	0.986
						Geology_class6_ua	-0.027	0.019	1.995	1	0.158	0.973
						Geology_class10_ua	-2.860	644.681	0.000	1	0.996	0.057
						Geology_class11_ua	-0.034	0.013	7.191	1	0.007	0.967
						Constant	-0.031	1.025	0.001	1	0.976	0.970
Category 3												
KS-C3-wa-ch,lu M17	30.067 (0.000)	0.429	77.5	84.3	65.5	Area_wa	2.421	1.017	5.663	1	0.017	11.255
						Ch_slope	0.142	0.085	2.783	1	0.095	1.152
						%Ch_length2	0.061	0.023	7.275	1	0.007	1.063
						%Ch_length 3	0.115	0.044	6.659	1	0.010	1.121
						Land_class2_wa	2.110	1.454	2.106	1	0.147	8.247
						Land_class4_wa	2.117	1.458	2.110	1	0.146	8.309
						Land_class5_wa	2.111	1.458	2.098	1	0.147	8.260
						Constant	-230.327	145.484	2.506	1	0.113	0.000
KS-C3-wa-ch,lu2+4 M18	25.820 (0.000)	0.378	77.5	84.3	65.6	Area_wa	2.777	0.972	8.163	1	0.004	16.069
						Ch_slope	0.179	0.073	6.008	1	0.014	1.196
						%Ch_length2	0.064	0.022	8.858	1	0.003	1.066
						%Ch_length 3	0.104	0.038	7.639	1	0.006	1.110
						Constant	-21.952	7.279	9.095	1	0.003	0.000
KSJB-C3-wa-ch,lu M19	33.242 (0.000)	0.354	74.3	87.5	55.6	Area_wa	1.972	0.662	8.869	1	0.003	7.184
						Ch_slope	0.113	0.054	4.363	1	0.037	1.120
						%Ch_length2	0.030	0.014	4.687	1	0.030	1.030
						%Ch_length 3	0.092	0.029	10.168	1	0.001	1.096
						Land_class2_wa	1.431	0.884	2.622	1	0.105	4.181
						Land_class5_wa	1.423	0.887	2.574	1	0.109	4.148
						Land_class4_wa	1.429	0.886	2.600	1	0.107	4.174

						Constante	-157.441	88.500	3.165	1	0.075	0.000
KSJB-C3-wa-ch,lu2+4 M20	25.009 (0.000)	0.276	70.6	84.4	51.1	Area_wa Ch_slope %Ch_length2 %Ch_length 3 Constant	2.005 0.134 0.031 0.095 -15.818	0.599 0.043 0.013 0.027 4.329	11.215 9.577 5.759 12.422 13.353	1 1 1 1 1	0.001 0.002 0.016 0.000 0.000	7.428 1.144 1.032 1.099 0.000