Autor: RASCHER Eric

ENVIRONMENTAL SEDIMENTOLOGY OF MOUNTAIN REGIONS

HUMAN IMPACT ON SEDIMENT DYNAMICS IN UNGLACIATED ALPINE CATCHMENTS (JOHNSBACH VALLEY, AUSTRIA)

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Erstbegutachter:	SASS Oliver, Prof. Dr. Institut für Geographie Universität Bayreuth
Zweitbegutachter:	LIEB Gerhard Karl, Ao.Univ.- Prof. Dr. Institut für Geographie und Raumforschung Karl-Franzens-Universität Graz
Drittbegutachter:	HECKMANN Tobias, PD Dr. Institut für Geographie Katholische Universität Eichstätt-Ingolstadt

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SUMMARY

Mountain regions often show high rates of sediment transfer which can lead to geomorphological hazards and risk where population and infrastructure have developed. To prevent harm obstruction measures along the natural sediment transport paths are established. Further, future climatic changes could lead to intensified sediment availability and transport. As mountain regions are highly sensitive to such disturbances the critical evaluation of the current sediment dynamics are fundamental for the future sediment management.

This study investigates the sediment dynamics in the Johnsbach Valley where extensive anthropogenic and environmental change occurred in the past. Therefore, this cumulative dissertation addresses questions concerning: the sediment connectivity between different morphological compartments, the sediment budget and its internal sediment dynamics, the consequences of anthropogenic impact and climate change on sediment dynamics, and appropriate sediment management strategies for future sediment flux scenarios.

A semi-quantitative modeling approach was applied and combined with maps of erodible sediment sources to display and quantify connectivity parameters. Further, several tributary trenches of the Johnsbach River were investigated using terrestrial laser scans to clarify the sediment dynamics and the degree of coupling to the main river system. A comprehensive analysis of sediment relocation was achieved by means of airborne laser scans and an integrative bedload monitoring system at the outlet.

The anthropogenic impact led to disturbed sediment fluxes, followed by severe geomorphological and ecological consequences. Today's management strategies partially support the idea of restoring a natural sediment flow. Currently, effects of climate change and anthropogenic impact are not easily separated, especially when internal sediment dynamics are adapting to restoration strategies and reacting to external forcing at the same time.

ZUSAMMENFASSUNG

Gebirgsregionen weisen oft hohe Sedimenttransportraten auf, was zu geomorphologischen Gefahren und Risiken für die Bevölkerung und Infrastruktur führen kann. Zum Schutz wurden Verbauungsmaßnahmen entlang der natürlichen Sedimenttransportwege errichtet. Eine erhöhte Verfügbarkeit und verstärkter Sedimenttransport kann zudem durch zukünftige Klimaveränderungen erfolgen. Da Gebirgsregionen besonders auf solche Störungen reagieren, ist eine kritische Bewertung der aktuellen Sedimentdynamik von grundlegender Bedeutung für das zukünftige Sedimentmanagement.

Diese Arbeit untersucht die Sedimentdynamik des Johnsbachtals, mit seinen umfangreichen Veränderungen in der Vergangenheit. Diese Dissertation adressiert daher folgende Themen: die Sedimentkonnektivität zwischen verschiedenen morphologischen Einheiten, das Sedimentbudget und die interne Sedimentdynamik, die Folgen anthropogener Einflüsse und des Klimawandels auf die Sedimentdynamik sowie geeigneten Strategien zum zukünftigen Sedimentmanagement.

Ein semi-quantitativer Modellierungsansatz wurde angewandt und mit potentiellen Sedimentquellen kombiniert, um Konnektivitätsparameter zu bestimmen. Mehrere Seitengräben des Johnsbachs wurden mittels terrestrischer Laserscans untersucht, um Sedimentdynamiken und Kopplungsgrade zum Hauptgerinne zu beschreiben. Es erfolgten eine flächendeckende Analyse der Sedimentverlagerungen mittels luftgestützter Laserscans sowie die Messung des Geschiebetransportes.

Die Eingriffe des Menschen führten zu einem gestörten Sedimenttransport mit schwerwiegenden geomorphologischen und ökologischen Folgen. Die angewandten Managementstrategien zielen auf die Wiederherstellung eines natürlichen Sedimentflusses ab. Gegenwärtig sind die Auswirkungen klimatischer Veränderungen und des anthropogenen Einflusses auf die Sedimentdynamik schwer zu trennen, vor allem wenn sich die interne Sedimentdynamik an die Sanierungsstrategien anpasst und gleichzeitig auf äußere Einflüsse reagiert.

CONTENT

PART A

PART B

PART C

LIST OF ABBREVIATIONS

ALS	Airborne Laser Scan
AOI	Area of Interest
AS	Alluvial Section
CH	Channel Section
DEM	Digital Elevation Model
dGPS	differential Global Positioning System
DoD	DEM of Difference
EWFD	European Water Framework Directive
FWF	Fonds zur Förderung der wissenschaftlichen Forschung (*Austrian Science Fond*)
GIS	Geographic Information System
GS	Gseng
GWZ	Greywacke Zone
HABITALP	Habitats of the Alps
IC	Index of Connectivity
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature and Natural Resources
LA	Langgries
LiDAR	Light Detection and Ranging
LIFE	L'Instrument Financier pour l'Environnement (*Financial instrument for the environment*)
LoD	Level of Detection
NCA	Northern Calcareous Alps
NPG	National Park Gesäuse
RCP	Representative Cell Points
SDE	Standard Deviation of Error
SEDYN-X	Sediment Dynamics Xeis
SEMP	Salzach-Ennstal-Mariazell-Puchberg
SL	Slope Catchment
TauDEM	Terrain Analysis Using Digital Elevation Models
TLS	Terrestrial Laser Scan

WLV	Wildbach- und Lawinenverbauung (*Austrian Forest Technical Service for Torrent and Avalanche Control*)
ZAMG	Zentralanstalt für Meteorologie und Geodynamik (*Central Institute of Meteorology and Geodynamics*)
ZMS	Zwischenmäuerstrecke

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PART A

1. GENERAL INTRODUCTION

1.1. Motivation and Background

The Alps, as a mountain range, have been subject to constant change for several million years. Starting with the collision of the Adriatic and the European plate, plate tectonic processes and the resulting orogeny have formed the alpine area ever since. The recent shape of the alpine environment is mainly the result of coupled geomorphological processes (e.g. gravitational, glacial, fluvial) affecting the relief especially since the last glacial maximum. Today most of these processes are still involved in modeling the landscape to its present image. In this context, weathering and erosion play a decisive role in preparing and forcing many of these current geomorphological processes. As a product of weathering and down wearing of bedrock, the sediment is the important driver for the current alpine landscape formation. Sediment is present in every part of the alpine environment, whether on the slopes or in the valleys. The availability and structure of its deposits is a crucial factor for surface processes. Besides, climate forces are an important agent controlling further sediment transport in the fluvial system and to its final deposition. However, nature was recently distressed noticeably. The Alps have been stressed jointly by human pressure and variations in climate forcing over the last decades. This led to environmental changes which are inevitably driven by natural processes reacting to changes in the cycles of energy and matter.

Human settlements and urban areas, in further consequence, have spread and captured almost every flat part inside the alpine valleys. Land use management has changed from traditional agriculture and alpine farming to an economy which supplies (even in alpine landscapes) nearly every good needed. Infrastructure design (installation as well as expansion) has reached a whole new level, making everything available and accessible at any time. For that reason nature and its natural development needed to be obstructed. For decades, it was tried to restrict sediment transport by means of barriers, sills and other river training structures. Slope processes were dammed and redirected to protect the human dispersion and resources (e.g. sediment and wood) were mined and used to press this expansion ahead. Especially in fluvial systems the following lack of sediment and the resulting morphological changes have led to certain disruption. Sediment transport and self-forming processes are crucial for a sustainable river management. Thus, the downstream continuum of sediment is essential to replenish hydromorphological units, including their ecological functions as spawning, refuge and adult habitats.

For a long time the mountain topography of the Alps has changed as a result of the balance between tectonic uplift, subsidence by deposition of sediments and mountain erosion with its associated surface processes. However, the current and future evolution of the alpine landscape, and especially of the surface sedimentary processes, seems to be imposed by changed environmental conditions. The global hydrological cycle became more intense during the recent past and is expected to further intensify in the future in the context of global warming (IPCC, 2014). The uncertain future intensification carries the potential of enhanced probability of heavy precipitation events as well as an increase in thawing processes (especially in the cryosphere) and raises concerns about higher frequencies of geomorphological and hydrological hazards (IPCC, 2014). Therefore, the availability of sediment and the structure of its deposits in the landscape become more and more prominent, as sediment, next to water, is one of the rising risk agents. Once in motion sediment is the most important factor concerning monetary damage and protection measures in alpine torrents.

The previously described considerations lead to the following discrepancies: (1) the human impact and the effects of climate change on earth system processes are often inseparable (Glade et al., 2014). The processes and interactions on the earth's surface are decisively changed and influenced through the spatial and temporal appearance and actions of humans in their environment. As a result, it is no longer possible to differentiate exactly between cause and effect. (2) There is no doubt that global warming leads to a significant glacier retreat and that thawing permafrost destabilizes rock walls both eventually being followed by considerable, hazardous consequences (IPCC, 2014). However, unglaciated alpine catchments often appear less important when focusing on the impact of climate change on slope and fluvial system processes even though they have by far a larger areal extension than glaciated and permafrost-dominated areas. (3) There is an appearing conflict of interest between the anthropogenically restricted sediment transport in the past and the probably increasing sediment transport in the future resulting from a higher chance of extreme events. This critical management situation has made river restoration a major issue in the Alps trying to ensure that rivers attain a good ecological status, reinforced by the European Water Framework Directive (EWFD), and that flood management and resilience of the river system will be improved (Habersack and Piègay, 2008).

Out of former river engineering research projects and from previous experiences and debates in the scientific community (e.g. Bravard et al., 1999b; Habersack, 2000; Brierley and Fryirs, 2005; Habersack and Piègay, 2008) the following conclusions can be drawn:

- in the Alps, almost every river and mountain torrent is anthropogenically influenced,
- many rivers have already reached a critical state of morphodynamic development where "natural" river restoration will be almost impossible,
- sediment transport and river morphodynamics play a central role in river restoration and need to be incorporated,
- a link must be drawn between the past and the future with respect to restoration actions,
- implementing the EWFD will promote river restoration, the goal being to reach good ecological status of running waters,
- beside ecological parameters, hydromorphological variables should be also included in the monitoring programs of the EWFD to evaluate the development of rivers and to promptly react to critical trends, which themselves negatively influence the ecological status,
- a scale-oriented approach has to be developed to practically implement river restoration,
- future restoration measures should involve major individual measures but also day-to-day management actions, and
- a bridge between natural, technical, and social sciences is crucial for successful river restoration, taking a cross disciplinary approach ranging from river engineering, landscape, and areal planning to biology.

Today, the major challenge in river restoration in alpine environments is that processes and key parameters have to be identified with which both geomorphological and ecological conditions can be improved. Therefore, successful restoration projects in high-energy and bedload transport dominated systems must include the full spectrum of scales. Across many disciplines restoration experiences from the Alps are currently evaluated focusing on a variety of activities. Now it is necessary to discuss the basic arguments behind such actions, their limitations and research challenges.

1.2. Research in the framework of the project: "SEDYN-X – Interdisciplinary sediment flux research in the Johnsbach Valley"

Effective sediment management requires profound knowledge on the sediment cascade in the headwaters. In most cases, the sources and (temporary) sinks of sediments are unknown and the river system is treated as a "black box". To address this issue the FWF-founded research project "SEDYN-X (SEdiment DYNamics - Xeis) - Interdisciplinary sediment flux research in the Johnsbach Valley" was developed. The project ran from the beginning of October 2012 to the end of April 2017 with a regional focus on the Johnsbach Valley, a part of the Gesäuse region (colloquially referred to as Xeis) in Upper Styria (Austria). It was carried out by the Department of Geography and Regional Science at the University of Graz and the Institute of Water Management, Hydrology and Hydraulic Engineering at the University of Natural Resources and Life Sciences in Vienna. The primary intention of the project was to develop a conceptual model of coupled and decoupled sediment routing to quantify the most prominent sediment fluxes and sediment sinks (Figure 1.1). Finally, the detailed understanding of the sediment cascade within the catchment would allow assessing the impact of climate change on sediment yields (even if this is reckoned to be less significant than anthropogenic influences). A short insight into the project is given by Rindler and Rascher (2015) (see appendix).

The National Park Gesäuse (NPG) has a particular interest in the investigation of these sediment fluxes. The NPG initiated the EU funded LIFE-project (L'Instrument Financier pour l'Environnement) "Conservation strategies for woodlands and rivers in the Gesäuse Mountains". One of its objectives was to restore the northern part of the Johnsbach Valley, the so-called "Zwischenmäuerstrecke" (ZMS), thereby fulfilling the EWFD and accordingly, to ensure the possibility of passing for the aquatic fauna throughout the whole river system. Currently renaturation is in the process, but the lack of sediment in the river turned out to be a new problem. Most of the openings beneath the bridges of the road into the valley are too small and thus, high annual costs for sediment excavation are incurring to ensure the safety of the local infrastructure. As one of the objectives of the project these costs of road maintenance should be weighed against the costs of innovative measures to finally find out which measures are appropriate to ensure the permeability of the river

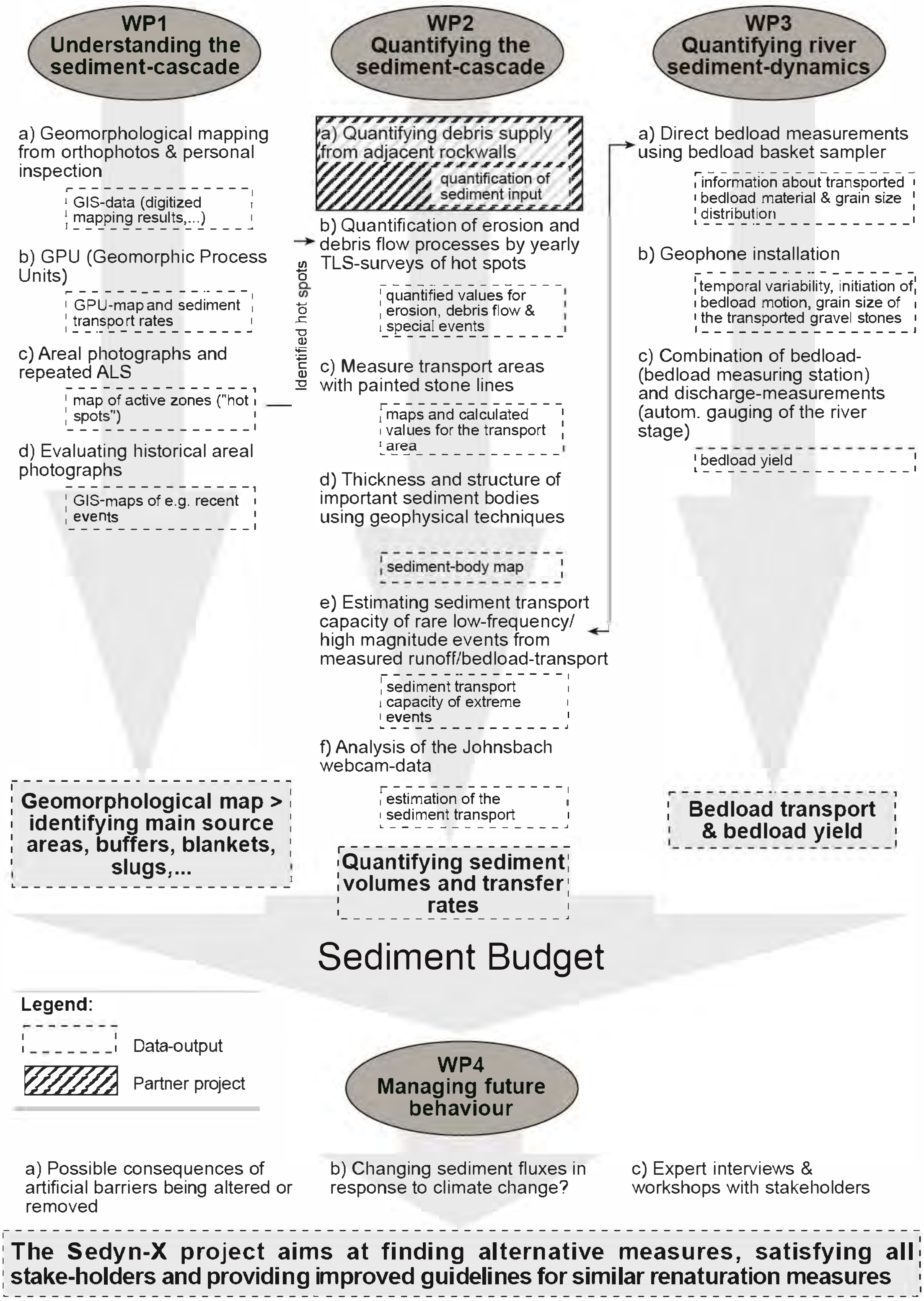

Figure 1.1: *Organization chart of the SEDYN-X project.*

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To accomplish the central aim of this thesis the following questions will be addressed:

(1) *Can we infer patterns of sediment connectivity and (sedimentary) coupling effects between different morphological compartments?*
(2) *What can the sediment budget tell us about the internal sediment dynamics and the spatial and temporal variations?*
(3) *Can we observe the consequences of anthropogenic impact and climate change on the sediment budget and how can both be separated?*
(4) *What are appropriate sediment management strategies concerning the future sediment flux and the related landscape development?*

The Johnsbach Valley, a remote, unglaciated alpine catchment, represents an ideal environment for this investigation and the study. Two main geological units are colliding inside the valley with one of them having a high weathering potential. This leads to an enormous amount of sediment being available for transport. During the last 70 years, extensive interventions (e.g. obstructions inside the fluvial system, gravel mining, river restoration) have taken place with a sustainable impact on the sediment flux inside the catchment and further downstream. Further, the extensive amount of sediment could lead to hazards and risks resulting in a need for protection for the local community and the infrastructure (access road into the valley and extensive forest road network).

1.4. Guide through the thesis

Part A, which includes the chapters 1 to 3, is introducing into this thesis as well as giving an overview on the current state of the art in environmental sedimentology and characterizing the study area.

Chapter 1 is an introductory part and is providing a brief overview of the thesis. It describes its motivation and shows how the thesis is embedded in a framing project which deals with the research in sediment fluxes in the particular area. From this background the major objectives are identified and the key contributions are summarized.

Chapter 2 is providing a state of the art overview on environmental sedimentology of mountain regions. The chapter specifies the important characteristics of mountainous terrain in detail. General models of alpine environments (slope and stream channel) are described and are linked to the mountain sediment cascade. Different stages in sediment source-to-sink relationships are highlighted. The concept of sediment budgets is presented as well as the main controls having an impact on sediment fluxes.

Chapter 3 is presenting a particular overview of the study area. It describes the environmental characteristics of the whole catchment and further focuses on anthropogenic disturbances and landscape recovery in the ZMS since the second half of the 20th century.

Part B combines three empirical studies (chapter 4 to 6), which are published as journal articles or book chapters. Each study is presented in an individual chapter and addresses a particular topic associated with alpine sediment dynamics (e.g. connectivity, coupling, sediment flux, sediment budget).

In **Chapter 4** a semi-quantitative modeling approach (index of connectivity) was applied and combined with maps of erodible sediment sources. The aim was to display and quantify connectivity parameters of the catchment as a baseline for further research on quantitative sediment budgets.

Chapter 5 is an empirical study on the linkage of landscape units by sediment transport and its degree of coupling. Several tributary trenches of the Johnsbach River were investigated by multi-temporal TLS surveys to clarify the seasonal sediment dynamics inside the trenches and the degree of coupling to the main river system.

Chapter 6 discusses the consequences of historical gravel mining in the two main side channels on the sediment supply. By using a sediment budget model it is demonstrated how these mining activities affect the overall sediment dynamics in the ZMS and how recent renaturation measures, especially in the fluvial system, are having an impact on the current and the future sediment dynamics.

In the last **Part C** an overall synthesis is provided in **Chapter 7**, which highlights the main outcomes of the thesis. Therefore, the methodological approaches presented will be discussed and evaluated and the research questions will be answered by focusing on the results of the three empirical studies. Finally, **Chapter 8** provides the conclusions drawn in this study and closes with an outlook on future research objectives.

1.5. Overview of publications and author contributions

The empirical studies (Publication I - III) presented within the framework of this thesis are published in international peer-reviewed journals and books and are presented in Part B, chapters 4 - 6. The further contributions (publication IV - VI) are more of the science-to-public type and were presented in regional journals. They deliver insights into the project SEDYN-X itself and address smaller-scaled investigations. Publications IV - VI are attached in the appendix.

Publication I / Chapter 4:
Comparative analysis of sediment routing in two different alpine catchments

Citation:
Stangl, J., Rascher, E., Sass, O., 2016. Comparative analysis of sediment routing in two different alpine catchments. In: Beylich, A.A., Dixon, J.C., Zwolinski, Z. (Hg.), Source-to-sink-fluxes in undisturbed cold environments. Cambridge University Press, Cambridge, 364-377, doi.org/10.1017/CBO9781107705791.026.

Contribution: (own share is about 50 %)
All three authors (J.S., E.R. and O.S.) jointly developed the structure and objectives of the study. J.S. and E.R. designed the basic requirements (DEM transformation) for the models and interpreted the modeling results. E.R. performed the computations and created figures and diagrams focusing on the Johnsbach Valley whereas J.S. dealt with the Schöttelbach Valley. E.R. (introduction and discussion) and J.S. (methods) wrote the main part of the paper and split the writing on the results chapter; O.S. contributed to all chapters.

Publication II / Chapter 5:

Evaluating sediment dynamics in tributary trenches in an alpine catchment (Johnsbach Valley, Austria) using multi-temporal terrestrial laser scanning

Citation:

Rascher, E., Sass, O., 2017. Evaluating sediment dynamics in tributary trenches in an alpine catchment (Johnsbachtal, Austria) using multi-temporal terrestrial laser scanning. In: Zeitschrift für Geomorphologie, Supplementary Issues 61(1), 27-52, doi.org/10.1127/zfg_suppl/2016/0358.

Contribution: (own share is about 90 %)

Both authors (E.R. and O.S.) jointly developed the structure and objectives of the study. E.R. did the field work and the analysis of the data, created all figures and diagrams and interpreted the results. E.R. wrote the paper; O.S. contributed to all chapters.

Publication III / Chapter 6:

Impacts of gravel mining and renaturation measures on the sediment flux and budget in an alpine catchment (Johnsbach Valley, Austria)

Citation:

Rascher, E., Rindler, R., Habersack, H., Sass, O., 2018. Impacts of gravel mining and renaturation measures on the sediment flux and budget in an alpine catchment (Johnsbach Valley, Austria). In: Geomorphology 318, 404-420, doi.org/10.1016/j.geomorph.2018.07.009.

Contribution: (own share is about 75 %)

Two authors (E.R. and O.S.) jointly developed the structure and objectives of the study; the other two authors (H.H. and R.R.) agreed. E.R. did the analysis of the data, created all figures and diagrams and interpreted the results. E.R. wrote the paper; H.H. and R.R. provided the texts and diagrams associated with the integrative bedload monitoring system, O.S. contributed to all chapters.

Publication IV / Appendix I:

Sediment DYNamik – Xeis: Eine interdisziplinäre Untersuchung zum Sedimenthaushalt im Johnsbachtal

Citation:

Rindler, R., Rascher, E., 2015. Sediment DYNamik – Xeis: Eine interdisziplinäre Untersuchung zum Sedimenthaushalt im Johnsbachtal. In: Im Gseis 24, 17.

Contribution: (own share is about 50 %)

Both authors (R.R. and E.R.) jointly developed the structure and objectives of the article. R.R. and E.R. shared the writing and the selection of pictures equally.

Publication V / Appendix II:

Johnsbach in Bewegung

Citation:

Sass, O., Rascher, E., Rode, M., Kreiner, D., 2016. Johnsbach in Bewegung. In: Da Schau Her. Die Kulturzeitschrift aus Österreichs Mitte 37(2), 8-11.

Contribution: (own share is about 25 %)

All authors (O.S., E.R., M.R. and D.K.) jointly developed the structure and objectives of this contribution. They all equally shared the amount of writing and the selection of pictures and graphics.

Publication VI / Appendix III:

Der Langgriesgraben - Ein dynamischer Raum im Gesäuse und Gegenstand intensiver Forschung

Citation:

Schöttl, S., Rascher, E., Sass, O., 2018. Der Langgriesgraben - Ein dynamischer Raum im Gesäuse und Gegenstand intensiver Forschung. In: Im Gseis 30, 4-7.

Contribution: (own share is about 40 %)

All three authors (S.S., E.R. and O.S.) jointly developed the structure and objectives of the study. S.S. did most of the writing; E.R. decided on pictures and figures. E.R. and O.S. contributed to the writing.

agricultural niches) for the everyday life which makes it important to understand the environmental sedimentology of these regions. Then again mountain areas are also heavily affected by socio-economic changes, increased recreation and traffic, and changing land-use (Warburton, 2007). These types of environmental degradation are also associated with changes in sedimentary processes. Therefore, as Warburton (2007, p. 32) stated, "[to understand] the environmental sedimentology of mountain areas provides a useful framework for studying the effects of humans and environmental change on active surface sedimentary systems".

2.2. Mountain environments and geomorphologically significant characteristics

Mountains are an important feature in defining the world's landscape. They account for one-fifth of the earth's surface (Ives, 1992) and belong to the most complex landforms on Earth, due to the interplay between tectonic and structural influences and the work of denudation processes. McGregor (1990, p. 245) describes mountains as "extreme, high-energy geomorphological systems, characterized by intense physical weathering, rapid and varied mass movements, the imprint of past and present glaciations and distinctive associations and patterns of hydrological events". Yet the problem of finding a general definition for mountains has been approached many times in the past (e.g., Penck, 1894; Troll, 1941, 1972; Ives and Barry, 1974; Price, 1981; Gerrard, 1990) so that Messerli and Ives (1997, p. 8) came to the conclusion that "...the world`s mountains do not lend themselves to unifying definition that goes beyond the simple combination of ´steepness of slope´ and ´altitude´ ... It follows that several definitions, which are region-specific, are needed". However, as Barsch and Caine (1984) argued, at least four characteristics of mountains are important to describe the landform and the processes acting upon it: (1) elevation (often in absolute terms); (2) steep gradients; (3) rocky terrain; and (4) the presence of snow and ice. In general, these are the most popular features throughout the literature. These mountain characteristics are also useful for differentiating between mountain systems in a semi-quantitative manner (Table 2.1) where the change in elevation or relative relief is used to classify successively more mountainous environments (Barsch and Caine, 1984).

Besides the four main characteristics from above, there are others that need to be mentioned to complete a geomorphic understanding of mountains. Barsch and Caine (1984) refer to: (1) the internal diversity and variability (derived from elevation, relief, exposure) of mountain areas; (2) a clear evidence of late-Pleistocene glaciation of most mountain system; (3) a tectonic activity of many mountain areas, and especially the highest of them; and (4) the existence in a metastable state of many mountain environments leading to a particular vulnerability to disturbance. Other characteristics that are significant for defining the mountain environment involve the vertical differentiation of climate and vegetation cover (Barry, 1992) or climatic-vegetative belts (Troll, 1941, 1972, 1973). Of all these characteristic elements especially the relative relief, the vegetation cover, and the climate are highly important in terms of the environmental sedimentology of mountain regions. This results from their potential impact on erosion and sediment transport as the climatic control on weathering affects sediment production, the high energy of steep slopes is inevitably linked to the transport and removal of sediment and the diminished vegetation decreases the resistance to erosional processes.

Table 2.1: *Relief contrast in different types of mountain systems (after Barsch and Caine, 1984).*

Type	**Altitudinal difference (over 5 km distance)**	**Relative relief**
	[m]	**[m km^{-2}]**
High mountain system	> 1000	500
Mountain system	500 - 1000	200
Mountainous terrain	100 - 500	100
Hilly terrain	50 - 100	50

Caine (1974) distinguishes between physical (e.g. geologic, physiographic, climatic, and hydrologic factors), biotic, and historical characteristics. Therein lithology and structure are perhaps the most important geologic factors as they control the response of a landform to stress-induced processes (e.g. the erosional resistance of the surface material). The tectonic instability of alpine areas associated with earthquakes and possibly triggered landslides is another important geologic factor having an active influence. In alpine environments the most important physiographic factor are the steep slopes characterized by a high rate of energy transfer. Climatic factors are usually aiming at the effects of altitudinal change of precipitation and temperature, but also e.g. the spatial variation in radiation due to topography and vegetation and its seasonal influence on snow coverage. In further consequence the hydrologic factors are conditioned by the climatic ones as e.g. the runoff responses to snowmelt and seasonal rainstorm events. Therefore "the time of greatest discharge is [...] likely to be the occasion of greatest fluvial geomorphic activity in alpine river channels" (Caine, 1974, p. 724). Other important characteristics include biotic (e.g. vegetation type and cover and its vertical differentiation, as well as the existence of soil layers and there stability) and historical features (e.g. glacial effects and their significance on presently acting processes).

Generally, "many environmental influences of potential importance to geomorphic processes [...] originate from the physical and biotic milieu of alpine mountains or from their historical development" (Caine, 1974, p. 722). They produce a geomorphic environment of substantial diversity in both time and space which is considered to be the "single most significant characteristic of the alpine zone" (Caine, 1974, p. 722).

However, the characteristics of mountain environments that are most relevant to environmental sedimentology (after Warburton, 2007) can be summarized as follows:

- Mountains are generally regions of abundant sediment supply and high erosion potential (Milliman and Syvitski, 1992).
- High rates of sediment production translate into elevated rates of sediment transfer and increased sediment deposition (Marutani et al., 2001).
- The importance of steep slopes is fundamental to many processes operating in mountain environment (Jones, 1992).
- There is considerable variability in the spatial and temporal rates of sediment transfer (Butler et al., 2003).
- Mountain environments are sensitive to disturbance both from climate change and anthropogenic impacts (Ives and Messerli, 1989).
- The incidence of geomorphological hazards tends to be high in mountainous, high-energy environments where narrow valley floors are juxtaposed with steep unstable side slopes (Gerrard, 1990).
- Mountain sediment systems are often only a part of a larger drainage basin structure. The degree of coupling needs to be established (Brizga and Finlayson, 1994; Piégay et al., 2004).

Table 2.2: *Typical terrain features of a high-mountain environment (after Fookes et al., 1985).*

Mountain Zone	Description	Materials	Denudation processes	Slope forms
1	High altitude glacial and periglacial	Snow and ice, glacial deposits (all grain sizes), bare rock exposures (mainly intrusive igneous and metamorphic rock types at the center of mountain chains), coarse weathering products (boulder, cobble and gravel size), periglacial deposits around margin of former or present-day ice masses including angular weathered rock fragments and debris rubble of mixed grain sizes.	Mechanical weathering especially processes related to frost and freeze / thaw cycles, glacial erosion, instability in rock and snow masses, solifluction.	Landforms of glacial erosion (e.g. U-shaped valley forms, cirques, angular rock ridges and peaks), and glacial deposition (e.g. moraine ridges, till sheets), angular rock walls, glaciers, snow and ice fields, ice sheets, high-angle debris slopes, solifluction forms (e.g. sand flows, coarse debris forms, drift sheets).
2	Free rock faces and debris slopes	Bare rock exposures, coarse debris products from weathering of rock faces, boulder fields, scree or talus, taluvium (transported soils comprising mixed sand, gravel and cobbles with some fines).	Mechanical and chemical weathering, instability in rock masses, instability in soil (debris) masses, sub-surface water erosion (near-surface through flow), talus creep and soil creep, possible frost and freeze / thaw activity.	Rock walls and cliffs, moderate high-angle, coarse debris-mantled slopes, boulder fields, scree slopes, rock failure forms (e.g. fresh rock scars, conical accumulations of weathered rock debris).

3	Degraded middle slopes and ancient valley floors	Ancient river terrace and fan deposits in-situ residual soil mantles (mainly on low-angle valley side slopes), colluvium (transported soil comprising a mixture of coarse grains in a clayey matrix).	Chemical weathering, soil creep, unconcentrated and concentrated surface water erosion.	Low-angle or flat remnants of erosion surfaces, post-degraded low-moderate angle valley side slopes, ancient terrace levels, ancient fans, ancient soil and rock failure forms (e.g. degraded rock scars, subdued and vegetated accumulations of landslide debris).
4	Active lower slopes	Taluvium and colluvium overlaying in-situ weathered rock, some bare rock exposures with associated boulder fields and scree.	Instability in rock masses, instability in soil masses, chemical and mechanical weathering, unconcentrated surface water erosion (sheet flow), concentrated surface water erosion (gullying), soil creep, sub-surface water erosion (near-surface through flow in loose soil).	High-angle debris-mantled slopes (usually straight), small rock faces and cliffs, a wide range of soil and rock failure forms, active and degraded (e.g. degraded rock and soil scars, hummocky ground, cones and mounds of slipped soil and rock debris), steep-sided seasonal and perennial gullies.
5	Valley floors	Mainly coarse alluvial materials from river deposition (e.g. channel floor alluvium, terrace and fan materials covering complete range of grain sizes), rock exposures in incised channel beds.	Concentrated surface water erosion in perennial streams and rivers, small scale instability in soil masses (e.g. undercutting of terrace banks).	Low-angle or flat river channel, terrace and fan slopes separated by small steep bluffs, landforms of fluvial erosion (meander scars, bedrock-cut terraces), and deposition (e.g. alluvial terraces and fans, gravel bars and sheets).

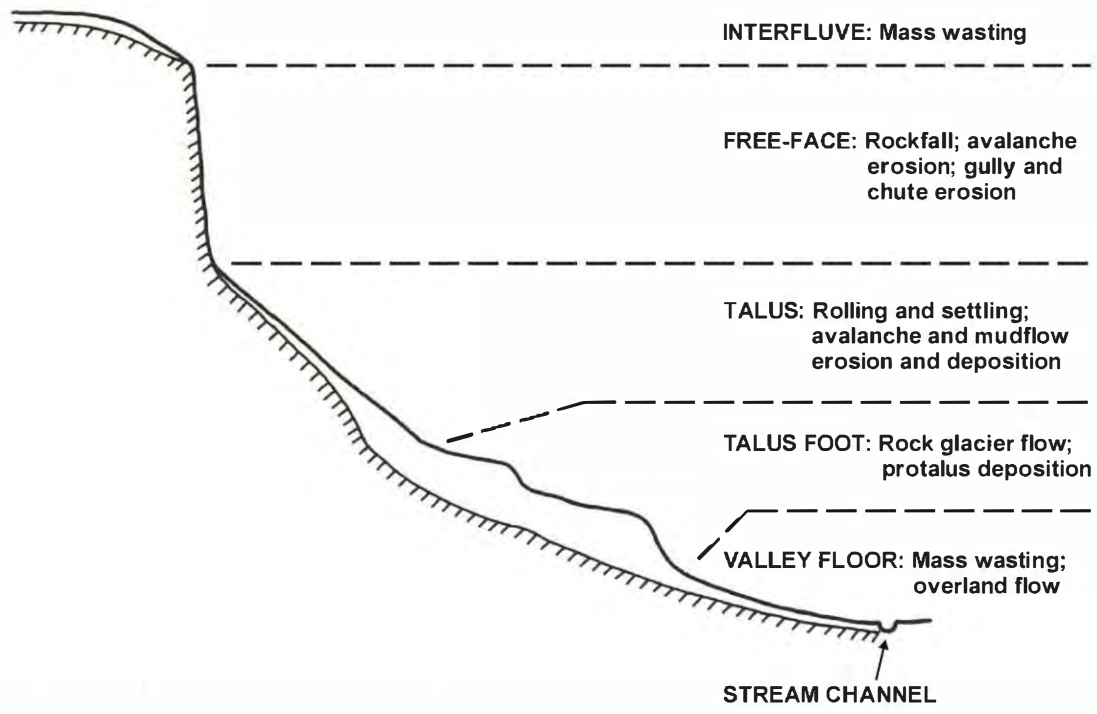


Figure 2.2: *Hypothetical alpine slope profile outlining the alpine sediment cascade process system (after Caine, 1974).*

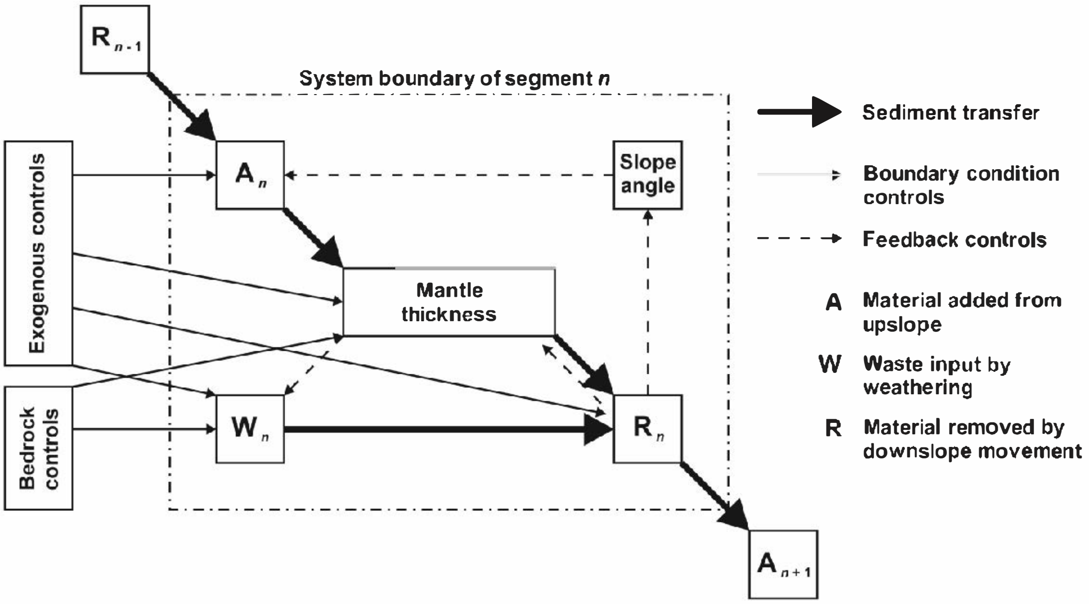


Figure 2.3: *The hillslope waste budget model (after Caine, 1974).*

2.3.1.2. The stream channel model

Headwater mountain catchments can be considered as sediment production zones feeding bedload and suspended sediment downstream. Accompanying the fluvial forms along a river profile vary from the steep channel dominated headwaters through the meandering lowlands to the coastal zone (Figure 2.4). This sequence of channel form patterns and a systematical decrease in grain-size downstream are generally common in fluvial systems if there are no relevant variations in different sediment source rock types and in the absence of significant tributaries (Rice and Church, 1998). Therefore sediment load in the headwaters is generally dominated by coarse bedload whereas downstream the fine suspended load usually exceeds 80-90 % of the total load (Warburton, 2007).

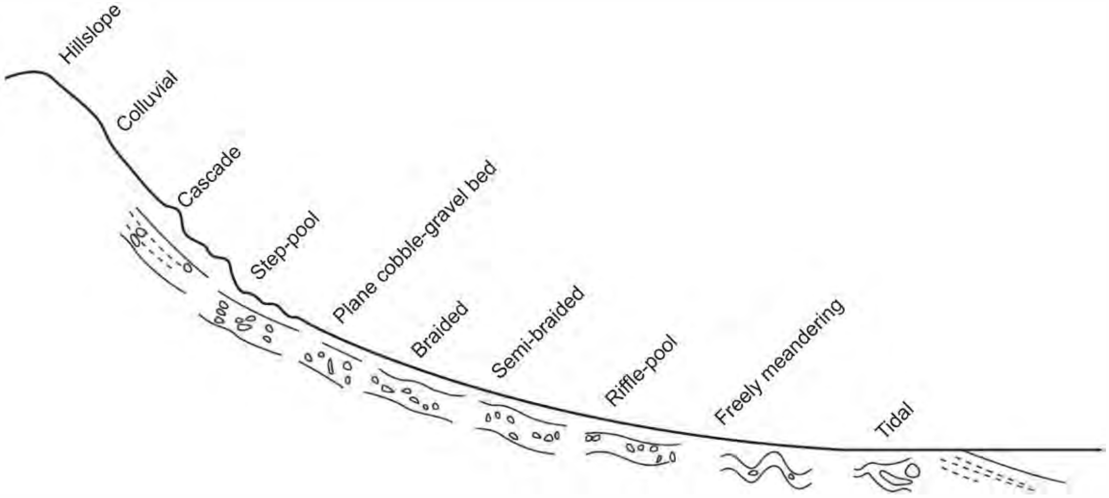


Figure 2.4: *Schematic diagram showing transitions in the fluvial system along a river profile (modified from Mosley and Schumm, 2001).*

"[...] the stream channel may be considered a parallel to the valley wall subsystem for it, too, involves a linear sequence of sediment transfer" (Caine, 1974, p.727). The interaction of a channel segment with its adjacent upstream and downstream segments along a stream channel can be illustrated in Figure 2.5. The model can be expanded by external controls (e.g. climatic, hydrologic, and geologic) as well as internal feedback links due to the basic assumption of the relatively simple coupling effect of stream discharge and sediment movement.

mobilized, routed, stored, remobilized and deposited through different subsystems. Sediment storages are built up by a variety of different geomorphological processes and depleted by another (Burt and Allison, 2010). In a mountain environment the final output is transferred to the next low-order valley (e.g. main stream channel) from which it is transported to the outlet. An example of a mountain sediment cascade for the ZMS in the Johnsbach Valley, Austria is depicted in Figure 2.6. Four different, but dynamically linked, subsystems have been identified, each of them containing its own set of sediment transport processes and storage landforms. The former three subsystems (rockwall, slope, and valley bottom) represent the slope model as earlier characterized in chapter 2.3.1.1 whereas the latter describes the stream channel model (see chapter 2.3.1.2).

In general, the alpine drainage basin consist of at least two dynamic subsystems (the slope and the stream channel), as exemplified in Figure 2.6. These are overlain by four sediment subsystems (a valley glacier sediment system, a coarse debris system, a fine sediment system, and a geochemical system) as described in detail by Caine (1974) and Barsch and Caine (1984) (Table 2.3). Each of these subsystems is defined by the nature of the sediment involved and is characterized by different controls, responses and rates of activity. However, as they overlap in both time and space they interact and transfer material between the different systems.

Figure 2.6: *(Next page) Conceptual model of the sediment cascade in the ZMS, Johnsbach Valley, Austria, using the example of the Gseng side catchment (following the illustration and concept of Schrott et al., 2002).*

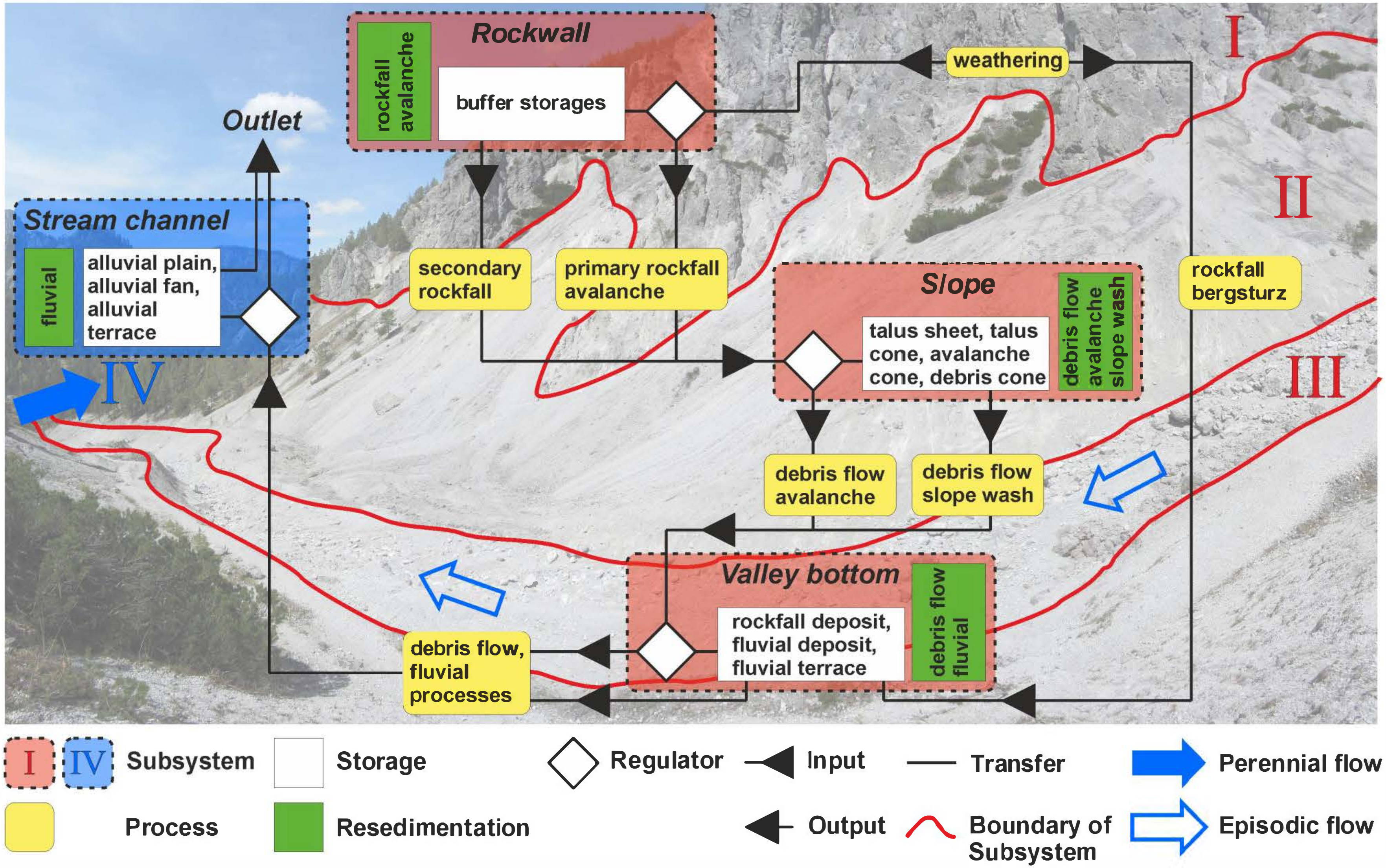

Rockwall
rockfall avalanche
buffer storages
weathering
I
Outlet
II
Stream channel
fluvial
alluvial plain, alluvial fan, alluvial terrace
secondary rockfall
primary rockfall avalanche
Slope
talus sheet, talus cone, avalanche cone, debris cone
debris flow avalanche slope wash
rockfall bergsturz
III
IV
debris flow avalanche
debris flow slope wash
Valley bottom
rockfall deposit, fluvial deposit, fluvial terrace
debris flow fluvial
debris flow, fluvial processes
I
IV
Subsystem
Storage
Regulator
Input
Transfer
Perennial flow
Process
Resedimentation
Output
Boundary of Subsystem
Episodic flow

Table 2.3: *Examples of mountain geomorphological process subsystems and typical geomorphological units (adopted from Warburton, 2007).*

Sediment system	**Morphological units**	**Transfer processes**	**Typical mountain environments**	**Case study**
Glacial	Glacierized valleys and terrain; moraine	Glacial Transport	Icelandic glaciers Ggjkull and Kvrjkull	Spedding (2000)
Coarse debris	Steep bedrock slopes and talus	Rock fall, avalanches; debris flows; rock slides; talus creep	Randa rock slide, Valais, Switzerland	Götz and Zimmermann (1993)
Fine sediment	Waste mantled slopes	Solifluction; soil creep; slopewash	Colorade Front Range, USA	Benedict (1970)
Fluvial and geochemical	Stream channels; valley floors; fans and lakes	Fluvial transport; solute transport; lake sedimentation	Kärkevagge, northern Sweden	Rapp (1960)

2.4. Sediment fluxes in mountain environments: source-to-sink relationships in alpine catchments

“A catchment is a single fluvial system that is linked internally by a network of channels” (Fryirs and Brierley, 2013, p. 29). The catchment body is typically demarcated by a ridge line and separates the surface flow from one hydrologic system to another. In general catchments are divided into steep, rugged headwaters, moderate-slope mid-catchments and low-lying plains. Relating these landscape compartments to sediment transport relationships, three zones (Figure 2.7A) can be differentiated: zones of sediment erosion (sediment production in source areas), zones of sediment transfer (sediment transport) and zones of sediment deposition (sediment storage in sinks). These three subdivisions are artificial because sediments are obviously eroded, transported and stored throughout the drainage basin; nevertheless, within each zone one process is usually dominant (Schumm, 1977; Knighton, 1998). This longitudinal process

being major hazards (Gerrard, 1990). However, such transformations and catastrophic events are initiated by the weakening and breakdown of bedrock. This is generally referred to as weathering and/or erosion. If either terms can actually be used identical or a sharp line should be drawn between them was discussed by several authors (e.g. Gilbert, 1877; Kennedy, 2000; Dixon and Thorn, 2005; Gregory, 2010). There is clearly some overlap between both terms as a continuum of types of processes exists between them, yet definitional uncertainties need to be acknowledged.

Weathering refers to a group of processes that provide the basic input to a geomorphic system and are the primary source of waste production. It is understood as the alteration and reduction of rock and minerals (in situ, at or near the earth´s surface) in finer particles caused by the prevailing environmental conditions which usually differ from those under which most rock materials were formed (Yatsu, 1988; Dixon, 2004). In general, weathering is divided into a range of processes following three main categories: physical or mechanical weathering, chemical weathering and biological weathering. An attempt to conceptualize the major components of weathering was made by Viles (2013a). As shown in Figure 2.8 the entity of weathering includes many different effects, agents, processes and mechanisms which produce sediment, contribute to soil development, release elements for further cycling effects, and initiate and contribute to relief development at various scales. Even though the conceptual diagram of weathering can be categorized clearly many different mechanism are usually involved at certain processes often leading to a mixture of weathering categories.

Weathering processes in mountain systems, mainly focusing on physical and chemical weathering, have been reviewed by Caine (1974), Gerrard (1990), and Janke and Price (2013). However, most of the attention, while focusing on weathering in high mountain systems, is given to the two following agents: temperature and water. By doing so the effects of freeze-thaw cycles (e.g. Matsuoka, 1994; Matsuoka and Murton, 2008; Messenzehl and Dikau 2017; Schnepfleitner et al., 2017) and a changing rock moisture content (e.g. Sass, 2005a; Rode et al., 2016) seem to be the main drivers of bedrock weathering especially in permafrost affected areas (e.g. Krautblatter et al., 2013; Draebing et al., 2014). The importance of chemical processes for rock weathering was already distinguished by Rapp (1960) and Caine (1976). Particularly in carbonate rich bedrock recent investigations have shown (e.g. Sass, 1998; Sass, 2005b; Krautblatter et al., 2012), that dissolution processes can cause micro-scale fracturing, possibly leading to larger joints and eventually to high-magnitude rock-slope failures.

Weathering is linked in a complex manner to the erosion and evolution of rock slopes. Therefore, rock slope instability in alpine geomorphic systems (Messenzehl, 2017) is of major significance for long-term erosion rates, landform evolution, sediment production and the overall efficiency of catchment sediment fluxes. As both the strength of rock slopes and the stresses that act upon them are influenced by weathering the alteration of bedrock and the rockfall supply chain consist of multiple processes, acting over different spatial and temporal scales, with many complex inter-linkages. The links between rock weathering, rockwall instability and sediment supply have been recently discussed by Viles (2013b) and Messenzehl et al. (2018).

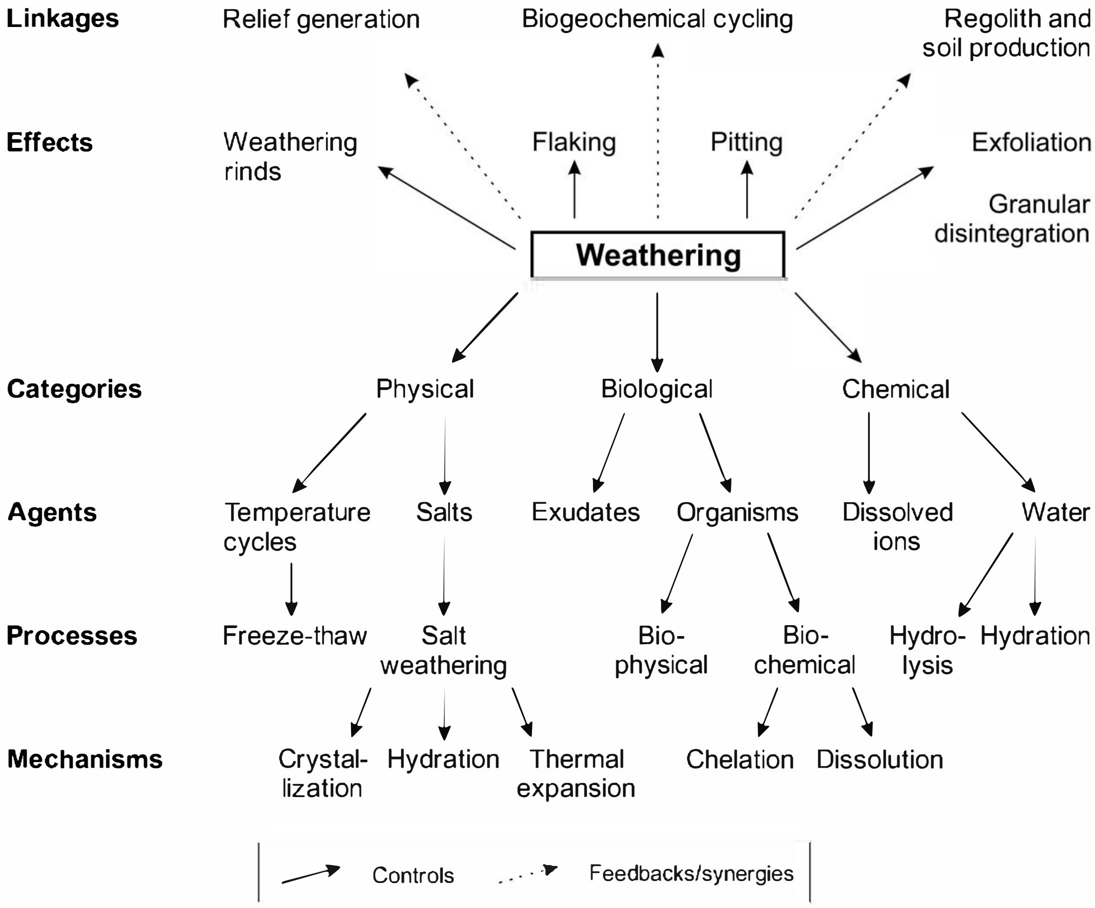


Figure 2.8: *Conceptual diagram showing the linkages, effects, categories, agents, processes and mechanisms involved in weathering (after Viles, 2013a).*

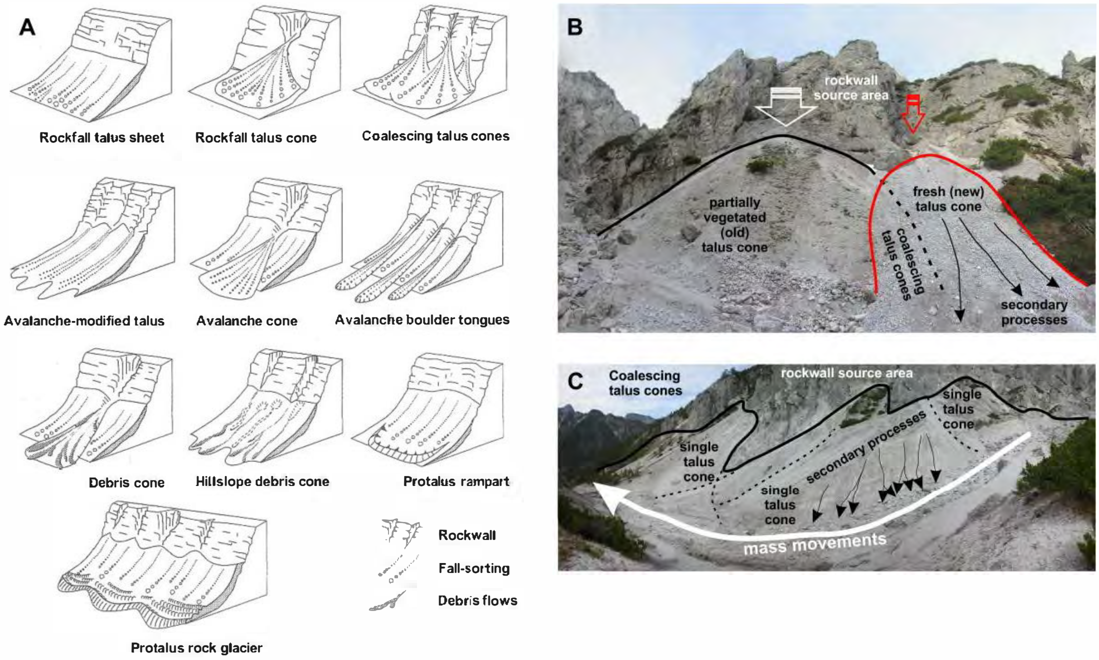


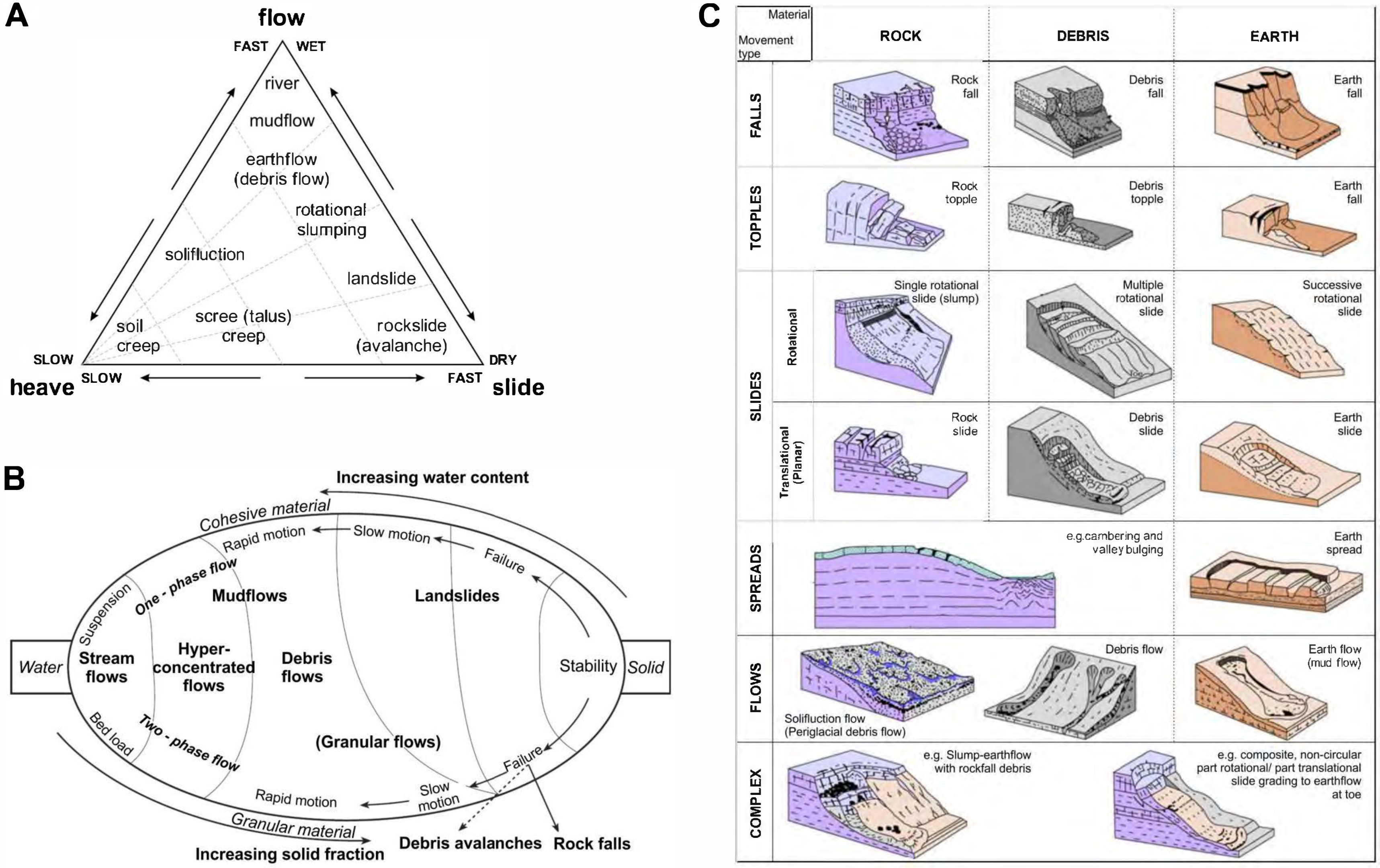
Figure 2.9: *Talus slopes and related landforms and processes.* ***(A)*** *Classification of talus slopes (after Ballantyne and Harris, 1994).* ***(B)*** *Talus cones along a rockwall in the Johnsbach Valley (Langgries, April, 30th 2015) and* ***(C)*** *coalescing talus cones being reworked by secondary processes and supplying material for subsequent mass movements (Gseng, April 3rd 2014).*

Rockwalls provide the waste, mostly deposited on talus slopes, which is needed for further downhill processes to happen. The movement of weathered material, including soil, loose stones and rocks, under the force of gravity is termed a mass movement (Waugh, 1990). Generally, this excludes movements, where ice, water or wind is the driving force. However, if ice, snow or water is released on a slope it will immediately begin to flow (Pierson, 1988) and will rapidly entrain further material along its way. The behavior of such a flowing mass depends on the material type and the ratio of sediment to water. This leads to another important parameter for classifying mass movements, the type and speed of the movement itself. Commonly the movement of waste material is either defined as ´fast` or ´slow` (Sharpe, 1938; Varnes, 1958). With this the periodicity of the process can often be deduced, as fast processes usually tend to have a long return period and result in catastrophic events whereas processes defined as slow generally act more continuously through both space and time (Caine, 1974). If this actually is the case and how a different magnitude and frequency of geomorphic processes is responsible for the evolution of specific features of the landscape was discussed by Wolman and Miller (1960).

Classifying mass movements and landslides has been a challenging task over several decades and still is (Cruden, 1991). The classical approach (Figure 2.10A) using the speed of movement (between fast and slow) and the amount of moisture present (between wet and dry), as a basis to distinguish between the various types, was made by Carson and Kirkby (1972). A more recent scheme on mass movements (Figure 2.10B) that operates in mountain environments was proposed by Coussot and Meunier (1996). They combined the material type (from fine, cohesive clays to coarse, cohesionless granular materials) and the proportion of solid in the moving mass (from water flow, to hyperconcentrated flows, to debris flows and landslides). Other descriptions and classifications of slope movement types or landslide types have been made e.g. by Varnes (1978); Cruden and Varnes (1996) and Hungr et al. (2014) as shown in Figure 2.10C. They differentiate between the type of movement (falls, topples, slides, spreads, flows or complex types) and the material type (rock, debris, earth) to account for a landslide classification.

Based on the variety of classifications for sediment transfer processes and storage types on hillslopes in alpine catchments a lot of investigation took place during the last decades. A general overview on alpine slope processes and related landforms combined with a summary of work on those topics has been done by Caine (1974); Gerrard (1990); Ballantyne and Harris (1994); and Janke and Price (2013). Finally, after a sequence of different processes, the sediment usually attains the fluvial system.

Figure 2.10: *(Next page) Classification of mass movements.* ***(A)*** *The classical approach (modified from Carson and Kirkby, 1972).* ***(B)*** *Steep slopes as a function of solid debris fraction and material type (after Coussot and Meunier, 1996).* ***(C)*** *Classification of landslides divided into types of movement and material type (after Varnes, 1978 and Cruden and Varnes, 1996).*


A
flow
FAST
WET
river
mudflow
earthflow (debris flow)
rotational slumping
solifluction
landslide
soil creep
scree (talus) creep
rockslide (avalanche)
SLOW
DRY
heave
SLOW
FAST
slide
B
Increasing water content
Cohesive material
Rapid motion
Slow motion
Failure
One - phase flow
Suspension
Mudflows
Landslides
Water
Stream flows
Hyper-concentrated flows
Debris flows
Stability
Solid
Bed load
Two - phase flow
(Granular flows)
Failure
Slow motion
Rapid motion
Granular material
Increasing solid fraction
Debris avalanches
Rock falls
C
Material
Movement type
ROCK
DEBRIS
EARTH
FALLS
Rock fall
Debris fall
Earth fall
TOPPLES
Rock topple
Debris topple
Earth fall
SLIDES
Rotational
Single rotational slide (slump)
Multiple rotational slide
Successive rotational slide
Translational (Planar)
Rock slide
Debris slide
Earth slide
SPREADS
e.g.cambering and valley bulging
Earth spread
FLOWS
Solifluction flow (Periglacial debris flow)
Debris flow
Earth flow (mud flow)
COMPLEX
e.g. Slump-earthflow with rockfall debris
e.g. composite, non-circular part rotational/ part translational slide grading to earthflow at toe

2.4.2.2. The components of the fluvial system

"Mountains may be worn down primarily by frost action and mass wasting, but if streams did not transport [...] the material away, the valleys would [...] be buried by the weathered material" (Janke and Price, 2013, p. 152). Rivers play an important role in the denudation of mountain environments. Most of the material transported in streams is obtained from hillslopes in the headwaters of drainage basins. Depending on the discharge of the stream sediment transport is an episodic process that can be characterized as a jerky conveyor belt (Kondolf, 1994).

Sediment transport in fluvial systems or rather the motion of a sediment grain in a mountain stream is basically depending on the size of the grain, the forces acting upon it, the amount of water or the discharge available and the inclination of the surface. The energy of the flowing water is able to perform geomorphic work which means transporting sediment and deforming channel boundaries. Hjulström (1935), as one of the first, describes the relationship between grain size and flow velocity and shows the transition between the phases of sediment entrainment, transport and deposition. By trend a grain spends more time in storage than in actual transport. The transport of the different grain-size fractions actually happens via different mechanisms. A detailed overview on the mechanics of flow and fluvial sediment transfer is given by Leopold et al. (1964), Schumm (1977), and Knighton (1998).

The behavior of water and sediment and the associated open channel processes of rivers in alpine regions do not markedly differ from those in the lower altitudes. Nevertheless, some characteristics of the mountainous environment may have an influence on the factors involved in the hydraulic geometry of a channel. In Figure 2.11 the interactions between the channel, the discharge and the sediment load are combined in different sets. These sets are interdependent which shows the connection between the various components of the fluvial system. In this structure the alpine footprint may be primarily found in the drainage behavior (e.g. highly variable discharge) and the sediment composition (e.g. size and type), which together form the boundary conditions for further hydraulic interaction eventually leading to sediment erosion, transfer and deposition.

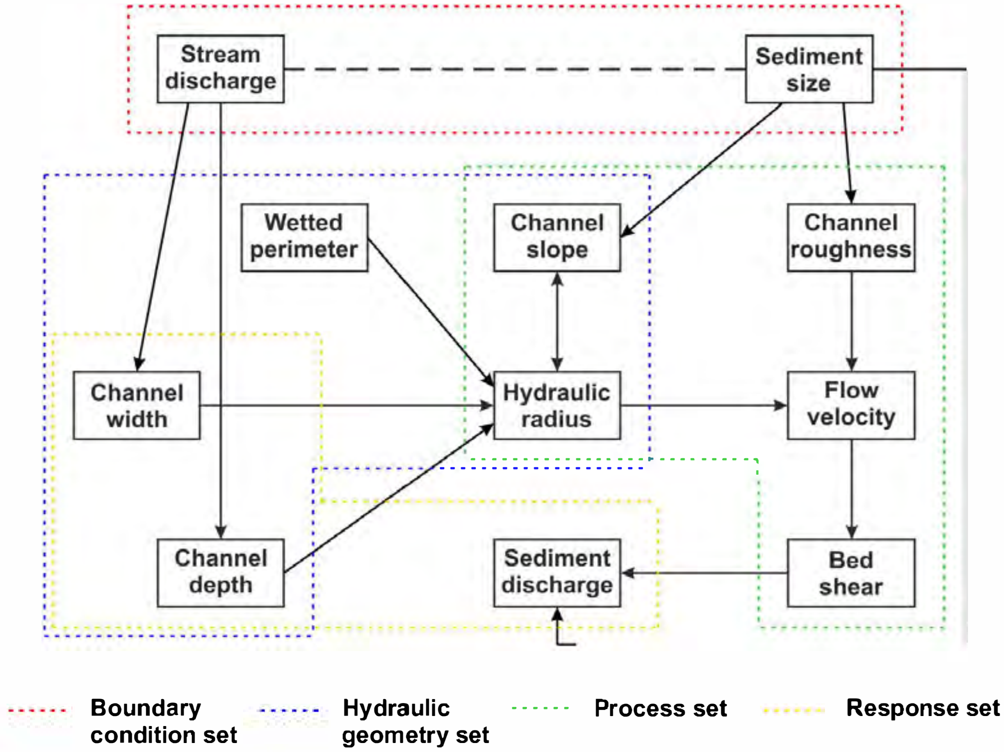


Figure 2.11: *General relationships between the factors involved in the hydraulic geometry of a channel (after Chorley, 1969). Note: arrows suggest the direction of influence.*

In the fluvial system stream channel processes can also be treated in terms of a source-to-sink model at a smaller scale (Figure 2.12). Apparently, the outputs from the hillslopes become the inputs to the channels such that a continuation of the sediment transfer is assured (Figure 2.1, 2.6). The material being delivered from the valley sides can be subdivided according to its size and therefore implies the differentiation between surface and subsurface processes. Further, sediment input is provided via the transit of sediment from channel segments upstream and the erosion of the channel boundaries itself (Figure 2.5). However, bed and bank erosion is not restricted to the channel itself but could also affect the valley floor as the stream breaks out of its channel due to higher discharges. Besides the composition of the sediment itself several hydraulic parameters are responsible for fluvial transportation (Figure 2.11). The load carried by streams can be separated into bed-material load, suspended load and dissolved load, depending on the type of transport. Though, this distinction is arbitrary to a certain extent as there is an interchange of particles between the first two modes of transport. The composition of the total load and the significance of the three types therein may vary for each

Estimating the geomorphological activity or the sediment output, respectively, from a particular mountain environment, can be achieved by measuring the sediment yield of a catchment draining such an area. "The sediment yield is defined as the total sediment outflow from a basin over a specified time period [...]" (Knighton, 1998, p. 88). However there is considerable spatial and temporal variation in global patterns of fluvial sediment yield (e.g. Walling and Web, 1983; Milliman and Syvitski, 1992). The main factors controlling that variation are climate (especially precipitation) and runoff characteristics, relief and tectonics, soil erodibility and plant cover (Knighton, 1998; Warburton, 2007). To evaluate the sediment output three main approaches exist: direct measurements of the fluvial sediment transport at the outlet, measurements of erosion at the source area and lake or reservoir surveys. For the first approach concurrent measurements of the fluvial sediment transport components and the discharge are required. Since both are highly variable in time survey periods need to be long enough to ensure a reliable relationship. The second method uses the concept of sediment delivery or the sediment delivery ratio being defined as the ratio between sediment delivered at the outlet and gross erosion within the catchment (Roehl, 1962; Walling, 1983; Richards, 1993). Erosion can be estimated either by measuring erosion rates or by using erosion models, e.g. USLE (Wischmeier and Smith, 1978). Finally the sediment yield can be predicted by connecting the gross erosion and the sediment delivery ratio, which can be determined in dependence of the basin area (Knighton, 1998). The third approach, sampling sediment from lakes or other reservoirs, has the potential to provide long-term records of variations in sediment yield. Therefore, a changing character in sediment sources or changing environmental conditions can be exposed. All three of these approaches, to estimate the sediment yield of a drainage basin, are often supplemented by sediment routing models to describe the transport of sediment from source to sink.

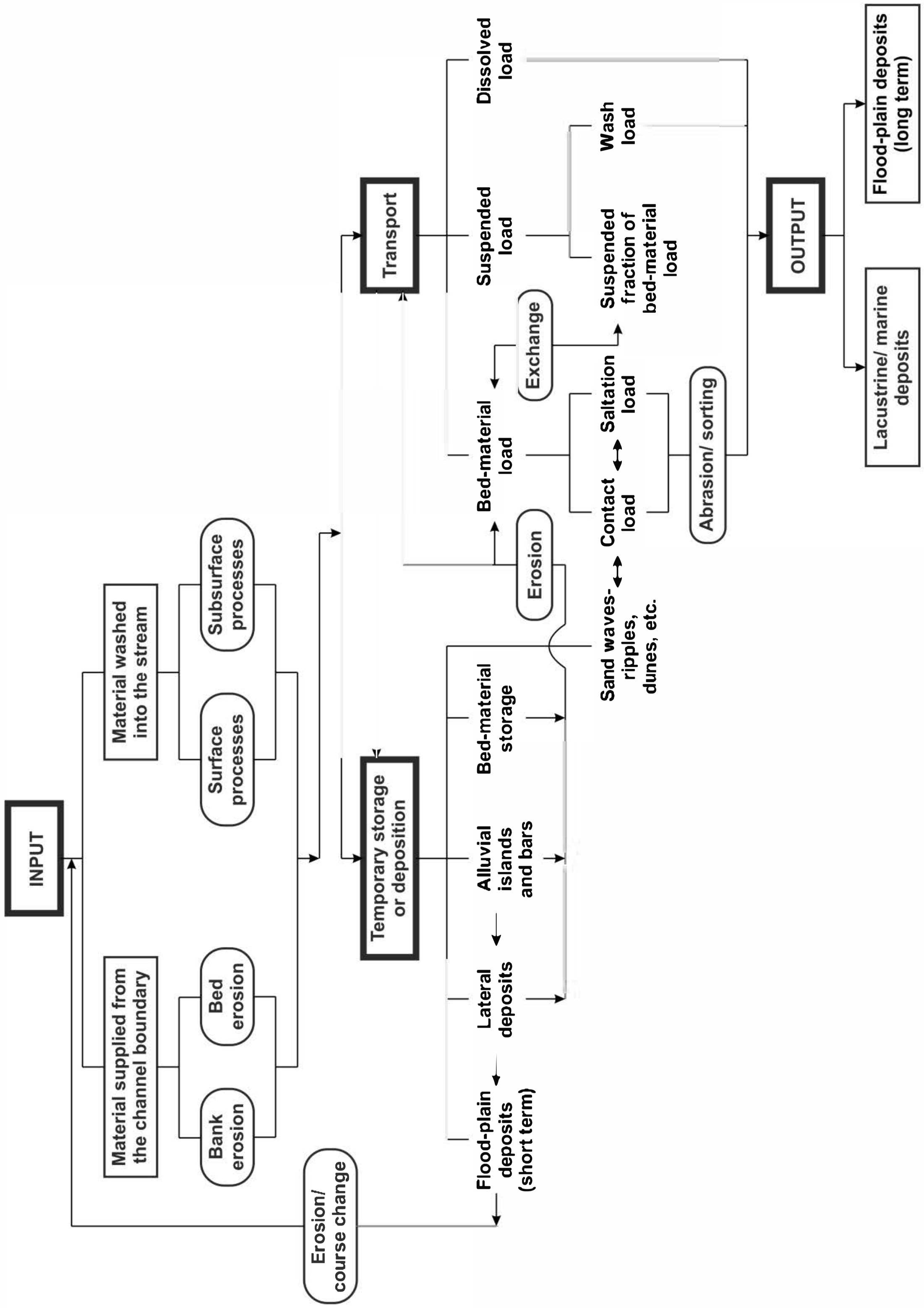


Figure 2.12: *Schematic diagram of sediment movement in and through the fluvial system (after Knighton, 1998).*

$$\boldsymbol{I_{X;\,W;\,D;\,N} = \Delta S_{X;\,W;\,D;\,N} + O_{X;\,W;\,D;\,N}}$$

The concept of connectivity or rather "connectivity thinking" has a long history in geographical research. The concepts of system analysis (Chorley and Kennedy, 1971) and sensitivity and coupling (Brunsden and Thornes, 1979) were among the first systematic considerations, in a geomorphological context, in which connectivity is documented and used to explain geomorphic change. Since then, connectivity has been widely used in various disciplines and contexts. Extensive summaries on conceptual connectivity frameworks and specifically on sediment connectivity have been compiled by Bracken et al., 2015; Poeppl et al., 2017; and Heckmann et al., 2018.

Sediment connectivity emerges at various spatial scales making it relevant to determine the spatial and functional elementary entities of the observed landscape. Therefore, sediment connectivity is divided into structural and functional connectivity (Wainwright et al., 2011) but is based on the interplay between them both (Figure 2.14). While the first describes the spatial arrangement of landscape units, the latter is established through the actual transfer of sediment between multiple structural characteristics of the system. Thus, sediment connectivity is dependent on all aspects of the geomorphic system that control sediment flux as well as on characteristics of sediment deposition and residence times (Sandercock and Hooke, 2011). This is in close relationship to the sediment connectivity framework, published by Bracken et al. (2015), which explains the connected transfer of sediment from source to sink in a system via sediment detachment and sediment transport. Within this framework three interrelated key elements of sediment detachment and transport are included: (i) their frequency-magnitude distributions; (ii) their spatial and temporal feedbacks; and (iii) their mechanisms. All three characteristics have formed the basis for prior geomorphological research, but Bracken et al. (2015) emphasize the co-dependency (relationships and feedbacks) of each of the three. By doing so they stimulate a continuum based approach in sediment transfer (understanding pathways, routes and scales of movement) rather than the stop-and-go type of transport between different sediment storages providing a better understanding of system complexity (Poeppl et al., 2017).

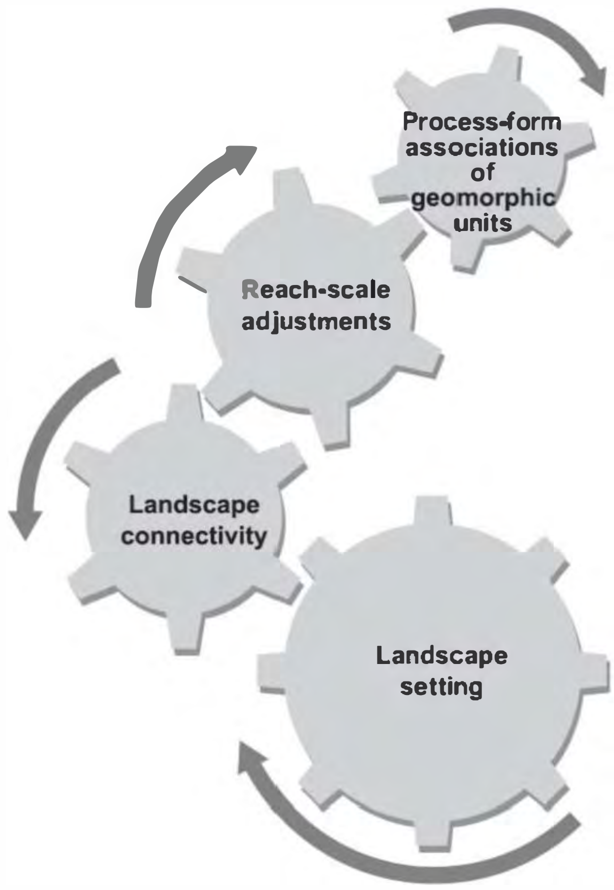


Figure 2.15: *Conceptualization of controls upon sediment flux at-a-catchment scale (after Fryirs and Brierley, 2013).*

The first control is the imprint of the landscape setting on source-to-sink relationships. Boundary conditions, such as tectonics and lithology, are important drivers for erosivity/erodibility of the landscape and mainly contribute to the amount of sediment that is made available. In relation to the hydrologic regime this determines whether the landscape is supply-limited or transport-limited (Gilbert, 1877; Carson and Kirkby, 1972) which further results in different reach patterns (bedrock-controlled or alluvial) (Montgomery et al., 1996; Turowski, 2012). The slope and the valley morphology itself are important determining areas at which sediment can be stored and/or reworked. Therefore, this is a major influence for the distribution of sediment sources, transfer paths and accumulation zones. The second regulator is the impact of landscape connectivity (Figure 2.16) on source-to-sink relationships with lateral, longitudinal and vertical linkages. The summary of all three types determines the degree of connectivity and shows how effective various parts of a catchment contribute to the sediment cascade. Within and between the landscapes compartments various landforms restrain the sediment transfer. These blockages can be generalized as buffers (landforms that affect sediment transfer from hillslopes to the channel network), barriers (landforms that impede downstream conveyance of sediment within the channel network) and blankets (features that disrupt vertical linkages) (Fryirs et al., 2007; Fryirs, 2013). The third control on sediment fluxes is represented by the sensitivity of the river reach. Whether certain reach acts as a transfer zone or an accumulation zone is strongly dependent on the different river type (e.g. confined or alluvial) resulting in a varying sensitivity and capacity for sediment fluxes (Fryirs and Brierley, 2010). Naturally, these conditions are not stationary and can change over time depending on the types and severity of disturbance. As a result former sediment accumulation zones can be remobilized into sediment source areas potentially releasing significant amounts of sediment into the cascade. In contrast the formation of blockages can disconnect certain reaches by transforming its geomorphic structure. At the smallest scale, the fourth control is the process-form association. This means that the recurrence interval and the residence time of geomorphic units determines the extent to which sediments are stored and transported. The different (impelling and resisting) forces acting on a single grain (Rickenmann and Recking, 2011), the roughness of various surfaces (Buffington and Montgomery, 1999) and the degree of sediment organization (packing or armoring of river beds) can have significant impact on the flows of various magnitude and frequency and its work on sediment transfer (Wilcock and DeTemple, 2005; Wang and Liu, 2009). The role of vegetation, on slopes as well as in river channels, can be extremely important as well (Osterkamp et al., 2012). Healthy vegetation and reforested areas are rather steady resistance elements whereas missing vegetation (e.g. due to forest clearance or burning) can speed up erosion and sediment transport (Sass et al., 2012; Harden, 2013). Deadwood can cause blockages and log jams which could lead to catastrophic sediment releases and transfer once they are breached (Comiti et al., 2006).

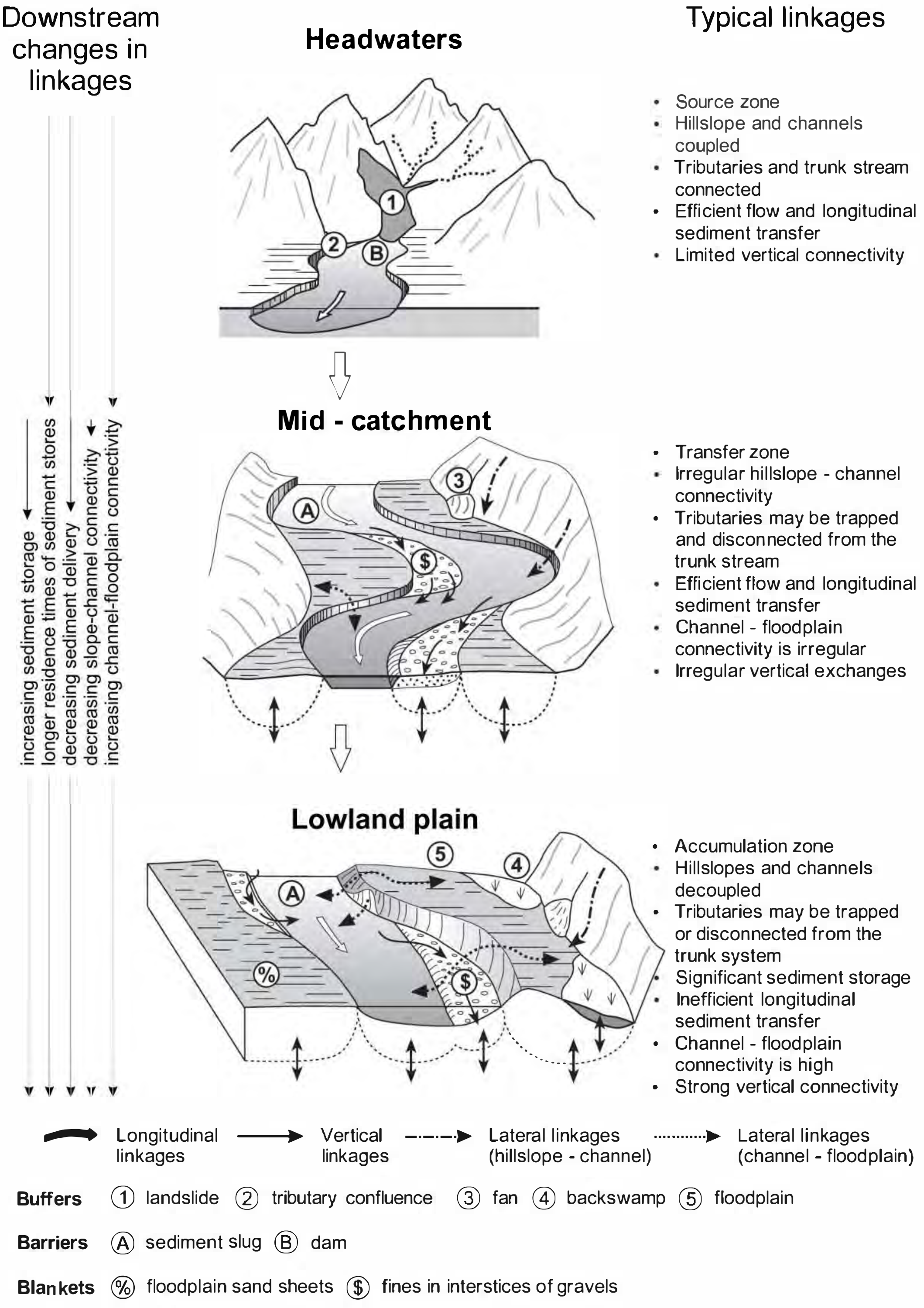


Figure 2.16: *Spatial dimensions of landscape connectivity in an idealized catchment. Patterns of longitudinal, lateral and vertical linkages have different strength in headwater, mid-catchment and lowland plain settings. This is largely dependent on the configuration of each process zone and the location of blockages in the system (modified from Brierley and Fryirs, 2005).*

2.4.6.2. Climatic controls

Besides the configuration of the catchment itself other factors might be significant when it comes to discussing the controls on sediment fluxes. Probably one of the most important driving forces in sediment dynamics is the climate with its diverse parameters, both globally and regionally. Since climate change occurs (IPCC, 2007) and is a topic of great importance it seems comprehensible to highlight the consequences on the sediment dynamics in alpine catchments. "Climate change defines a statistically significant variation either in the mean state of the climate [...] or in its variability, persisting for an extended period" (Borgatti and Soldati, 2013, p. 306). As far as recent and present climate is concerned the Intergovernmental Panel on Climate Change (IPCC) unequivocally states that the global and regional climate system is warming (IPCC, 2007). Considering the influence that climate exerts on the development of sedimentary environments, current and future climatic and environmental changes are potentially significant for the functioning of most sediment systems (Perry and Taylor, 2007).

The two climatic agents most significant for the alpine sediment systems and therefore for hillslope processes (Borgatti and Soldati, 2013) and catchment hydrology (Hudson-Edwards, 2007) are precipitation and temperature (Figure 2.17). First of all, rising temperatures are the unique driver for glacial retreat, melting icecaps, permafrost reduction and related phenomena and a changing cryosphere in general (Fischer et al., 2006; Haeberli et al., 2016; Avian et al., 2018). As a result the hydrological cycle and the sedimentological budget primarily in the proglacial area are reacting to those changes (Koboltschnig and Schöner, 2011; Carrivick et al., 2013; Fischer et al., 2015; Heckmann et al., 2016; Carrivick et al., 2018). Especially at high energy events, such as outburst floods (Cenderelli and Wohl, 2001; Harrison et al., 2006), the increased sediment supply and transport will be apparent. Further, temperature changes can have an important influence on weathering regimes such that rockwalls will provide more material for intensified surficial sediment fluxes (Ravanel and Deline, 2011; Kellerer-Pirklbauer et al., 2012).

Secondly, most sediment transport, and therefore the majority of morphological changes that occur in sedimentary environments, is a result of low-frequency but high-magnitude events. Usually these are associated with storms or high (seasonal) rainfall episodes which continuative lead to higher stages and runoff in the fluvial system. Although sediment can be mobilized and transported during normal flow conditions, floods play a major role in eroding and depositing fluvial sediment, and modifying river channels and floodplains (Knighton 1998). Goodbred (2003) reports from the Ganges river system that around 80 % of fluvial discharge and 95 % of sediment load are delivered over the 4 month summer monsoon period. A similar relationship, were annual sediment yield of a basin is strongly related to the precipitation, was already verified by Langbein and Schumm (1958). This symbolizes a strong seasonal control of the sediment linkages from the source areas through the catchment basins to the final depots in the sea. Rivers are particularly sensitive to changes in climate and significantly show a relationship between these changes and sedimentation in the fluvial system. Interactions between climate conditions and the sediment cascade in general were highlighted by Lane et al. (2007) and Rainato et al. (2018) and in relation to extreme events by Rainato et al. (2017). Addressing the fact of climate change again to the issue of precipitation, future scenarios show on the one hand an increasing shift towards the winter season (Gobiet et al., 2014). On the other hand, however, the intensity of the storms during the summer season is expected to rise (Schroeer and Kirchengast, 2018). Assuming that the temporary sediment storages inside the sediment cascade are replenished intensified summer rainfalls could lead to a higher sediment discharge both on the hillslopes and in the river channel.

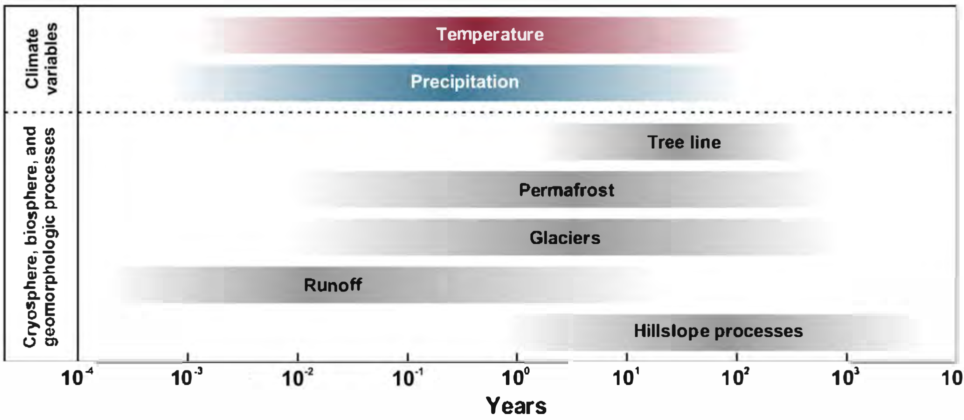


Figure 2.17: *Dependency between climate variables, components of the hillslope cryosphere and biosphere, and geomorphological processes (after Borgatti and Soldati, 2013).*

Mainly depended on climatic variables and thus especially affected by the consequences of climate change is the vegetation cover. Vegetation plays an important role when it comes to sediment supply, transfer and storage (Sandercock and Hooke, 2011; Osterkamp et al., 2012). However, specifically in mountainous

2013), and livestock farming (Butler, 2013). These activities resulted in increased soil erosion, soil creep and landslide events as well as a rise in flooding and flood peaks, which in turn result in higher rates of sediment input to rivers and of valley-floor alluviation (Evans et al., 2000; Knox, 2001; Glade, 2003). A clear link between anthropogenic activity and sedimentary system response can be assessed in areas where construction works (infrastructure, river regulation and channelization, dams and reservoirs) (Surian and Rinaldi, 2003; Magilligan et al., 2013; Overeem et al., 2013; Petts and Gurnell, 2013) or resource extraction activities (especially mining of aggregates) (Mossa and James, 2013) result in downstream sediment starvation. The reduced sediment supply has resulted in remarkable changes in the behavior and geomorphology of fluvial systems. In the Alps sediment deficits have been recorded in many rivers over the past 30-40 years. The result, on many upland rivers, has been widespread erosion and entrenchment (Descroix and Gautier, 2002). To counteract this evolutionary trend in riverine systems river management has seen increasing growth since the 1980s (Gore, 1985). Restoration plans include creating sustainable geomorphological features, managing riparian zones, restoring the hydrological stability and ensuring a sufficient sediment flow to keep the river in balance in terms of sediment yield and to facilitate renaturation measures (Hudson-Edwards, 2007).

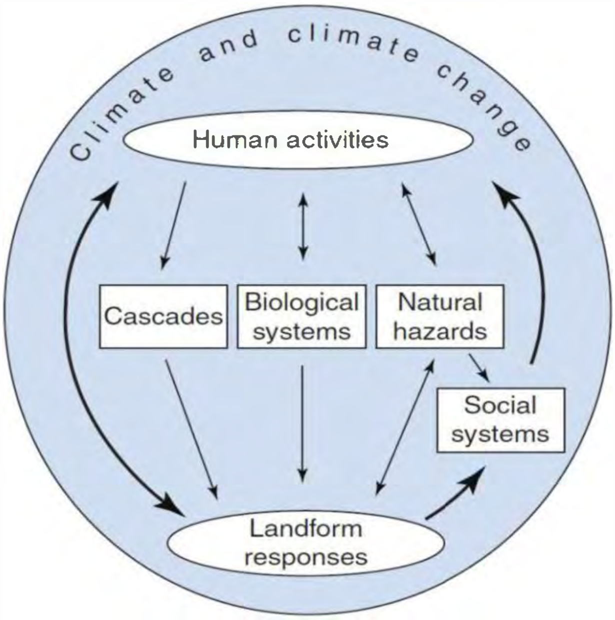


__Figure 2.18:__ System diagram for interrelationships between human activities and landform response (after James et al., 2013).

The Johnsbach Valley is a non-glaciated, longitudinal alpine valley belonging to the Gesäuse area. The Gesäuse (see the outline of the NPG in Figure 3.1) is the area along the Enns Valley, starting to the E of Admont until Hieflau, with its surrounding mountains and side valleys. The thundering and swooshing noises (*German translation: sausen*) of the River Enns gave the whole region its name "Gesäuse" (Sterl and Kreiner, 2010). Topographically the Johnsbach Valley is part of the Ennstaler Alps which is a mountain range of the Northern Calcareous Alps (NCA) and the Eisenerzer Alps which can be attributed to the Greywacke Zone (GWZ). The highest main mountain peaks in those ranges are Großer Ödstein (2335 m a.s.l.), Hochtor (2370 m a.s.l.) and Gsuchmauer (2116 m a.s.l.) in the N/NE, Leobner (2036 m a.s.l.) and Blaseneck (1969 m a.s.l.) in the S and Admonter Reichenstein (2251 m a.s.l.) in the W.

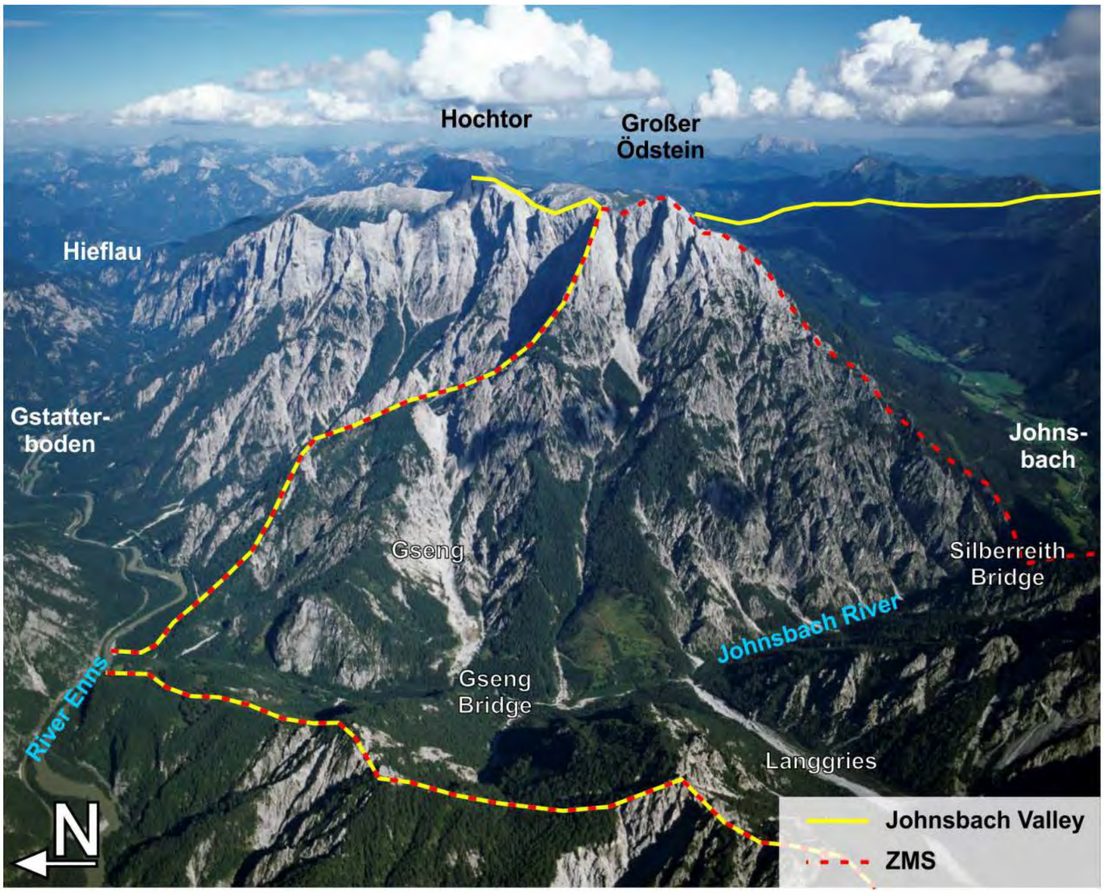


Figure 3.2: *Aerial image (eastward direction) of the ZMS (picture by NPG, 10/2004).*

the disharmonic tectonics theory. Addressing the evolution of the Gesäuse area since the ice ages van Husen (1987) focused on the glacier extends during the different stages on a larger scale and described how the Enns Valley bottom evolved during the quaternary (van Husen, 1968).

The location of the Gesäuse gorge, in a geological perspective, is described by Ampferer (1935) as "...recht merkwürdig" (*english translation: quite strange*). The course of the Enns Valley, starting at the Admonter Basin, seems untypical in that case for it leaves the border between the consolidated NCA and the more straticulate GWZ which it has been following before. The reason for that is a geological fault (Gesäuse Störung) parallel to the Gesäuse gorge approximately 1 km to the N (Ampferer, 1935). This fault is a sinistral strike slip fault and is part of the Salzach-Ennstal-Mariazell-Puchberg (SEMP) fault system. The SEMP is one of the great, and still active (Plan et al., 2010), lines of motion in the Alps and extends over 400 km from Innsbruck to the Vienna Basin. The Gesäuse Störung was considered to be a break in the E descending anticline of the Gesäuse Mountains at which the area to the S was lowered compared to the area to the N by up to 1,500 m (Büchner, 1970). Furthermore the Gesäuse Mountains are showing disharmonic tectonics due to the different mechanical properties of the rocks being involved in deformation processes (Büchner, 1970; Bauer, 1998).

The Johnsbach Valley is geologically divided into two main nappes the NCA to which the Gesäuse Mountains belong and the GWZ (Figure 3.3) (Ampferer, 1935; Tollmann, 1967; Büchner, 1970). The structure of the Gesäuse Mountains is widely determined by Triassic carbonate rocks mainly limestone and dolomite. Most significant for that structure is an approximately 2000 m thick carbonate plate starting with Werfener Formation and reaching to the Dachstein Limestone (Figure 3.4). The lower most Präbichl Formation is Permian while the upper Gosau is Cretaceous (Büchner, 1970).

The summit regions of the central Gesäuse Mountains are almost exclusively built from Dachstein Limestone. The thick bedded rock can reach a thickness of up to 700 m. Due to the strength of the rock, it typically breaks in large blocks and usually forms rugged rock faces. The underlying Dachstein Dolomite has a lower stratification and a higher brittleness than the Dachstein Limestone. The Raibl Formation is a 20-30 m narrow band separating the Dachstein Dolomite and the Wetterstein Dolomite. Their occurrences lie between 1100-1600 m a.s.l. The Wetterstein Dolomite (or Ramsau Dolomite) is the predominant geological basis of the montane level. The rock has a fine crystalline structure which is characterized by its light brittleness due to the fine joints. It is particularly prone to weathering, forming an erosional landscape with steep slopes and providing large amounts of sharp-edged debris. Heavy rainfall events erode large quantities of this debris which is being transported further on in troughs and ditches to the valley bottom. The lowest part of the carbonate plate is the Werfener Formation which is present at the surface only to a small extent. A detailed map on the distribution of the carbonate rocks in the ZMS (Figure 6.3A) is presented in Chapter 6. (Ampferer, 1935; Büchner, 1970; Bauer, 1998)

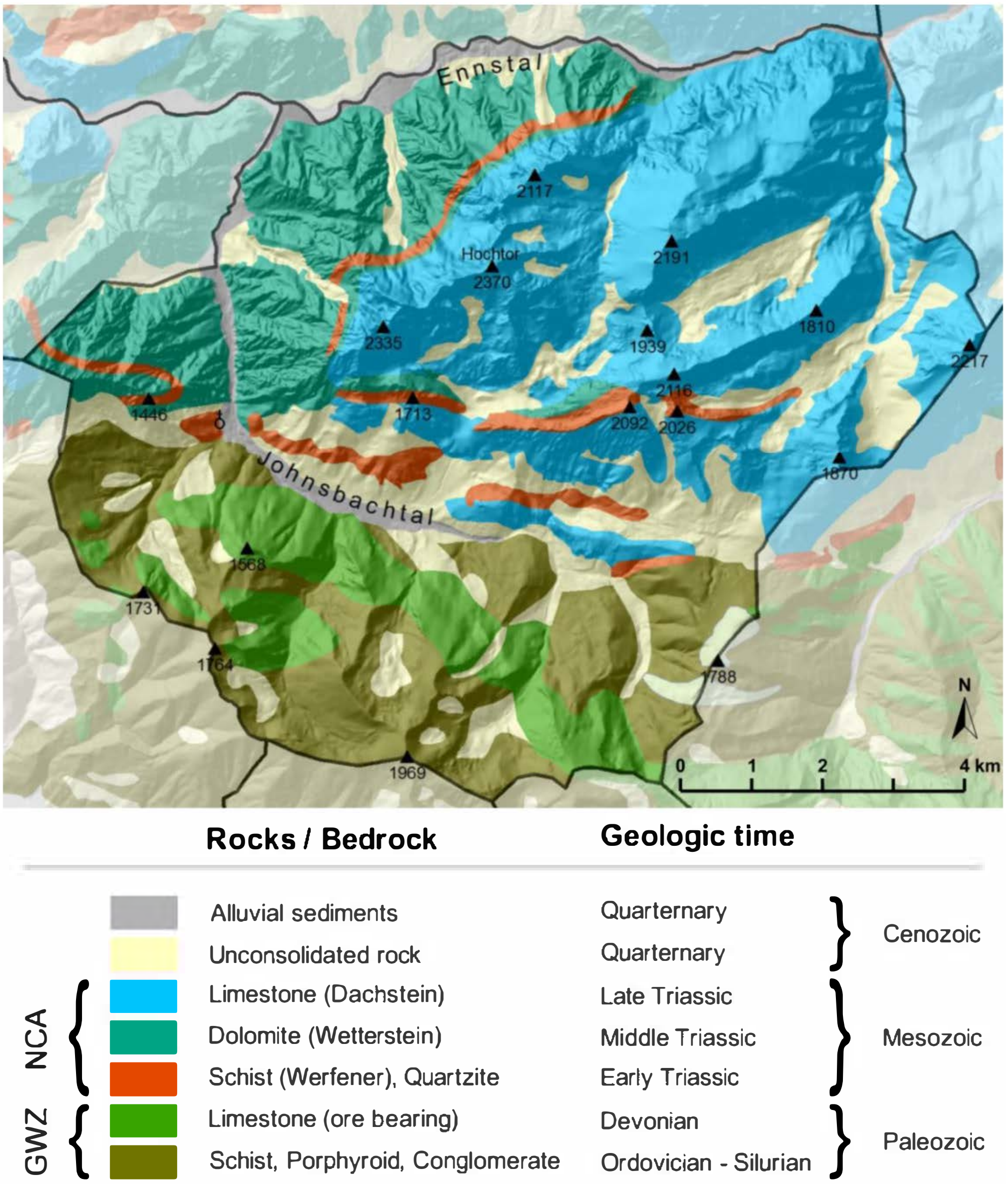


Figure 3.3: *Simplified geological map of the Gesäuse Mountains and the Johnsbach Valley (modified from Hasitschka and Lieb, 2012).*

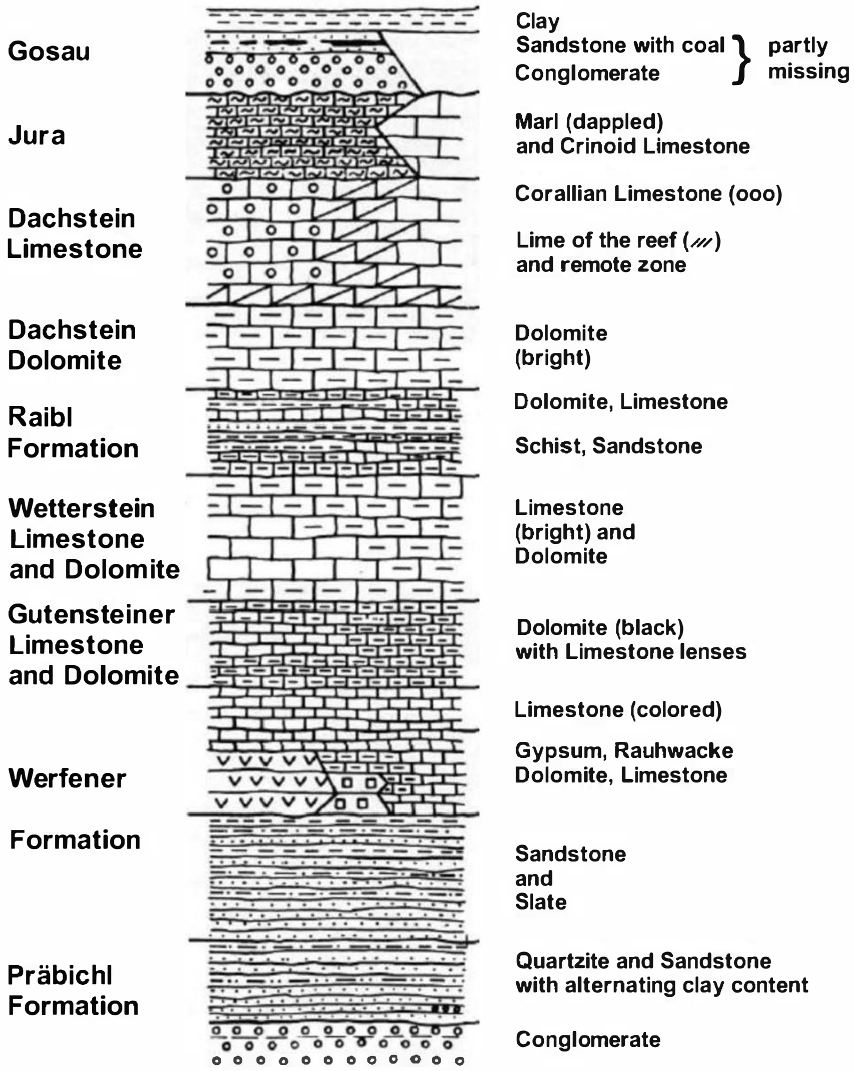


Figure 3.4: *Stratigraphic scheme of the Gesäuse Mountains (after Büchner, 1970, p.9).*

Remnants of the ice ages can still be found in isolated positions. Interglacial Breccia which is more or less calcified talus is located e.g. in the ZMS at the slopes to the E of the Admonter Reichstein and to the W of the Großer Ödstein. The extents of the glaciers during the different stages are rather hard to identify in the Johnsbach Valley. Morainic remains from local glaciers are present e.g. in the ZMS in the Kainzenalbl side catchment. Widespread alluvial deposits form the valley bottoms in the Gesäuse region and in the Johnsbach Valley. These deposits are usually fine sandy sediments which can be overlaid by hillside debris from the surrounding slopes. (Ampferer, 1935; Büchner, 1970; van Husen 1968)

The S-adjacent GWZ belongs to the same regional tectonic unit ("Oberostalpin") as the NCA and is split into a southern Veitscher nappe and an overlaying northern Norische nappe. The Norische nappe is bordering the NCA to the N. Its stratigraphy ranges from Ordovician to Devonian (Figure 3.3) and is mostly characterized by crystalline rocks (porphyroids and schists/phyllites) and partially by ore-bearing carbonate rocks. (Ampferer, 1935; Rucker, 1982)

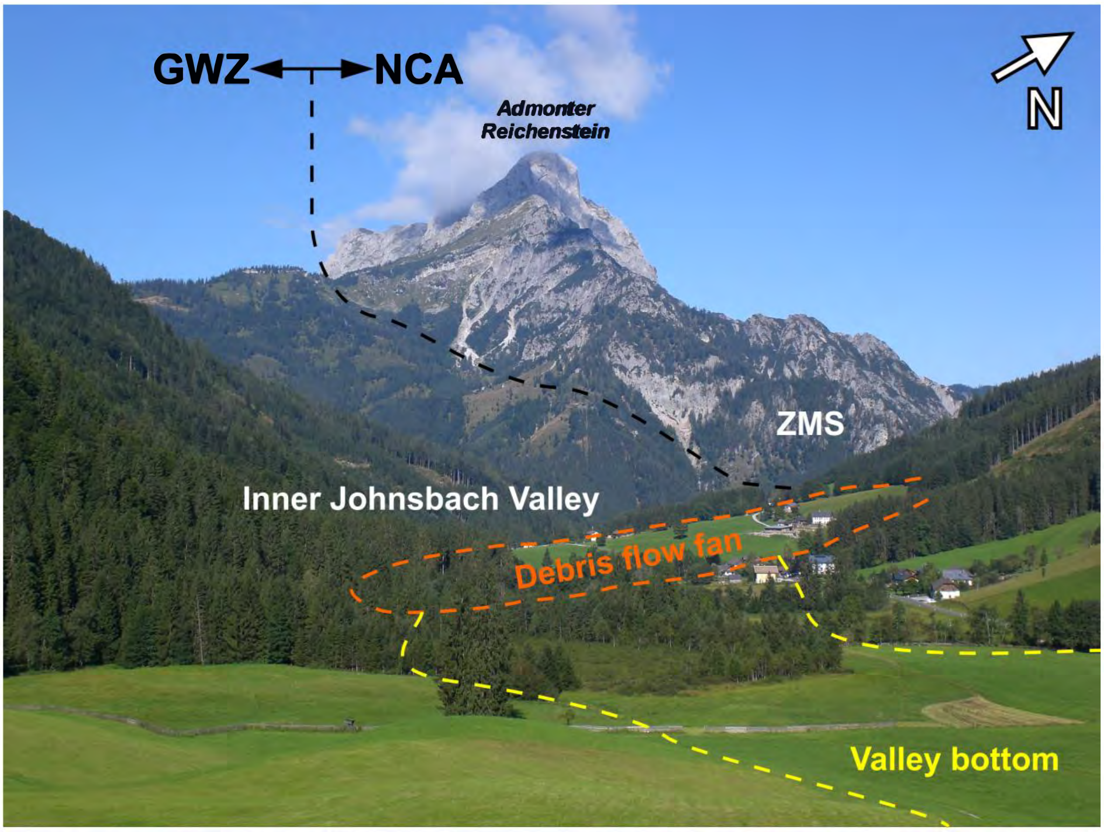
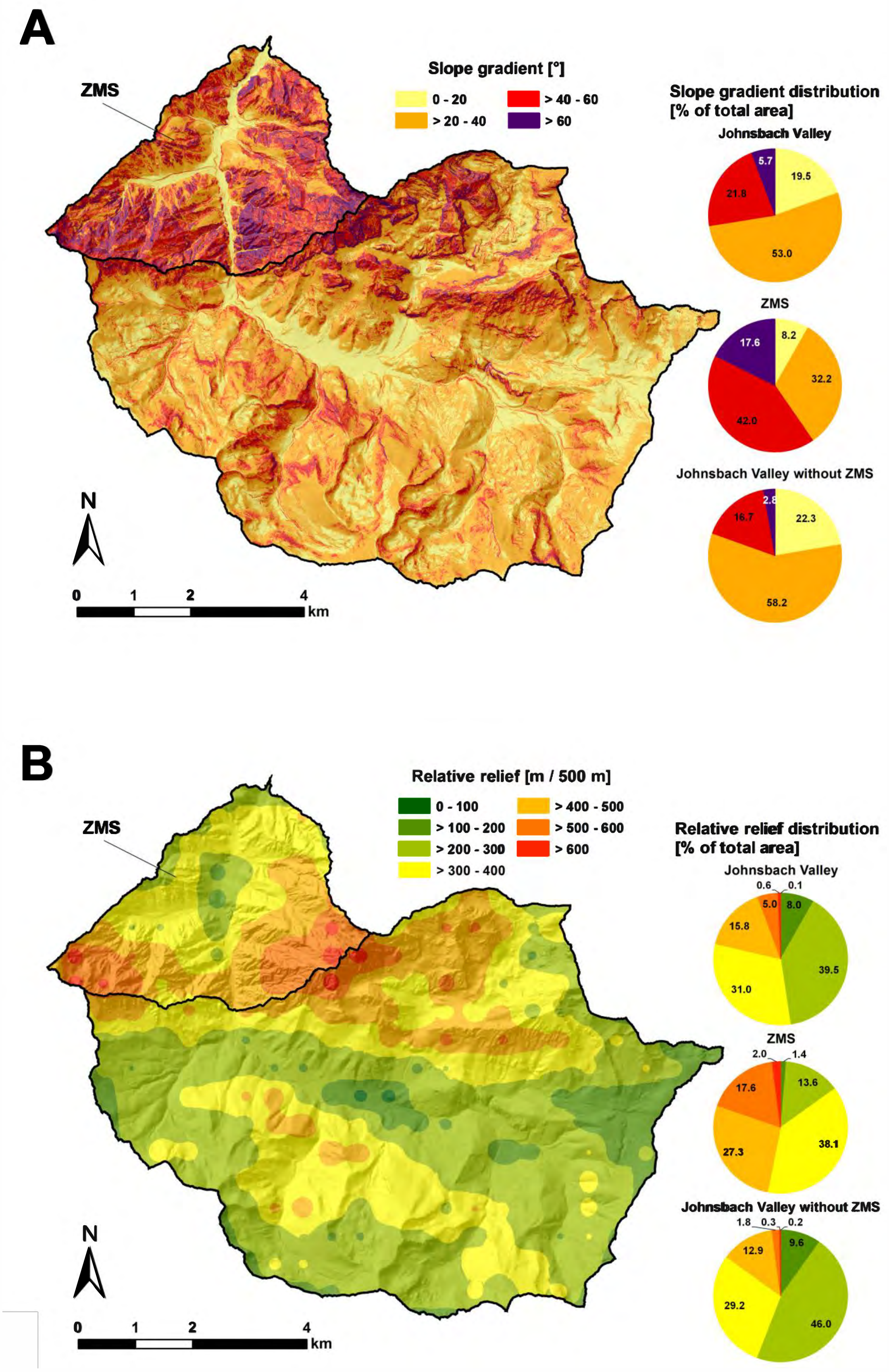


Figure 3.5: *View to the **WNW** from the inner Johnsbach Valley to the Admonter Reichenstein (adopted from Lieb and Premm, 2008).*

In the Johnsbach Valley a prominent contrast evolves between the surface shapes of the NCA and the GWZ which is due to the geological setting and the geomorphological processes. In the NCA the surface is sparsely vegetated and mostly shaped by rugged rock walls, steep furrows and deeply incised channels whereas in the GWZ a more flattened, mainly forested landscape prevails (Figure 3.5). The steepness of the terrain results from the resistance of the rocks to weathering which is why the ZMS is showing a greater distribution of higher slope gradients compared to the rest of the Johnsbach Valley (Figure 3.6A). The steeper the relief (Figure 3.6B) (with elevation differences of up to 1700 m between the valley bottom in the ZMS and the Großer Ödstein), the more processes appear that are caused solely or mainly by gravity. Usually these falling processes include a wide range of rockfalls depending on the volume of the event. An extensive compilation of the gravitational processes in the Gesäuse area was made by Stangl (2009). The sediment is being transported downslope from the upwardly branching gully system and is finally accumulated in talus cones and sheets. The debris is being reworked by debris flows and avalanches into the channels of the side catchments, especially during severe summer rainstorm events. Finally, this results in high sediment input rates into the Johnsbach River (Rascher and Sass, 2017) where it is an essential component in river dynamics. The sediment transport processes and storage types in the ZMS were mapped by Krenn (2016) in more detail. The sediment yield of the Johnsbach River is being determined almost exclusively by the relocated sediments in the ZMS. The inner part of the valley has been dammed by a huge debris flow fan (Figure 3.5) leading to a valley step of about 100 m (Lieb and Premm, 2008) and forming the valley bottom of the inner Johnsbach Valley. Due to the extensive forest cover in the GWZ the morphodynamic activity is rather low compared to the ZMS. Occasionally, slow mass wasting processes (e.g. sagging) occur where slopes are steepened by former glacial erosion resulting in a loss of stability. This finally leads to a deformation of the rocks due to the impact of gravity. If the relevant slip planes are present in the underground even faster processes (e.g. landslides) form the landscape at steeper slopes.

Figure 3.6: *(Next page)* ***(A)*** *Distribution of the slope gradient for the Johnsbach Valley.* ***(B)*** *Distribution of the relative relief for the Johnsbach Valley. Note: due to the medium sized catchment the reference distance (for the relative relief) is 500 m in contrast to 1 km which is generally used throughout the literature (e.g. Barsch and Caine, 1984).*


A
ZMS
Slope gradient [°]
0 - 20
> 20 - 40
> 40 - 60
> 60
Slope gradient distribution
[% of total area]
Johnsbach Valley
5.7
19.5
21.8
53.0
ZMS
17.6
8.2
32.2
42.0
Johnsbach Valley without ZMS
2.8
16.7
22.3
58.2
N
0
1
2
4
km
B
ZMS
Relative relief [m / 500 m]
0 - 100
> 100 - 200
> 200 - 300
> 300 - 400
> 400 - 500
> 500 - 600
> 600
Relative relief distribution
[% of total area]
Johnsbach Valley
0.6
0.1
5.0
8.0
15.8
39.5
31.0
ZMS
2.0
1.4
17.6
13.6
27.3
38.1
Johnsbach Valley without ZMS
1.8
0.3
0.2
12.9
9.6
29.2
46.0
N
0
1
2
4
km

3.1.3. Climate

The Johnsbach Valley can be assigned to the winter-cold valley-climate type (Wakonigg, 1978) with lower temperatures during the winter season and a longer snow cover, especially in altitudes ranging from 600-1000 m a.s.l., compared to the Gesäuse Gorge / Enns Valley region. Generally, Wakonigg (1978) is characterizing this climate type as winter-strong, summer-cold, and extremely rich in precipitation (both fluid and solid). The Gesäuse area is located at the weather side of the NCA with typical orographic rainfall events occurring during air currents from the W-NE (Wakonigg, 1978). If air currents occur from the S the region will be influenced by typical foehn effects. In addition, the continuity of the Northern Alps leads to a good exchange of air masses, whereby a frequent weather change is possible (Wakonigg, 1970). The high altitude and relief intensity seem to be two of the most important climatic parameters in the Gesäuse area which lead to the development of a "Schluchtenklima" (*english translation: gorge-climate*) in the Gesäuse and especially in the ZMS (Amt der Steiermärkischen Landesregierung, 2018). It is characterized by balanced temperature conditions and a sharp contrast in insolation which is heavily affecting the duration of the snow cover. Since the inner Johnsbach Valley is almost enclosed with mountain ranges a "Beckenklima" (*english translation: basin-climate*) type is present with less wind, lower night and winter temperatures and fog occurring more frequently.

The climate diagrams presented in Figure 3.7 correspond to the two stations in the Johnsbach Valley (Oberkainz and Weidendom) and a station close to the Gesäuse region (Admont). Oberkainz and Weidendom show data from a short observation period (2012-2017) which reflects the conditions during the work of this thesis whereas Admont illustrates the comparable current climate period (1991-2017).

The distribution of the annual precipitation amount (Figure 3.7) is showing at all stations a primary maximum during the summer period and a secondary maximum in the winter season. The minimum can be associated with the late fall and early spring season. The predominant factors for these climatic conditions are the strong precipitation effects of the weather conditions (NW, N, Vb) with its associated long-lasting and orographic rainfall events. The influence of the storm events during the summer is according to Wakonigg (1978) proportionally low in the Gesäuse area but can be perceived on a local scale when looking at short time intervals (compare Figures 3.7). The annual average amounts of precipitation range from 1041 mm yr^{-1}

at Oberkainz to 1261 mm yr^{-1} at Admont according to the relevant observation periods. Since snowfall is not considered at Oberkainz and Weidendom the (annual) precipitation amounts should be higher in absolute terms. Likewise, there is a strong increase in the annual amount of precipitation with height which can lead up to 2500 mm yr^{-1} in at the summit regions (Amt der Steiermärkischen Landesregierung, 2018).

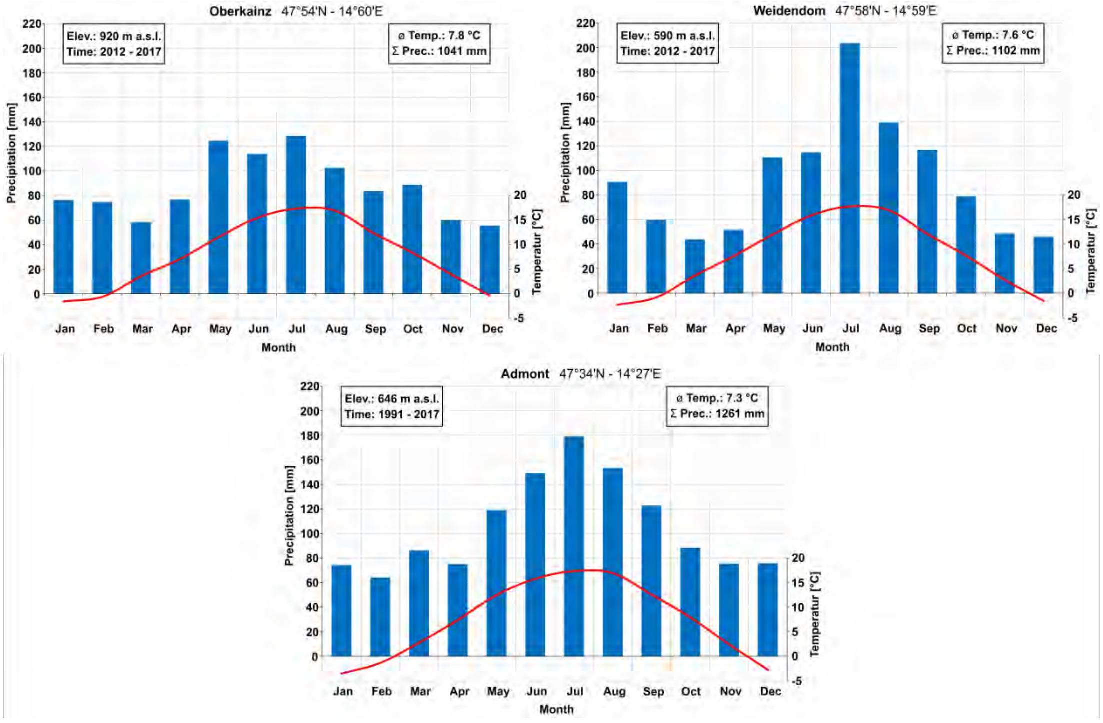


Figure 3.7: *Climate diagrams of the Gesäuse region:* ***(top left)*** *Oberkainz,* ***(top right)*** *Weidendom and* ***(bottom)*** *Admont (for location see Figure 3.1). The red curve represents the annual course of the temperature and the blue columns represent the monthly precipitation. Note: for Oberkainz and Weidendom snow is not considered in the precipitation amounts. Elev. = elevation, Time = observation period, Ø Temp. = mean annual temperature, Σ Prec. = mean annual amount of precipitation.*

The temperature profiles of all three climatological stations (Figure 3.7) are showing a uniform character. Mean annual temperatures are almost even, ranging from 7.3 °C at Admont to 7.8 °C at Oberkainz. Nevertheless, the range of the temperatures between summer and winter (20.9 K at Admont, 20.0 K at Weidendom, 18.9 K at Oberkainz) mirrors the more balanced conditions inside the Johnsbach Valley (according to the “Beckenklima” type) compared to the Enns Valley and the area outside of the Gesäuse. In general, the temperature behavior in the Gesäuse is characterized by temperature drops and jumps (Wakonigg, 1978). On the one hand this is due to the location at the weather side of the NCA with continuous and therefore pronounced cold air intrusions; on the other hand air currents from the south (foehn) develop its full potential temperature gain in the valleys of northern Styria.

A high percentage of the precipitation during the winter months is due to snowfall in the Gesäuse. This is associated with a snow cover duration above-average, which is 20 to 40 days longer than the total alpine mean at the same altitude (Kollmann, 1975). Due to the climatic conditions the precipitation in the valley can more often occur as snowfall until spring leading to an extended phase of a temperate snowpack.

3.1.4. Hydrology

The Johnsbach River is a perennial stream draining the Johnsbach Valley (Figure 3.1). It originates upstream of the Grössinger alp in an altitude of approx. 1500 m a.s.l. in the Eisenerzer Alps. Until the confluence with the River Enns it overcomes a height difference of almost 900 m.

The river flows in a NW direction for the first 9 km until the guesthouse Donnerwirt with tributaries of different flow conditions (perennial, periodic, episodic). In this section the headwaters, including the dendritic source area, flow in deeply cut V-shaped valleys with high gradients. The course along the inner Johnsbach Valley meanders in long loops in a trough-like high valley with a mean gradient between 2-3 % (Thonhauser, 2007). The river is increasing its gradient (to 7 %) after passing the huge debris flow fan which is damming the inner part of the valley until the power station close to the guesthouse Donnerwirt. After that the Johnsbach River turns into a N direction and cuts into the carbonate rocks of the ZMS. The mean gradient in the ZMS drops to 2.6 % and tributary trenches show surface runoff only during episodic rainstorms. After Petutschnig (1998) the ZMS is characterized by changing valley forms. The parts showing a V-shaped type are often associated with gorge-like, rocky sections, a higher gradient and a very small width of the valley floor. In the V-shaped flood-plain valley sections the valley profile widens and the average gradient decreases.

The Johnsbach River shows a mountain nival river regime (Enns type) (Mader et al., 1996) with a unimodal character of the discharge hydrograph (Figure 3.8). Thus, the runoff at the Johnsbach River usually peaks in spring (May) which is due to the snow melt. The peaks during the summer season (July, August) are significant but less large and result from typical summer rainfall events which can lead to floods affecting the whole valley. The absolute minimum can be assigned to the winter months.

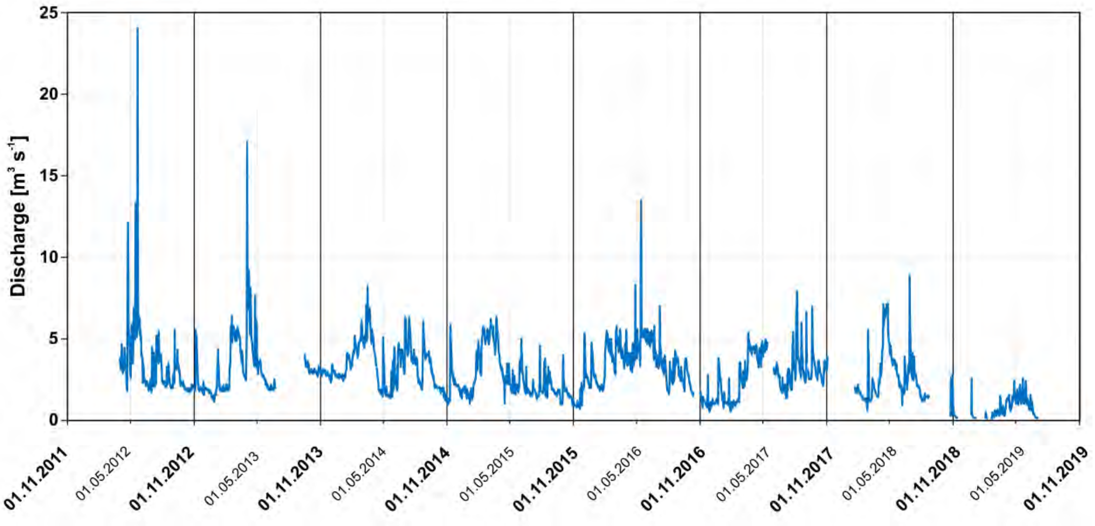


Figure 3.8: *Hydrograph of the Johnsbach River at the gauging station Gseng Bridge between 2012-2019 (at 08:20 a.m.). Note: missing data is due to failure in data acquisition.*

3.1.5. Land cover and Vegetation

The land cover of the Johnsbach Valley is highly dependent on its alpine character. The geological setting (with its two main contrasting units), the climatic conditions and the resulting morphological processes together with the human intervention over time are responsible for the development of the current land cover. Nowadays, the Johnsbach Valley is showing a rather oppositional distribution in land cover types comparing the ZMS to the inner valley (Figure 3.9). Inside the ZMS the land cover is dominated either by bedrock (41.9 %) and scree (6.5 %) or forest (36.6 %) and alpine shrub (12.4 %). In the rest of the Johnsbach Valley the forest covers more than half of the area (55.7 %) whereas the remaining portion is taken by many different land cover classes.

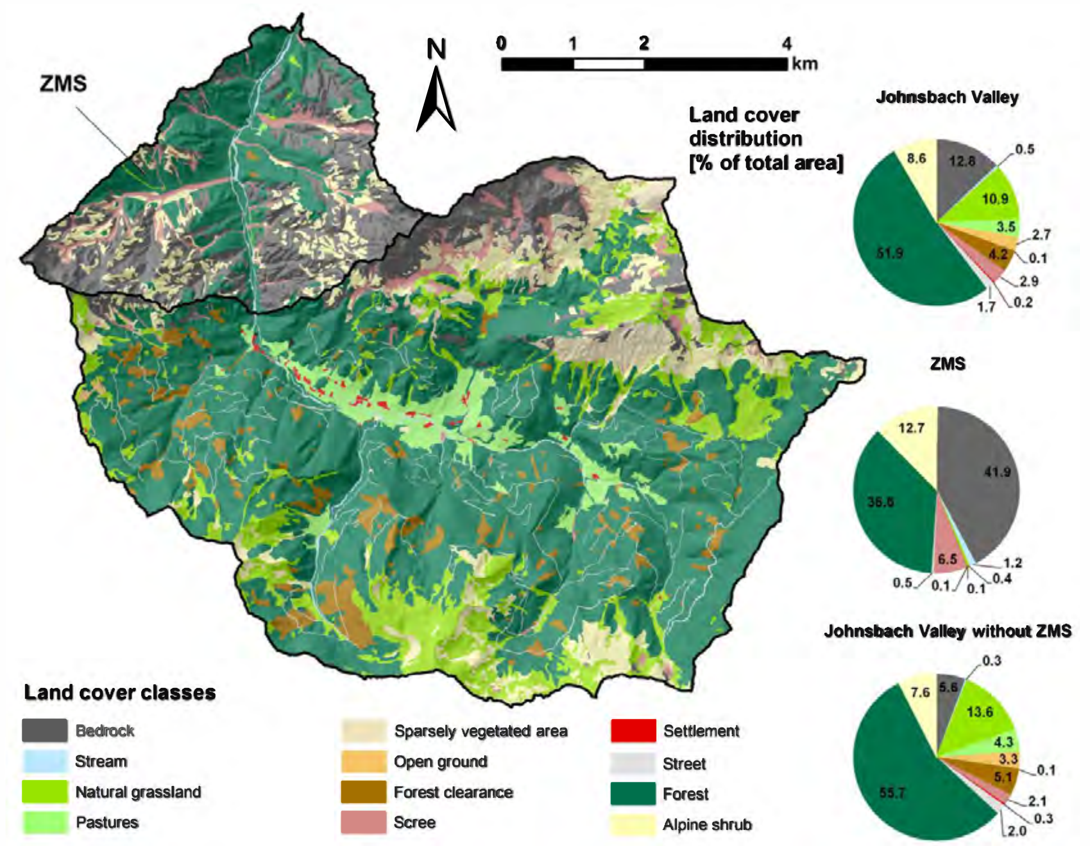


Figure 3.9: *Distribution of land cover classes for the Johnsbach Valley in 2013 (modified from HABITALP mapping by Wecht and Droin, 2016).*

Inside the ZMS almost 50 % of the surface is dominated by rockwalls and the associated unconsolidated material due to weathering processes which is transported in the active side channels. Excluding the river and the street, the other half is made up by different forest and shrub types. At the banks and in the floodplains pioneer species (e.g. butterburs), grey alder shrub, hoary willow and spruce (due to afforestation) prevail (Petutschnig, 1998). Further uphill a climatic graduation of the vegetation can be explored (Kilian et al., 1994). However, due to the geological setting in the NCA and the huge differences in relief intensity, a sharp demarcation of the individual zones is not always possible (Scharfetter, 1954). The montane zone (approx. 1400 m a.s.l.) is characterized by a mixed forest with beech, fir and spruce. Further uphill, in the subalpine zone (approx. 1900 m a.s.l.), mainly dwarf (pine) shrub prevails, with larch and Swiss stone pine in isolated places. In the alpine zone, with its extreme conditions in temperature, wind, and insolation, only a few specialized vegetation types like alpine grass heath or small prostrate evergreen shrubs are present. (Greimler, 1997)

At the inner Johnsbach Valley the valley bottom is mainly covered with pastures and different willow types (e.g. basket willow, hoary willow, pussy willow, white willow). The more gentle slopes of the GWZ result in a rolling, mainly forested landscape with wide areas of natural grassland. Two vegetation zones can be differentiated: on the one hand a spruce-zone in the lower parts and on the other hand a transition-shrub zone with shrub types of different heights. (Seiss, 2005)

3.2. Anthropogenic disturbances and landscape recovery in the ZMS since the 1950s

3.2.1. River regulation along the Johnsbach River and its consequences

The people of Johnsbach always said that the world was cut off from their home, if the road into the Johnsbach Valley could not be used during a flood. These floods, either triggered through severe rainstorm events in the summer season or by the huge amount of meltwater in the spring, had a major impact on the morphology and the accessibility of the valley. One of these events was the thunderstorm on August 19th, 1949, which was one of the most significant storms both in its effect and in its impact. The resulting flood and the triggered debris flows destroyed the road into the valley completely and buried it under meter-thick gravel (Zedlacher, 1999). The inhabitants of Johnsbach had to be cared for via the Mödlingerhütte and the town of Gaishorn am See which is located on the other side of the mountain range circumventing the Johnsbach Valley to the S (Zedlacher, 1999). This “horrible devastation” (Aichinger, 1953) was taken as an occasion to restore the Johnsbach River into its old state. Furthermore, the river should have more tractive power to discharge the bedload harmless by forcing the river into a controlled river bed (Aichinger, 1953). A time of serious change was imminent.

In the ZMS the course of the Johnsbach River was obstructed during 1950 and 1974. The Wildbach- und Lawinenverbauung (WLV) was instructed to install, supervise and potentially renew the necessary modifications. A comprehensive historical review and a detailed compilation of the annual building measures were compiled by Petutschnig et al. (1998) and Thonhauser (2007). In summary, the extensive measures after the disaster from 1949 can be described as follows: the course of the river was shortened by cut offs (Figure 3.10A) and regulation interventions (Figure 3.10B) which lead to an increase in the bed slope and therefore a rise in tractive power. To protect these measures gabion groins were installed over several hundred meters (Figures 3.10C,D). Over the years the scouring below those groins lead to sagging which stabilized the course of the river even more. The debris cones from the side channels had to be removed as they could push the river out of its new course. In the muddy valley floors along the river, the accretion zones were attempted to be stabilized by reforestation (Figure 3.10E). Especially the side channels on the western side of the ZMS continued to be very harmful as they had direct connection to the road. Therefore many of them were obstructed as well (Figure 3.10F) to redirect the sediment transport. During the 1960s and 70s the installation of further measures was pushed forward as new infrastructure (road and bridges) had to be protected (Figures 3.10G,H). All these measures have minimized the risk of outbreaks of the stream. Thus, certain areas of the valley floor have been cut off the natural dynamics of the river system. An increase in the tractive power of the river was responsible for an increased bedload transport rate. On the one hand the Johnsbach River could now remove the excessive amounts of gravel rather easy and on the other hand the road was largely secured.

Petutschnig et al. (1998) undertook a control survey and revealed a lot of ecological disturbances along the Johnsbach River at the end of the 1990s. The dynamics of the fluvial system were decreased especially in former areas of bifurcation due to the many protection measures installed in the ZMS. Furthermore, there is a loss of ecologically important areas of relocation, a loss in structural diversity, a decline in characteristic vegetation types with a rising monoculture in forest cover (due to the reforestation with spruce) and a limited possibility of migration for aquatic organisms. Many of the control structures showed significant damage and some of them were even destroyed completely. Thus, the effect of protection was very much limited and several ideas for restoration actions arose. The ZMS was now located in the IUCN II area (International Union for Conservation of Nature and Natural Resources, category II, National Parks) as well as in the Natura 2000 area AT 221000 (Haseke, 2006). This meant that a renewed assignment on control structures for the Johnsbach River should also be interpreted in the sense of an ecological regeneration.

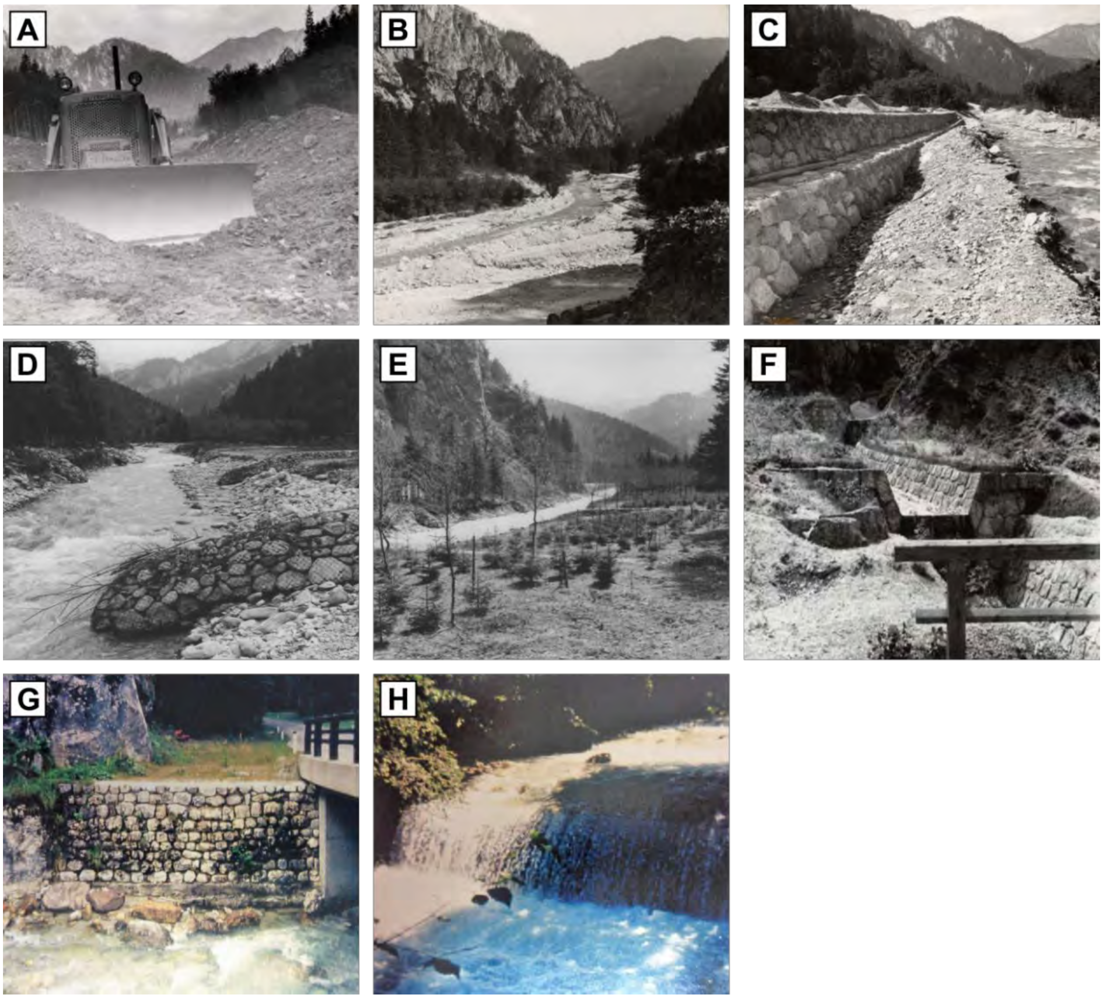


Figure 3.10: *River regulation along the Johnsbach River.* ***(A)*** *Cut off with caterpillar, 1952;* ***(B)*** *river course regulation, 1951;* ***(C)*** *gabion groin along the Johnsbach River, 1951;* ***(D)*** *river reach with several gabion groins perpendicular to river course, 1967;* ***(E)*** *reforestation of accretion zones, 1953;* ***(F)*** *obstructions at Breitschütt side channel, 1961;* ***(G)*** *sidewall to protect the street;* ***(H)*** *check dam in the river, 1970. Pictures A-F were taken from Thonhauser, 2007, G-H from Petutschnig et al., 1998.*

3.2.2. Gravel mining in Gseng and Langgries

In the ZMS and especially in the side catchments Gseng and Langgries dolomite is the prevailing bedrock type of the surrounding rock walls. Due to the high susceptibility of this rock to weathering enormous amounts of sediment accumulate at the foot slopes of these rock walls. Subsequently, this sediment is transported in huge debris flows which are characteristic features in the side catchments. This abundance of sediment led to the introduction of commercial gravel mining.

Kreiner (2016) describes that in the 1960s a company started to mine gravel in the lower parts of the Gseng and processed it immediately in an asphalt recycling plant nearby (Figure 3.11A). This intervention in the natural balance of the side catchment had a significant impact. Originally, the lower part of the trench was mostly covered with pine relict forest, which had to give way to the technical facilities. The mined gravel and processed asphalt were used for roadworks that took place in the Johnsbach Valley and along the River Enns. But the amounts of gravel needed to precede the works were insufficient such that the mining area had to be increased. Therefore, mining activities inside the Gseng trench had to move upward to where larger gravel terraces were located. This area was made accessible by building an almost 1 km long asphalted road uphill (Figure 3.11A) (Kammerer, 2006a). After the natural gravel formation and the accumulated reserves were no longer sufficient in Gseng, gravel was also mined from the neighboring Langgries side catchment (Figure 3.11B) starting in the 1970s (Kammerer, 2006b).

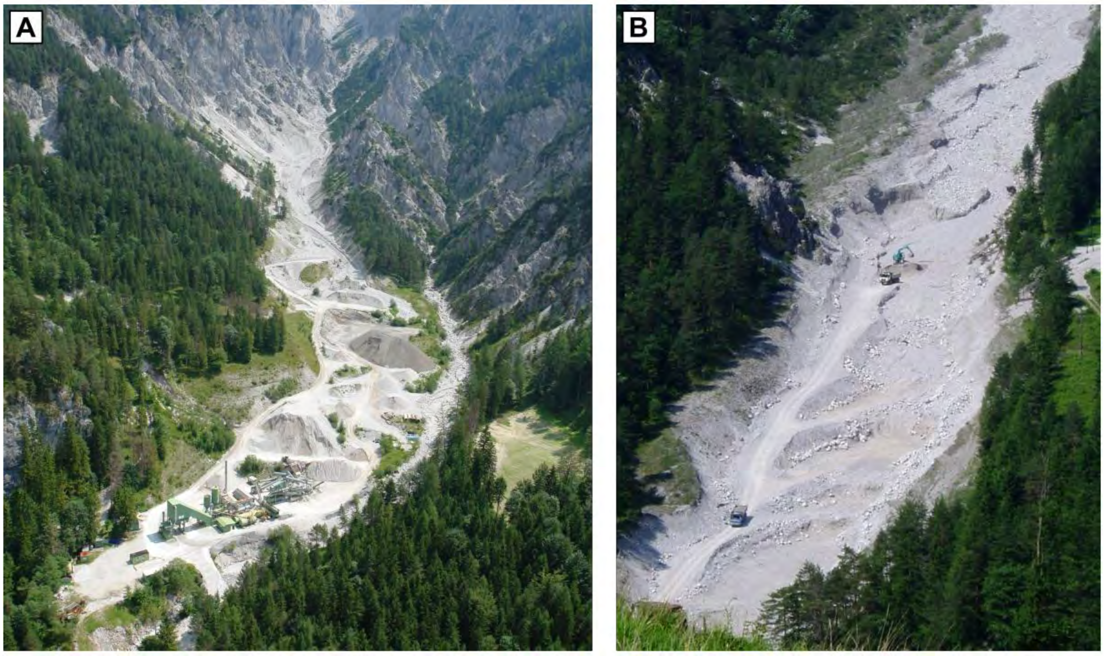


Figure 3.11: *Gravel mining activity in the ZMS.* ***(A)*** *Gseng side catchment in 2006, including the former mining factory;* ***(B)*** *Langgries side catchment in 2005. Pictures by NPG.*

It can be stated that the extensive mining activity in both side channels was interrupting the sediment flux substantially as huge amounts of sediment were excavated and used industrially. Due to the immense gravel removal and the associated erosion, both trenches lost their natural stability. Lateral erosion and undercutting of the roads were the result (Kreiner, 2016). Even in the Johnsbach River the effects of gravel mining were recognizable. The decrease of sediment input lead to a confirmed deficit in ecologically important bedload (Holzinger et al., 2012).

A precise documentation of all events happening inside both trenches since the beginning of the mining activities is not possible as there are only a few records. This changed when the company Asphalt and Beton GmbH (and later the STRABAG AG) took over the mining activities and received official contracts for Gseng and Langgries in 1984 and 1991, respectively (Fischlschweiger, 2004; Kammerer, 2006a, 2006b). Since then the annual amount of sediment being removed from both side catchments is reported with 15,000-20,000 m^3 yr^{-1} (Haseke, 2011). With the establishment of the NPG in 2002, the excavation of sediment had to be abandoned but was not terminated before 2008 because of still ongoing contracts. Subsequently, the gradual dismantling of the facilities and the renaturation of the mining area was initiated.

3.2.3. The foundation of the NPG and the river-ecological LIFE project: "Conservation strategies for woodlands and rivers in the Gesäuse Mountains"

The NPG (for location see Figures 3.1, 3.12) was found on the 26th October 2002 as the youngest and third-largest NP (approx. 11,000 ha) in Austria and was internationally recognized in 2003 by the IUCN as Category II protected area. Large areas of the NPG (94 %) are also part of the Natura 2000 network in the sense of the EU Fauna and Flora Habitat and Birds Directives. A significant aspect in the successful implementation of the NP was the fact that almost the entire area (99.3 %) is owned by the Steiermärkische Landesforste (e*nglish translation: Styrian Provincial Forestry Commission*).

Diversity is the dominant feature of the NPG. The River Enns provides the backbone of the area as the Gesäuse holds the last unregulated sections of this alpine river. Bodies of water and riparian forests along the River Enns and Johnsbach River are important features in the NPG even though they only make up 1 % of the total area. A wide area (approx. 45 %) is covered with forest in which the most common types are spruce (15 %) and subalpine coniferous forests, natural montane coniferous forests and beech forests (10 %). 15 % of the total area is covered by dwarf pine scrub. Almost a quarter of the total area is made up of boulders and scree with little or no vegetation. Treeless alpine grasslands, mountain pastures and avalanche chutes are covering about 11 % of the total area. (Sterl and Kreiner, 2010)

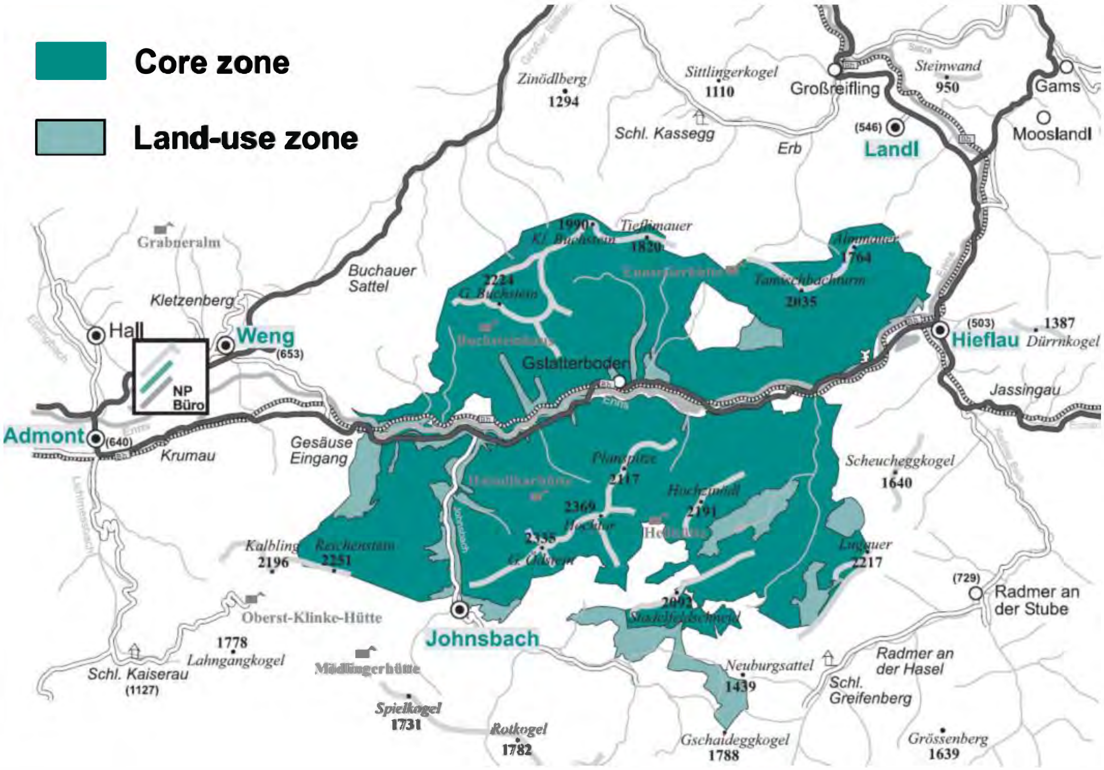


Figure 3.12: *The location of the NPG with its distribution into core zone and managed land-use zone.*

The area of the NPG is made up of two zones: a core zone (86 % of the area) where the protection of the natural habitats is paramount and a managed land-use zone (14 %) which mainly serves to maintain the cultural landscape. In the managed land-use zone especially the high mountain pastures enrich both scenery and biodiversity and demonstrate the positive interaction of nature and culture, man and environment. In the core zone the long-term objective for natural processes is to take their course without human intervention. Initially, however, regulating interventions were necessary. (Sterl and Kreiner, 2010)

In 2005 the EU funded river-ecological LIFE-project "LIFE05 NAT/A/000078 Conservation strategies for woodlands and rivers in the Gesäuse Mountains" (~2.4 Mio. Euro, 50 % co-financed by EU) was started and run until 2011. The main objective of the LIFE-project was to improve and enhance the habitats for target species along the River Enns and Johnsbach River, in the mountain forests adjacent to the floodplains and in the alpine pastures (Kreiner et al., 2012). Furthermore, a main focus was to dismantle and widely remove extensive engineering measures in the Johnsbach River (Figure 3.13A) and at the junctions to the side channels to improve the natural river dynamics (Haseke, 2011). This was meant to ensure that sediment can reach the river from the slopes and finally the River Enns in sufficient quantities (Holzinger et al., 2012), where it creates valuable habitats and ensures fish migration (Figures 3.13C,D). Finally, both former mining areas (inside the Gseng and Langgries side catchments) in the Johnsbach Valley had to be restored (Figure 3.13B) as industrial activities are not compatible with the regulations of the NPG.

The Gesäuse LIFE-project created and improved habitats along the River Enns and Johnsbach River, but also the forest, as a large-scale habitat, and the habitats of certain target species (Haseke, 2011). In order for this to be possible and to remain in the future, various approaches were chosen. The strategic orientations of nature conservation in the NPG formed the basis for the creation of several general management plans from which actions during and after the LIFE-project were arranged. These plans include the following topics: guidelines for the River Enns (Hohensinner et al., 2008) and the torrential Johnsbach River (Haseke, 2006), forest (Holzinger et al., 2009), pastures (Egger and Kreiner, 2009), and tourism and visitor control (Zechner, 2009). In addition, a plan for gravel management (Holzinger et al., 2012) and invasive plant species (Haseke and Remschak, 2010) were established.

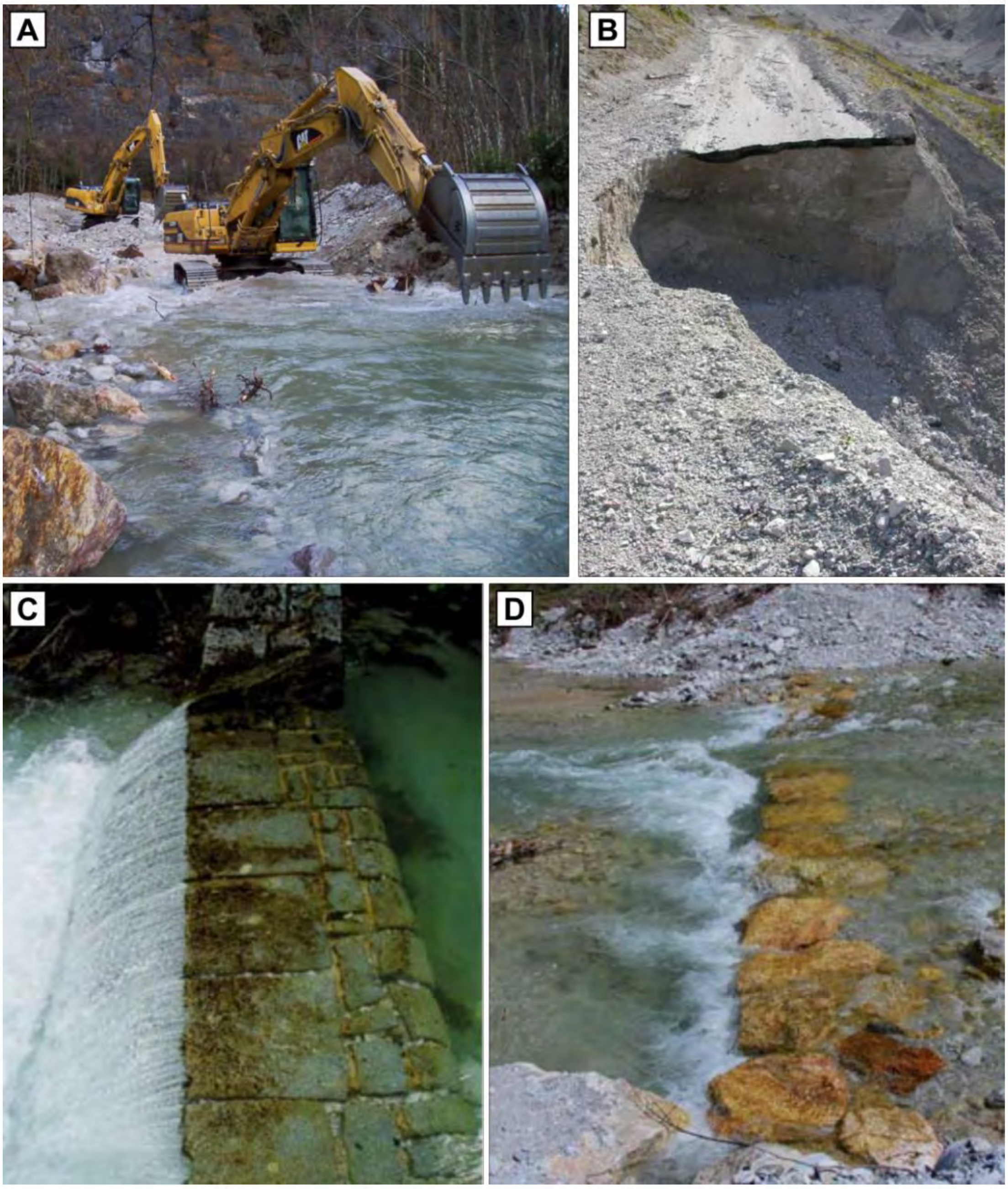


Figure 3.13: *Interventions into the landscape within the framework of the LIFE-project.* ***(A)*** *Implementation of measures at the Johnsbach River to eliminate obstructions and construct semi-natural structures.* ***(B)*** *Restoration of the former mining areas e.g. dismantling the paved roads. Examples of* ***(C)*** *an old "technical" groundsill and* ***(D)*** *a new, more ecological concept. Pictures by NPG.*

PART B

4. COMPARATIVE ANALYSIS OF SEDIMENT ROUTING IN TWO DIFFERENT ALPINE CATCHMENTS

Abstract

Sediment routing and sediment connectivity are key features to explain and predict sediment yields of arctic and alpine catchments. We applied a semi-quantitative modelling approach which relates upslope contributing areas to a gradient-weighted downslope flow length, and combined the model with maps of erodible sediment sources. The aim was to display and quantify connectivity parameters of the catchments as a baseline for further research on quantitative sediment budgets. The areas of investigation are two typical, non-glaciated alpine catchments in the eastern Austrian Alps (Schöttlbach, crystalline bedrock and Johnsbach, calcareous bedrock) with an area of approximately 70 km^2 each.

Numerous anthropogenic features, mainly forestry roads, led to unrealistic flowpaths when the original airborne laser scan (ALS)-derived digital elevation models (DEMs) were used. To achieve a more realistic model, a 'near-natural DEM' was first created by masking out anthropogenic features and in a next step, a 'valley DEM' was designed in which the forestry roads were supplemented by simulated stormwater infrastructure to ensure water and sediment flow at the junctions of roads and channels.

The results show that the 'valley DEM' mirrors the actual conditions quite well and is necessary to calculate realistic flowpaths. The elongated Schöttlbach catchment exhibits larger areas of low or very low connectivity to the outlet than the Johnsbach catchment. At the Johnsbach, more areas of active erosion are present (6 % of the area compared to 3 % at the Schöttlbach). The erodible sediments in the remote high-alpine areas are poorly coupled to the catchment outlet in both areas. Coupling of erodible sediments to the main creeks is mainly achieved close to the thalweg, by means of loose glacigenic sediments in the lower reaches of the Schöttlbach and large lobes of dolomite debris along the Johnsbach. In the future, simulations of sediment transport along the channel will be implemented to find out which sediment sources contribute to the yield at the catchment outlets during events of different magnitudes.

4.1. Introduction

Understanding and analyzing sediment dynamics within a river catchment have been widely discussed during the last decades (Slaymaker, 2003; Slaymaker, 2008; Walling and Collins, 2008; Brown et al., 2009; Hinderer, 2012; Wohl, 2014). Thereby fluvial systems play a major role in shaping the earth's surface by transporting fluxes of water and sediment from different sources to the outlet of the catchment. However, there are a lot of impediments (natural and/or anthropogenic) in between a basin which restrain sediment from moving downhill and downstream. This inefficiency results in a discrepancy between eroded sediment and sediment yield at the outlet and is termed the 'sediment delivery ratio' (Roehl, 1962; Richards, 1993). A so-called 'sediment delivery problem' was introduced by Walling (1983) and has stimulated a lot of geomorphologists since to examine sediment supply, transport and storage in different settings.

In this context connectivity describes the linkage between limiting factors and the efficiency of sediment transfer relationships in a catchment (Fryirs et al., 2007). Analyzing connectivity patterns on the spatial scale allows a classification of certain parts of a catchment to be identified as sediment sources and sediment transfer paths to a given sink. Especially in alpine headwaters both a complex morphology and heterogeneity in these sediment sources and transfer paths cause a variety of different sediment processes in size and effectiveness (e.g. Warburton, 1993; Mueller, 1999; Mao et al., 2009). These mobilized sediments can be of significant importance for infrastructures and inhabited areas in the valleys of the catchment as well as on the hillslopes. In this context a critical consideration of sediment transfer and delivery needs to be achieved to assess the coupling of different areas in terms of sediment movement and thus the connectivity of sediment sources to sinks.

The concept of connectivity has recently been widely used in research. Croke et al. (2005) divided connectivity into two types: direct connectivity via channels and gullies and diffuse connectivity via overland flow. Since this classification focuses on a combined movement of water and sediment Bracken and Croke (2007) chose different types of connectivity to separate: (1) landscape connectivity (e.g. Harvey, 1996; Brierley et al., 2006), (2) hydrological connectivity (e.g. Ambroise, 2004; Bracken et al., 2013) and (3) sedimentological connectivity (e.g. Harvey, 2001; Hooke, 2003) and identified key factors affecting the linkage between water and sediment.

Research on connectivity focuses on a variety of different topics and methods. Croke et al. (2013) used an extreme flood event to examine the spatial and temporal dynamics of hydrological and sedimentological connectivity between channels and floodplains. Beel et al. (2011) evaluated connectivity patterns in a slope-to-channel coupling scenario by focusing on fine sediments in a largely ice-free valley. By increasing the scale of the investigated area to a catchment size it could be proven that connectivity is a crucial determinant in landscape morphology (Faulkner, 2008). Baartman et al. (2013) have shown that sediment connectivity decreases with a landscape's increasing morphological complexity. (Dis)Connectivity at-a-catchment scale was described in detail by Fryirs et al. (2007) and Fryirs (2013) who have shown that different kinds of buffers, barriers and blankets slow down or even stop material from moving downstream. As a result, sediment cascades are decoupled and sediment is being prevented from moving to the outlet. Vegetation also has a major impact on sediment connectivity as it decreases the supply of sediment towards the channel through an increased resistance to erosion as well as an impeding of moving sediments (Sandercock and Hooke, 2011; Poeppl et al., 2012). Vegetation is therefore an important topic concerning land use scenarios (Lopez-Vicente et al., 2013) with soil erosion and agricultural studies. Furthermore, Croke et al. (2005) and Callow and Smettem (2009) have shown that especially in anthropogenic disturbed areas hydrological and sedimentological connectivity are profoundly affected by road networks and dirt tracks, as well as by farm dams and constructed banks. For this purpose, different kinds of barriers have been implemented in geographic information systems (GIS) to ensure accurate flow paths in hydrology and hence in sediment transport (Duke et al., 2003; Duke et al., 2006; Schäuble et al., 2008; Choi et al., 2011; Choi, 2012).

To get an impression of how different areas are coupled to each other DEMs have been used to model connectivity patterns at-a-catchment scale. Borselli et al. (2008) derived an index of connectivity (IC) which relates upslope contributing areas to a gradient-weighted downslope flow length. Cavalli et al. (2013) implemented this model and adjusted it to alpine catchments. Since the original model focuses on agricultural and vegetated landscapes they used a roughness index as a weighting factor which is more representative for high mountain environments. A different approach towards quantification of connectivity is presented by Heckmann and Schwanghart (2013) who use graph theory to delineate sediment contributing areas especially in high mountain catchments. The spatial interaction of sediment pathways and the corresponding process domains is the main focus to analyze sediment cascades.

In this chapter we focus on a semi-quantitative approach modeling sediment connectivity in two alpine catchments. The model is adopted from Borselli et al. (2008) including the additional specifications proposed by Cavalli et al. (2013). Since both catchments are highly affected by infrastructure, the first goal is to ensure correct flow directions in the used DEMs. Modeled flow paths often follow road ditches and similar tracks and fail to use road passages, if existing. Therefore an unrealistic pattern of accumulated flow arises which has to be adjusted. Secondly we evaluate the sediment connectivity in both catchments regarding different types of targets, at which sediment transfer would usually be prevented. Finally we focus on areas of erosion by connecting them to the determined indices of connectivity. Thus we can assess if sediment erosion hot spots are well connected to the chosen targets (i.e. valley floor and catchment outlet) or not. The investigations provide a baseline for further research and aim to highlight to what extent sediment routing in two catchments of approximately the same size can differ, and which consequences can be drawn for hazard assessment and ecological restoration purposes.

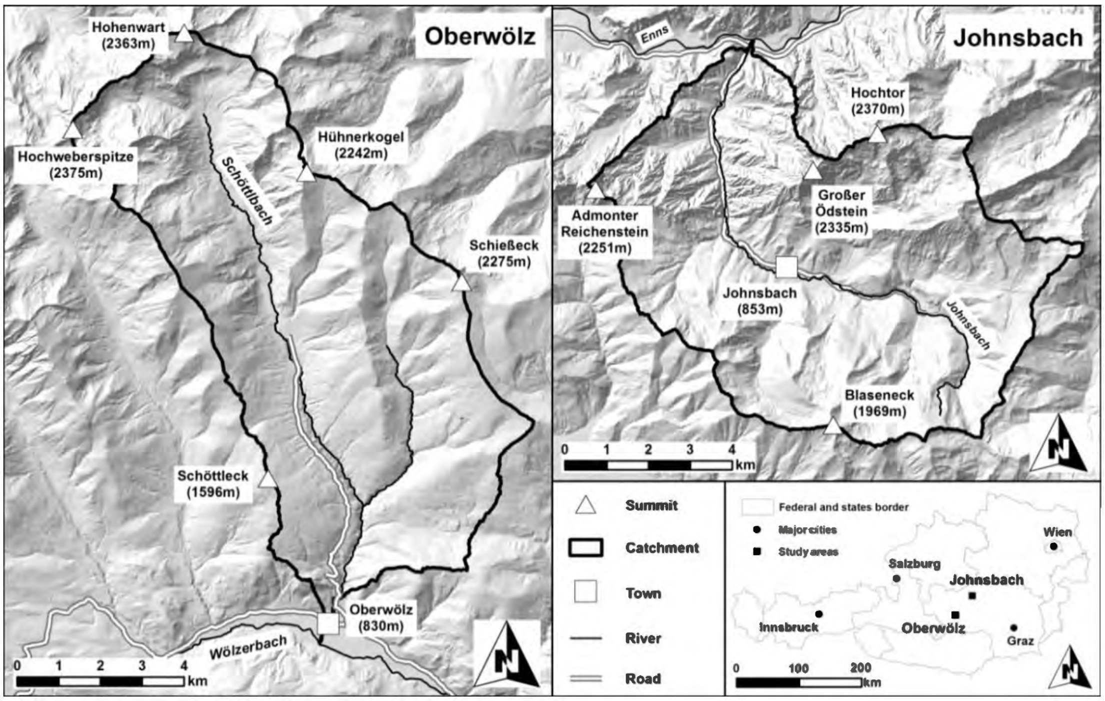


Figure 4.1: *Regional setting and detailed maps of the two study areas (background: hillshade of 10 m DEM).*

Both study areas a located in Upper Styria, Austria (Figure 4.1). The Schöttlbach Valley covers an area of about 71 km² reaching from 815 m to 2375 m a.s.l. The Johnsbach River drains a catchment of approx. 65 km² reaching from 584 m to 2370 m a.s.l. Environmental characteristics of the two catchments are summarized in Table 4.1.

Table 4.1: *Main properties of the two study areas, climate data for the towns of Oberwölz and Johnsbach are provided by Zentralanstalt für Meteorologie und Geodynamik (ZAMG) (2014) for the period 1971-2000.*

	Oberwölz Valley	**Johnsbach Valley**
Geographical coordinates (outlet)	47°12'N, 14°17'E	47°35'N, 14°35'E
Basin area [km²]	71.1	65.3
Minimum elevation [m a.s.l.]	815	584
Mean elevation [m a.s.l.]	1610	1348
Maximum elevation [m a.s.l.]	2375	2370
Elevation range [m]	1560	1786
Mean basin gradient [%]	54.4	73.3
Length of the main channel [km]	16.7	13.5
Mean gradient of the main channel [%]	5.9	6.1
Lithology	Mica Schists, Gneiss, Limestone, Dolomite	Limestone, Dolomite, Porphyroids, Schists
Mean annual temperature [°C]	6.4	6.5
Mean annual precipitation [mm yr^{-1}]	737	1418

The geological setting in the Johnsbach Valley is characterized by carbonate rocks and crystalline rocks belonging to both nappes, the NCA and the GWZ (e.g. Hiessleitner, 1935, 1958; Flügel and Neubauer, 1984). The NCA in the north and the GWZ in the south are separated by a WNW-ESE striking tectonic contact zone. Typical lithology units are carbonate rocks, mainly limestone and dolomite (NCA), as well as porphyroids, schists/phyllites and partially karstified regions with ore-bearing carbonate rocks (GWZ). The geological initial positions together with the climatic conditions result in an extremely high morphodynamic activity (Strasser et al., 2013). The ZMS, as part of the NCA, is barely vegetated and mostly shaped by steep furrows and channels running into the Johnsbach Valley from the east and west delivering the majority of the involved sediment. Further south, a rolling, mainly forested landscape prevails (GWZ), also covering the town of Johnsbach and an extensive forest road network. The Johnsbach River often reacts to heavy rainfall situations, especially in the ZMS. That is why the course of the river has been technically armed almost 60 years ago. During the last 10 years, the river has been restored in the framework of a LIFE project controlled by the NPG, to which the northern part of the Johnsbach Valley belongs. In the currently ongoing project Sedyn-X (interdisciplinary sediment flux research in the Johnsbach Valley) a sediment budget will be investigated for the Johnsbach Valley with regard to future sediment management strategies.

In contrary to the Johnsbach Valley, the Schöttlbach catchment is within one main alpine range, the Central Eastern Alps (subrange Lower Tauern) dominated by mica-schist and gneiss with some small amphibolite, limestone and dolomites enclosures. The highest peak in the catchment is the Hochweberspitze. In this upper part of the catchment (>1600 m a.s.l.) steep rock walls and mountain pastures prevail. Despite this high alpine topography, the main sediment sources lie in the lower part of the catchment close to the Schöttlbach, where the creek cuts a north-south facing gorge in a postglacial sediment body. Because of this, a check dam and a sediment retention basin were installed in the lower part of the Schöttlbach River. Nevertheless, on the 7th of July 2011, a three hour heavy rainfall event caused catastrophic flooding in this catchment with massive damage in the village of Oberwölz. Beside this high alpine area and the steep lateral valleys, the study area is characterized by forested areas and cultural landscapes.

4.2. Methods

Connectivity analyses of large areas, as we performed in the two catchments, need a computer based modeling approach to secure data continuity in all parts of the study area. Since this modeling is part of larger sediment budget calculations it is the first step to work out a conceptual model to understand the interlinkage and sediment transmissivity of the sub-catchments and the entire valley as a baseline for any further research.

4.2.1. The Connectivity model by Borselli et al. (2008) adapted by Cavalli et al. (2013)

Landscape development is primarily the result of sediment transport from sources - through channel networks - to sinks or receiving waters. The degree of connectivity in this network is an indicator for the probability that e.g. an unstable slope, a debris flow or channel erosion reaches downslope areas like the main channel or a lake. In this case the model treats the catchment from the view of a sediment grain, respectively from the view of a 1 x 1 m raster cell of a Digital Elevation Model (DEM). Therefore the IC after Borselli et al. (2008) was computed considering the upslope (D_{up}) and downslope component (D_{dn}) for every m² of the catchment area (Figure 4.2).

$$IC = log_{10}\left(\frac{D_{up}}{D_{dn}}\right) = log_{10}\left(\frac{\bar{W}\bar{S}\sqrt{A}}{\sum_i \frac{d_i}{W_i S_i}}\right)$$

d_i	length of the i-th cell along the downslope path (in m)
W_i	weight of the i-th cell (dimensionless)
S_i	slope gradient of the i-th cell (m/m)
$\bar{W}$	average weighting factor of the upslope contributing area (dimensionless)
$\bar{S}$	average slope gradient of the upslope contributing area (m/m)
A	upslope contributing area (m²)

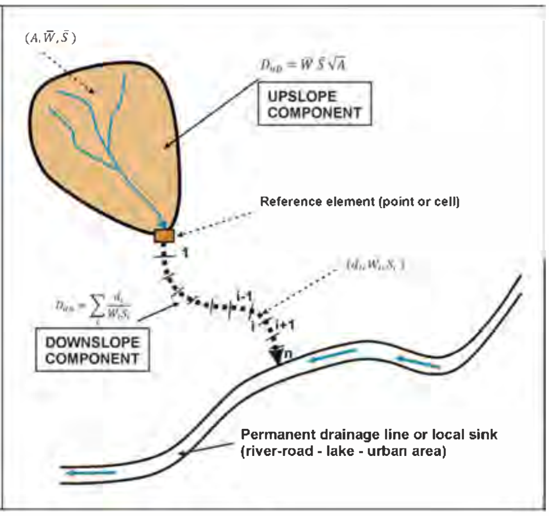


Figure 4.2:* *(Left) *equation based definition of the index of connectivity after Borselli et al. (2008),* ***(right)*** *simplified sketch of the connectivity model including the different calculation factors (Borselli et al., 2008).*

Almost all variables (*d*, *S*, *A*) of the above mentioned formula can be derived from a DEM, except for the weighting factor (*W*). Borselli et al. (2008) generate the weighting factor from the surface characteristics that influence runoff and sediment fluxes in a catchment area. Therefore the *W* used by Borselli et al. (2008) (after Wischmeier and Smith, 1978; Renard et al., 1997) summarizes the properties of vegetation, soil and land use management. Cavalli et al. (2013) in turn adapted the approach for mountain catchments. The first model adjustment concerns the slope gradient. In the original formula the S_0 was set to 0.005 m m^{-1} to avoid zeros and infinities in the equation. In addition to that an upper limit of 1 m m^{-1} (= 45°) was set for the mountain approach. In these steep terrains sediment storage is unlikely and the sediment mobilization happens in terms of rockfall in contrary to Borselli et al. (2008), where the main processes at this slope inclination are e.g. debris flow and bedload transport. The second modification was the use of a different GIS calculation method for the hydrological flow direction. The multiple flow D-infinity approach (Tarboton, 1997) shows a more natural flow path of the channels than the former used single-flow algorithm (O'Callaghan and Mark, 1984). The third and final adaption, using a different weighting factor, affected the model most. Cavalli et al. (2013) point out that inverse to Borselli et al. (2008) the *W* should be derived only from the surface characteristics which have a great influence on the runoff processes and sediment fluxes within a catchment. The roughness index (*RI*) was applied as the weighting factor. It is defined as the standard deviation of the residual topography (Cavalli et al., 2008), which was computed as the difference between the original DEM and the smoothed version calculated by averaging DEM values on a 5 x 5 cell moving window (Figure 4.3). The method computes a grid where the value at each location is a function of the input cells within a specified neighborhood.

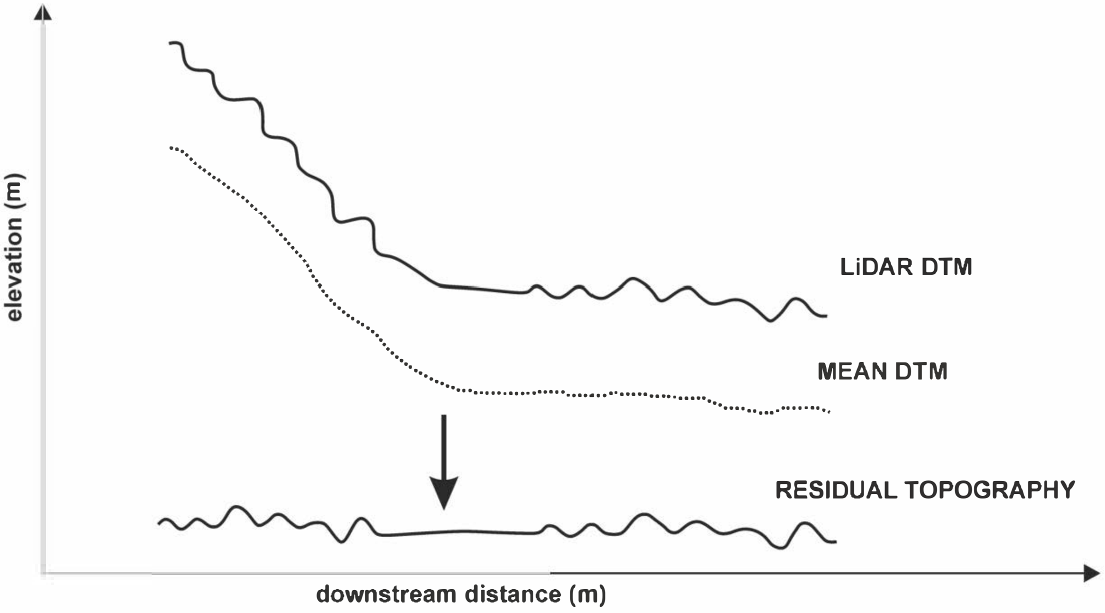


Figure 4.3: *One-dimensional example of the residual topography calculation. The dotted line is the profile of the mean DEM calculated over the LiDAR DEM (continuous line) with a neighborhood analysis approach. Residual topography is calculated as the difference between LiDAR DEM and mean DEM (Cavalli et al., 2008).*

indices when different sinks are considered, and (3) an analysis of the connectivity indices for the mapped erosion surfaces with regard to the different sinks.

4.3.1. DEM results

As a first result of our DEM adaption we derived two new DEMs, the Near-Natural DEM and the Valley DEM. The differences in the flow-accumulation compared to the original ALS DEM are shown in Figure 4.6 (center-right). The flow paths are partly similar and partly divergent. In some cases the forestry roads have a major effect on the flow direction but mostly the water and the sediment, respectively, follow the depression line.

Considering the flow accumulation and the flow direction created earlier, we located permanent sinks like lakes or geomorphological depressions and mapped them as disconnected areas. These regions have not been considered for the following IC calculations.

Figure 4.6 provides a comparison of the eight different IC results of a detail of the Schöttlbach catchment. The eight corresponding scenarios of the Johnsbach Valley are showing the same properties regarding the input DEM. The three results in the first row were derived from the unmodified ALS DEM. It is characterized by partly unrealistic flow paths as mentioned above. The Near-Natural DEM (disregarding the different sinks) in turn is unrealistic too, because of the complete disregard of all forestry roads and streets. Therefore it could be an example of the connectivity without human interventions. Nonetheless it is only an intermediate step towards the compromise of the Valley DEM which conveys a mixture of the two earlier DEMs. The main channels are continuous, but in some reaches the roads influence the flow paths like they do in reality.

The distribution of the IC classes between the different input DEMs (Figure 4.7) looks quite similar, but the absolute change in ha is quite recognizable, especially for the Oberwölz area. The differences can reach up to 300 ha, which can have a major effect on the whole sediment routing model. For example, a much smaller area is disconnected from the main creek when the bridge openings etc. are considered. This factor is less important in the Johnsbach Valley. The IC class values for the ALS and the Valley scenario (sinks: waterbodies) are obviously very similar in this area (Figure 4.7, left). However, this fact only says something about the size of the IC class areas, but nothing about their allocation. It can be assumed that in the ALS scenario, a high-connected area could fall outside the erosion area and for the Valley scenario the area could lie inside. On the whole it can be stated that the valley DEM reflects the real situation in most cases and is therefore the preferable elevation model.

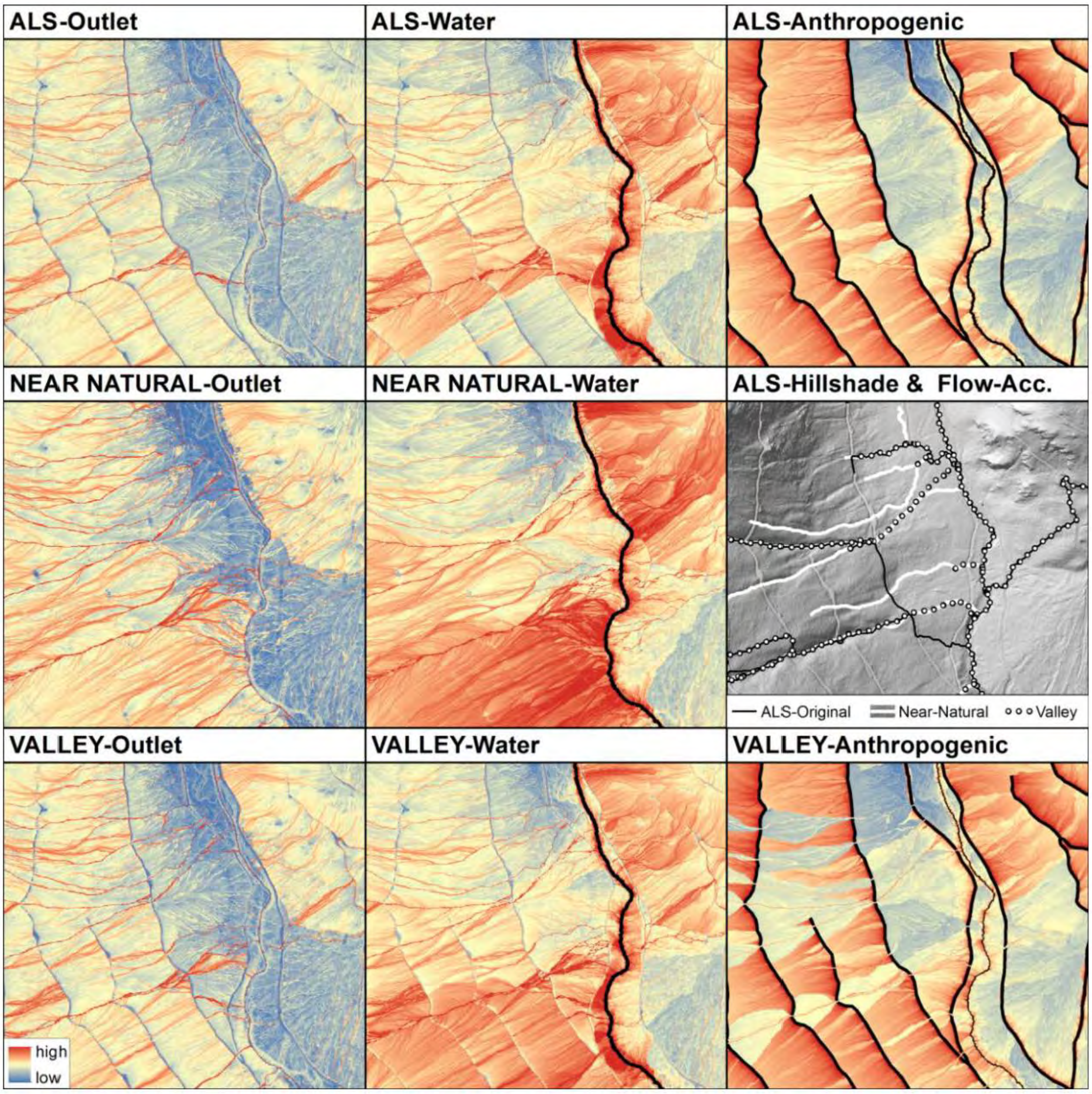


Figure 4.6: *Clip (1 x 1 km) of the Oberwölz catchment showing the connectivity routing (from low (blue) to high (red)) for the eight different scenarios. Sinks are colored in black (water and anthropogenic; outlet is not visible in this extend).* ***(Center-Right)****: differences in channel-shape depending on the input DEM. The channel shapes were generated by the Flow-Accumulation Tool of ArcGIS 10.1.*

are compared to the total catchment area and classifies them using the index of connectivity.

Comparing the valleys of Johnsbach and Oberwölz by focusing on the connectivity of erosional areas reveals distinctive features. First of all the size of the area of erosion is significantly higher in the Johnsbach Valley by a factor of 2. The disconnected erosional areas are almost equal in size (in the order of about 20 %) for both catchments and all scenarios. In the Johnsbach valley the size of those areas with a very low and low connectivity to their particular sink decreases from the anthropogenic target to the outlet target. By implication, this means that there are more areas of erosion with medium to very high connectivity if the final sink gets pushed out further to the "end" of the catchment. The amount of these areas almost doubles up focusing from anthropogenic sinks to the outlet. In Oberwölz a different situation occurs. In all three scenarios about 50 % of the erosional surfaces have very low to low connectivity to the particular sink. Areas with very low connectivity are almost missing in the scenario using the anthropogenic sink. Only 30 % of the erosional areas show a medium to high connectivity for all three scenarios with the exception that areas with very high connectivity are almost lacking.

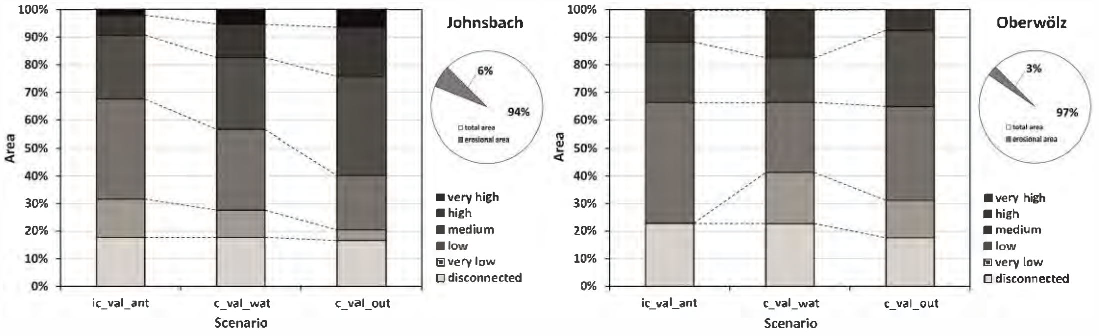


__Figure 4.9:__ Distribution of connectivity indices concerning areas of erosion for Johnsbach __(left)__ and Oberwölz __(right)__. The graph shows three scenarios using the Valley DEM in combination with one of the particular targets: anthropogenic (ic_val_ant); water (ic_val_wat); outlet (ic_val_out). The pie chart (inlet) shows the portion of the area of erosion within the total catchment area.

Areas of erosion are very scattered throughout both catchments (Figure 4.10). They are typically located in the higher altitudes which are especially the northern regions in Johnsbach and Oberwölz. Further areas storing erodible sediment can be found near the main creeks draining both catchments. Specifically in the Johnsbach

Valley there are a lot of steep furrows and channels, transporting most of the sediment. These are located in the Zwischenmäuer reach (northern parts of the catchment) in great quantities, which is due to the brittle dolomite lithology. Approximately one-fifth of the area of erosion is disconnected and is therefore not contributing sediment further downhill. These areas are smaller catchments of lakes or depressions in the landscape. In the case of the Johnsbach Valley the large disconnected area in the north-east of the catchment was formed through karst processes. Areas with available sediment and medium to high connectivity are typically located close to the main channel which follows the classical picture of hillslope-channel coupling.

Thus, erodible sediments at higher altitudes of the Johnsbach Valley are less connected and are therefore way less essential for significant sediment transport. This applies for the Schöttlbach catchment as well. However, the reason for disconnection lies in the mountain cirques in the northern Schöttlbach region, where small lakes and glacially-formed reverse gradients serve as sinks in terms of connectivity. Some other cirques are not entirely disconnected but very poorly connected. Thus, areas of erosion are often situated in disconnected parts of the catchment. There is, however, one important exception. In the southern half of the watershed the Schöttlbach River incised several tens of meters in the postglacial sediment body. Due to retrogressive erosion in the close side channels and lateral erosion, the river can (and did during the flood of 2011) take on an almost indefinite amount of erodible material on this short stretch. This also applies to the major tributary of the catchment, the Krumeggerbach River in the West. All this goes well together with the calculated IC values, because the few very highly and highly connected areas in erosive regions arise mainly from this small area relatively close to the main channel.

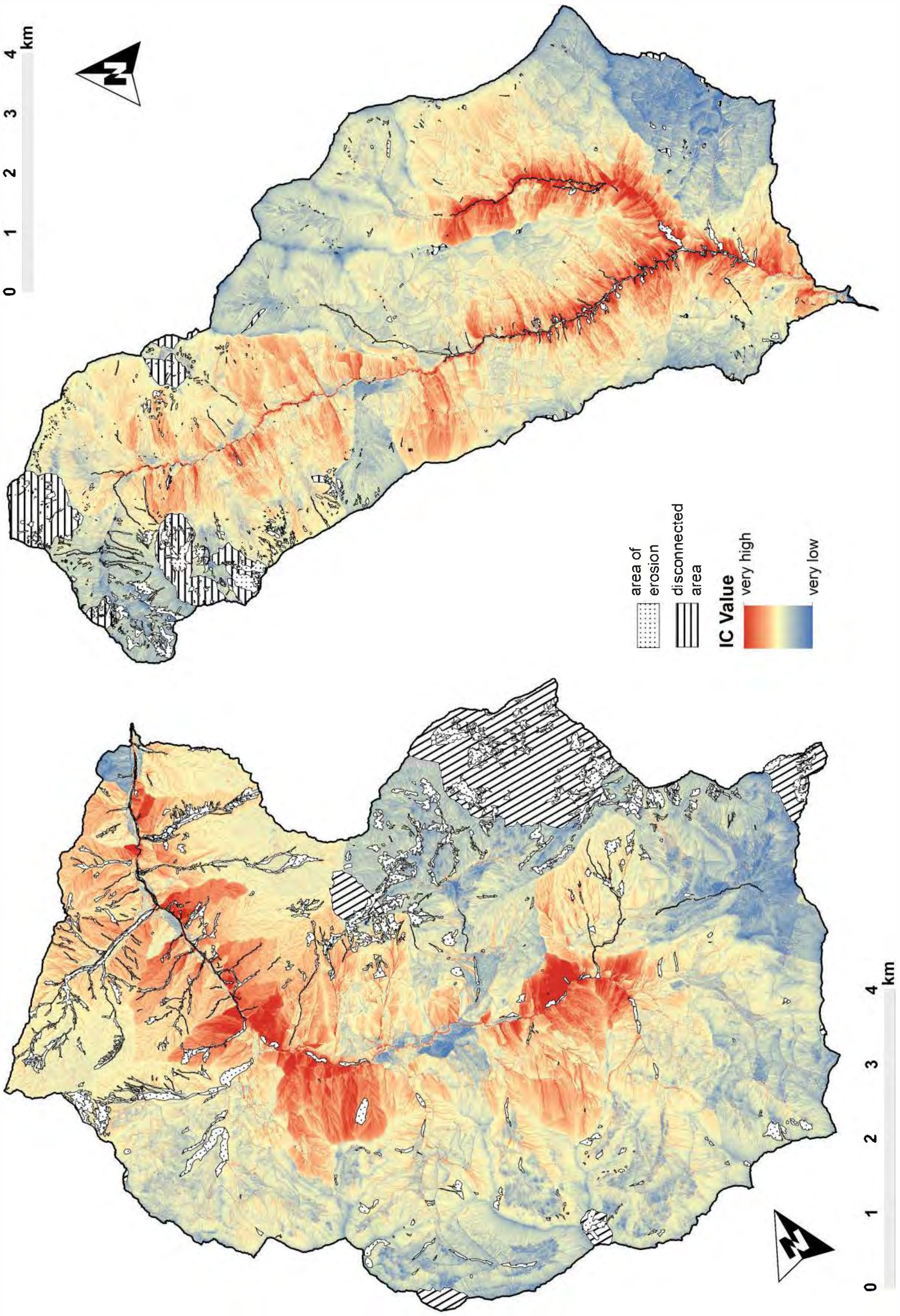


Figure 4.10: *Modeled connectivity indices (from low (blue) to high (red)) for the catchments of Johnsbach* ***(bottom)*** *and Oberwölz* ***(top)*** *using the Valley DEM and the water target in both cases. The disconnected areas and the areas of erosion are presented as well.*

4.4. Discussion and Conclusions

The intention of this chapter is to introduce the index-of-connectivity model for comparative analysis of large alpine catchments. A detailed connectivity routing compiled by field mapping for areas greater than a couple of square kilometers is difficult to apply, therefore, the used methodology proved to be a valuable tool. Nonetheless the IC model itself is strongly dependent on the input DEM. Forestry roads with small or even unregistered bridge openings or underground stormwater infrastructures are the major problem in deriving a realistic sediment routing result out of airborne laserscan data. Our way to a slightly but significantly modified DEM is a convenient technique to use the model even in catchments with a pronounced anthropogenic character, such as the Johnsbach and the Schöttlbach valleys. Of the derived eight different scenarios for both study areas, we found the scenario with the Valley DEM as input and the running/standing water as sinks to be the most realistic one. Overall the presented results show that the semi-quantitative approach used in this study is a good compromise between size of the study area and accuracy, although the real amount of mobilized sediments will always depend on event intensity and characteristics.

In terms of their topographic and geological features, the valleys are characteristic of many non-glaciated valleys in the Eastern Alps. In both areas, the superposition of erodible sediments and connectivity to the water course is mainly achieved for some sediment sources near the valley bottoms, while erodible sediments in the higher parts of the catchments are poorly coupled to the valley floors. Similar preconditions were observed e.g. by Schrott et al. (2002, 2003) or Otto and Dikau (2004). The results clearly show that anthropogenic modifications of the landscape are highly important for sediment routing (see e.g. Croke et al., 2005; Callow and Smettem, 2009; Poeppl et al., 2012).

Regarding sediment budgeting and natural hazard assessment, it is important to know that most of the sediments at the catchment outlet derive from the few source areas mentioned above. The results will provide a baseline to analyze if additional sediment sources could be coupled to the river system during high magnitude events (e.g. Fryirs et al., 2007; Morche et al., 2007; Croke et al., 2013). In a next step, transport along the main fluvial channels will be implemented into the models in order to assess which areas in fact deliver sediments to the outlet of the catchments.

Acknowledgements

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5. EVALUATING SEDIMENT DYNAMICS IN TRIBUTARY TRENCHES IN AN ALPINE CATCHMENT (JOHNSBACH VALLEY, AUSTRIA) USING MULTI TEMPORAL TERRESTRIAL LASER SCANNING

Abstract

The linkage of landscape units by sediment transport and its degree is among the most important factors during smaller time scales (several years to decades) determining the sediment yield of a catchment. In our study area (Johnsbach Valley, Styria, Austria), huge amounts of sediments are available due to surrounding brittle dolomite bedrock which is a challenge for river management. In the context of a renaturation project, it is important to understand where the sediments derive from and how they move through the system. In our study, we investigated several tributary trenches of the Johnsbach River to clarify the sediment dynamics and the degree of coupling to the main creek. Terrestrial Laser Scans (TLS) from several points were carried out half-yearly for approximately two years between summer 2013 and autumn 2015.

The results show that if only the first and last survey in each sub-area are considered, the amounts of erosion and accumulation are underestimated at least by a factor of two compared to the full dataset of 4-5 scans, because erosion and deposition in different periods may be cancelled out. This applies for both erosion and deposition. Accordingly, the calculated surface changes are minimum amounts because more surveys would have yielded higher rates.

According to the 2 year period, ~7400 $m^3 yr^{-1}$ were eroded in the surveyed areas and ~9900 $m^3 yr^{-1}$ were deposited. Only a minor portion of ~650 $m^3 yr^{-1}$ was delivered to the Johnsbach River. At two sub-sites (Unnamed V and Langgries), coupling to the river was evident while at one site (Gseng) there was no coupling to the main creek at all. At Langgries, erosion occurred in the upper area of a long gravel field and transport and deposition prevailed lower down; the transport into the Johnsbach River obviously occurred discontinuously in batches. In the areas Langgries and Gseng there is strong evidence that the rates of erosion and deposition are still governed by gravel mining 1-2 decades ago.

5.1. Introduction

Sediment transport in alpine torrential systems lies in the field of tension between ecological goals (usually aiming at the removal of artificial barriers), the protection of infrastructure against natural hazards, and the demands of hydropower plants (Habersack and Piégay, 2008). Understanding physical processes in sediment mobility, the connection between upslope contributing areas and downslope travel paths and finally the associated changes in channel morphology, is of crucial importance for defining river restoration strategies and finally to ensure a sustainable sediment management (Piégay et al., 2005; Liébault et al., 2008; Rinaldi et al., 2009).

In this context the geomorphological concepts of connectivity and coupling (Fryirs et al., 2007) are important to understand sediment dynamics in a catchment. These two approaches have been widely discussed during the last decades. Since there still seem to be ambiguities in the definition of both terms and how they are used within the context (Bracken et al., 2013), Bracken et al. (2015) defined coupling to be based on the morphological system at certain locations, which means the linkage of distinct landforms or landscape units by sediment transport (Harvey, 2001) while (sediment) connectivity relates to the continuum of a cascading system. Therefore, connectivity is understood as the degree of coupling between system components with effects of lateral (e.g. hillslope to channel), longitudinal (e.g. between river reaches) or vertical (e.g. surface to subsurface) linkages or a combination of them (e.g. Brierley et al., 2006; Bracken et al., 2015). Bracken and Croke (2007) identified three major types of connectivity that are used in hydrology and geomorphology: (1) landscape connectivity, which is describing the linkage between landforms (e.g. Brierley et al., 2006), (2) hydrological connectivity, which is relating to the passage of water from one part of the landscape to another (e.g. Bracken et al., 2013) and (3) sedimentological connectivity, which refers to the transport of sediments through the system. The latter determines the sediment yield of a catchment in which two aspects are of primary importance for this study: along-channel connectivity (e.g. Hooke, 2003) to determine the effects of sediment routing in tributary trenches of the investigated catchment and hillslope-channel connectivity (e.g. Harvey, 2001) to investigate if sediment is being supplied to the main channel system.

The connection between hillslopes and the channel network is of fundamental importance to understand the development of mountain landscapes particularly during smaller time scales (several years to decades). However, the connectivity between them depends on magnitude and frequency of sediment producing events and the internal coupling characteristics of the system. Over the years different methods evolved to observe and quantify this coupling behavior. Caine and Swanson (1989) used "erosional boxes" and measured the geomorphic work of different processes in the field to assess the degree of coupling over a 5-6 year period. Other approaches focus on the interpretation of geomorphological maps and aerial photography (Schrott et al., 2002), tracing sediment from their source areas via radionuclides (Smith and Dragovich, 2008), measuring the transport of fine sediments over a hillslope into the channel (Beel et al., 2011) or using dendrogeomorphic methods (Savi et al., 2012) to assess the hillslope-channel relationship and the sediment transfer dynamics. Especially during the last couple of years the generation of multi-temporal DEMs by differential GPS (Fuller and Marden, 2011) and Terrestrial Laser Scanning (TLS) (Bimböse et al., 2010) were increasingly used to quantify surface changes in slope to channel coupling or along a river reach (Wheaton et al., 2013). TLS has become a common tool for change detection surveys over different spatial and temporal scales (e.g. Milan et al., 2007; Schürch et al., 2011). Several authors focused their work on surface changes in alpine environments or other mountainous landscapes (e.g. Bremer and Sass, 2012; Carrivick et al., 2013; Picco et al., 2013; Baewert and Morche, 2014; Vericat et al., 2014; Bossi et al., 2015). All these surveys attempt to relate surface changes to sediment sources and sinks, and to infer rates of sediment transport and possible controls on intermittent storage and residence times.

Our study area in the eastern Austrian Alps is part of the National Park Gesäuse and the Johnsbach River, one of the main torrents, was restored in the cost-intensive EU funded LIFE-project "Conservation strategies for woodland and wild waters in the Gesäuse" from 2005 to 2011. The main focus of this project was to dismantle and widely remove extensive engineering measures in the river and at the junctions to the side channels which have been implemented approximately 60 years ago. Furthermore, the aim was to improve the self-organization of the river as well as specific habitats of target species. This raised the question if the amounts of transported sediments would be sufficient to provide certain aqua fauna habitats, and if intensified bedload transport might affect hazard protection and the efficiency of hydropower stations downstream. A research project was launched in 2013 to

The climate is characterized by annual mean temperatures of around 8 °C in the lower elevations of the valley and below 0 °C in the summit regions. Annual precipitation amounts to approximately 1500-1800 mm (Wakonigg, 2012a,b). Storm precipitation occurs almost exclusively in the summer months and can reach several tens of mm per hour. Thus, runoff at the Johnsbach River peaks in spring (snow melt) and summer while the tributary trenches show surface runoff and sediment transport only during episodic rainstorms.

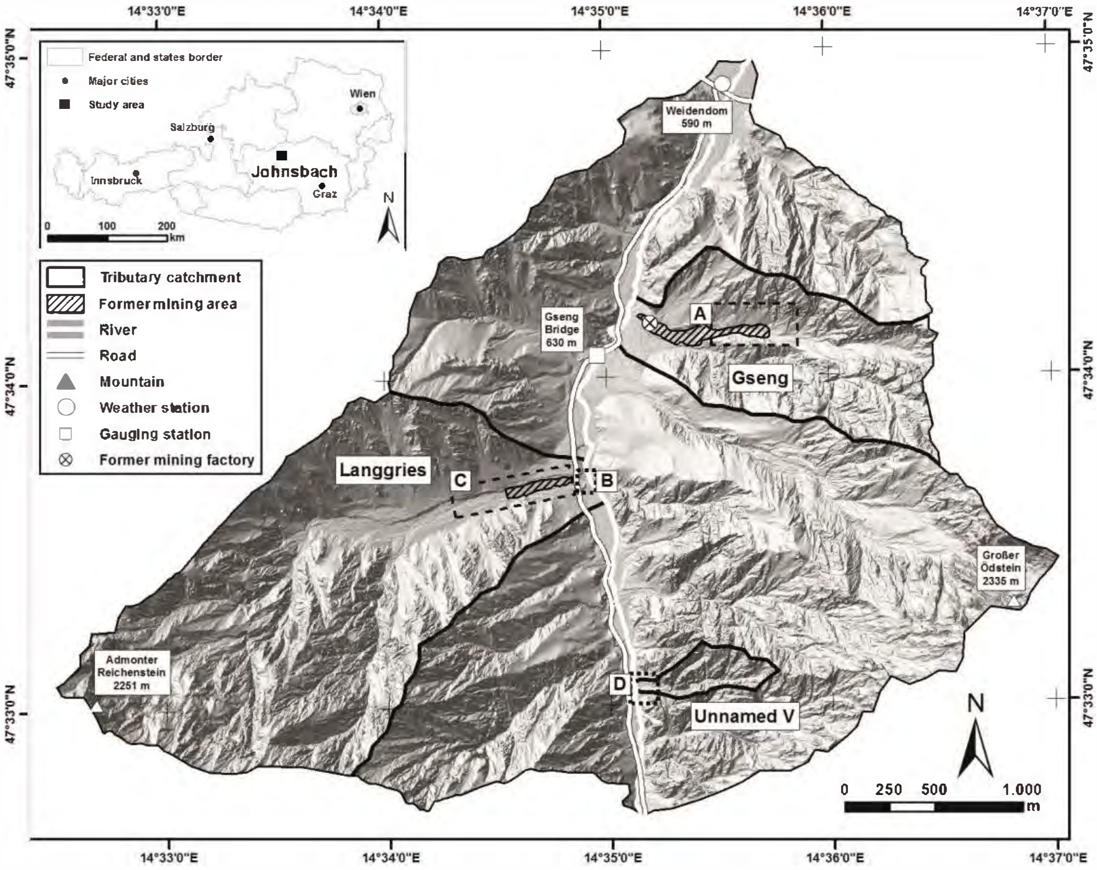

Figure 5.1: Location of the Johnsbach Valley (with inset map of Austria), hillshade map of a LiDAR derived DEM (Bureau of the Styrian Government, 2010) of the ZMS showing the distribution of the study sites (note: black rectangles with dashed lines mark the investigated areas): ***(A)*** *Gseng,* ***(B)*** *Langgries outlet,* ***(C)*** *Langgries long,* ***(D)*** *Unnamed V.*

The geological situation together with the climatic conditions results in a high morphodynamic activity, primarily in the ZMS (Strasser et al., 2013). The characteristics of carbonate rocks, mainly the brittle Wettersteindolomit which is especially prone to weathering, invoke that large amounts of sharp-edged debris

River) where the hillslopes are contributing sediment into the side channel forming a sediment body, which is moving slowly down to where the former mining factory (Figure 5.1) was set up. The factory has been dismantled in 2008 but the area around is still too flat to allow sediment movement across the site, obviously decoupling the active part of the Gseng trench from the main river system. Langgries is a very long sediment body moving slowly downhill. In this sub-catchment, two study sites were surveyed: the immediate confluence with the Johnsbach River below the road bridge and several 100 m long, inclined gravel field upstream to the bridge. This allowed studying coupling effects at the outlet of the system, sediment dynamics inside the trenches and sediment supply from the lateral slopes.

Figure 5.2: *Photographs of the study sites in the Johnsbach Valley:* ***(A)*** *Gseng in an eastward direction (26th July 2013) with inset (side-inverted) of the middle part (17th July 2014) during a severe thunder storm (photo by O. Gulas);* ***(B)*** *Langgries Outlet recorded from the road bridge on the west: top (17th September 2013), bottom (26th August 2015);* ***(C)*** *looking west into Langgries long (28th July 2013), note: the road bridge in the front and the Admonter Reichenstein in the back, the white rectangle locates the site of Langgries outlet;* ***(D)*** *the outlet of Unnamed V from the west: left (18th March 2014), right (26th August 2015). Note: red lines showing the areas of investigation, numbers are indicating the subsections as defined in Table 5.1, blue arrows indicate the flow direction of the Johnsbach River.*

Table 5.1: *Catchment characteristics for the three subcatchments as well as the study areas in between.*

Sub-catchment	**Sub-area**	**Sub-section**	**Area [ha]**	**Slope [°]**	**Altitude [m]**			**Relief energy [m ha^{-1}]**
				mean	**min**	**max**	**range**	
Gseng	total		113.78	45	619	1623	1004	9
	study site	total	2.34	29	710	868	158	68
		top (I)	0.98	30	786	851	65	66
		middle (II)	0.86	30	749	868	119	138
		bottom (III)	0.50	26	710	758	48	96
Langgries	total		330.15	45	650	2251	1601	5
	study site outlet	total	0.21	16	650	666	16	76
	study site long	total	3.01	16	663	769	106	35
		top (I)	0.88	22	720	769	49	56
		middle-top (II)	0.79	16	695	728	33	42
		middle-bottom (III)	0.85	13	677	701	24	28
		bottom (IV)	0.49	12	663	680	17	35
Unnamed V	total		15.75	60	682	1358	676	43
	study site	total	0.16	21	682	708	26	163
		top (I)	0.12	22	685	708	23	192
		bottom (II)	0.04	17	682	688	6	150

The weather conditions and the river discharge during the observation period are depicted in Figure 5.3. The location of the weather and the gauging station are shown in Figure 5.1. Air temperatures ranged from -11 °C to 34 °C in the observation period with a mean of 8.4 °C and rainfall was almost evenly distributed during summer and winter seasons with an annual amount of ~930 mm. The river discharge of the Johnsbach River had a base flow of ~1 $m^3\,s^{-1}$, a mean of ~3 $m^3\,s^{-1}$, and peaks of ~6-10 $m^3\,s^{-1}$. Missing discharge values in September and October 2013 as well as data gaps in the temperature record in December 2013 are due to failures of the recording instruments.

Table 5.2: *Information on the scan properties as well as results for alignment procedures for all study sites and survey periods.*

Survey site	Survey date	Positions	Distance [m] mean	Angular Resolution[a] [m] mean	Points[b] [in Mio] total	SDR[c] [cm] mean	Points AOI[d] [in Mio] total	[%]	Point density [pts m^{-2}]	Cell size [cm]	SDE[e] [cm] mean
Gseng	22.09.2013	3	270	0.15	31.3	1.0	17.2	55	733	20	0.8
	03.04.2014	3	270	0.15	29.4	0.7	16.4	56	698	20	0.7
	09.10.2014	3	280	0.15	30.7	0.9	13.7	45	582	20	0.8
	29.04.2015	4	225	0.16	23.1	0.6	15.5	67	659	20	0.4
	12.10.2015	4	240	0.16	42.0	0.7	18.9	45	807	20	0.6
Langries outlet	21.09.2013	3	40	0.03	16.1	0.6	8.9	55	4339	5	0.5
	03.07.2014	3	70	0.05	18.3	0.5	10.9	60	5321	5	0.5
	07.05.2015	3	70	0.05	21.7	0.8	12.5	58	6074	5	0.5
	12.10.2015	3	70	0.05	17.4	0.6	9.6	55	4667	5	0.5
Langries long	21.09.2013	2	350	0.20	17.4	0.7	7.8	45	261	20	1.2
	04.07.2014	2	375	0.20	17.8	1.1	8.0	45	268	20	1.4
	30.04.2015	4	300	0.19	25.9	0.8	15.3	59	511	20	0.8
	13.10.2015	4	300	0.17	39.3	0.9	18.0	46	599	20	0.6
Unnamed V	20.10.2013	4	70	0.05	21.2	0.8	7.4	35	4558	5	0.8
	14.08.2014	4	70	0.05	19.5	0.6	6.3	32	3848	5	1.1
	11.05.2015	4	70	0.05	21.3	0.6	6.6	31	4064	5	0.7
	28.08.2015	4	70	0.05	31.2	0.6	7.3	23	4512	5	0.8
	27.10.2015	4	70	0.05	24.8	0.6	6.3	25	3858	5	0.8

[a]: Mean angular resolution refers to the mean distance / [b]: Total amount of points recorded from all scan positions / [c]: Standard deviation after registration of all scan positions / [d]: Total amount of points inside the AOI after eliminating the vegetation, percentages are in terms of total amount of points recorded / [e]: Standard deviation of error.

$$\boldsymbol{U_{crit} = t\left(\sqrt{SDE_{DEM-A}^{2} + SDE_{DEM-B}^{2}}\right)}$$

moved within each system. The term "active area" is assigned to the parts of the investigated region in which surface change between two surveys is above the range of +/- LoD.

Table 5.3: *Summary of uncertainty range values of each raster cell.*

Study site	**Period**	**Raster Count (of AOI)**	**LoD [m]**		
			min	**max**	**mean**
Gseng	Sep. 2013 - April 2014	586,669	0	2.88	0.02
	April 2014 - Oct. 2014	586,669	0	2.75	0.02
	Oct. 2014 - April 2015	586,669	0	5.38	0.02
	April 2015 - Oct. 2015	586,670	0	5.38	0.02
	Sep. 2013 - Oct. 2015	586,669	0	2.43	0.02
Langgries Outlet	Sep. 2013 - July 2014	821,043	0	1.20	0.02
	July 2014 - May 2015	821,046	0	1.96	0.02
	May 2015 - Oct. 2015	821,046	0	1.97	0.02
	Sep. 2013 - Oct. 2015	821,043	0	1.22	0.02
Langgries long	Sep. 2013 - July 2014	751,710	0	6.11	0.04
	July 2014 - April 2015	751,710	0	6.11	0.04
	April 2015 - Oct. 2015	751,709	0	7.27	0.02
	Sep. 2013 - Oct. 2015	751,709	0	7.27	0.03
Unnamed V	Oct. 2013 - Aug. 2014	650,625	0	1.16	0.03
	Aug. 2014 - May 2015	650,623	0	1.16	0.03
	May 2015 - Aug. 2015	650,623	0	1.02	0.03
	Aug. 2015 - Oct. 2015	650,625	0	0.99	0.03
	Oct. 2013 - Oct. 2015	650,626	0	1.06	0.03

Table 5.4: *Sediment balancing (only values outside the LoD) for the AOI at all four study sites between successive survey periods.*

Study site	**Period**	**Section**	**Volume change** **[m³]** **erosion**	 **deposition**	 **balance**	 **[t]ᵃ** **balance**	**Areaᵇ** **[m²]**	 **[%]**	**Yieldedᶜ** **[kg m⁻²]**
Gseng	Sep. 2013 - April 2014	total	-290	337	47	66	11,464	49	3
		top	-90	107	17	24	4851	49	2
		middle	-95	106	11	16	3895	45	2
		bottom	-105	124	19	26	2718	54	5
	April 2014 - Oct. 2014	total	-1713	1772	59	83	14,460	62	4
		top	-379	305	-74	-104	5587	57	-11
		middle	-341	776	435	609	5080	59	71
		bottom	-993	691	-302	-423	3793	75	-84
	Oct. 2014 - April 2015	total	-1438	1035	-402	-563	13,847	59	-24
		top	-183	118	-65	-91	4998	51	-9
		middle	-856	107	-750	-1049	4664	54	-122
		bottom	-399	811	412	577	4186	83	-114
	April 2015 - Oct. 2015	total	-818	1152	335	469	14,561	62	20
		top	-315	89	-227	-318	6025	61	-32
		middle	-321	434	113	158	5032	59	18
		bottom	-181	630	449	629	3505	70	125
Langgries Outlet	Sep. 2013 - July 2014	total	-155	47	-108	-151	1535	75	-73
	July 2014 - May 2015	total	-51	54	3	5	1382	67	2
	May 2015 - Oct. 2015	total	-63	466	404	565	1583	77	275
Langgries long	Sep. 2013 - July 2014	total	-1530	3919	2389	3345	24,058	80	119
		top	-1189	933	-255	-357	7779	88	-40
		middle top	-132	1390	1257	1760	5954	76	223

		middle bottom	-115	1204	1089	1524	6214	73	180
		bottom	-93	391	298	417	4111	84	85
	July 2014 - April 2015	total	-5160	4042	-1118	-1565	26,668	89	-56
		top	-1760	1805	45	62	8051	91	7
		middle top	-1714	986	-727	-1018	7077	90	-128
		middle bottom	-1127	1052	-75	-105	7603	90	-12
		bottom	-559	199	-360	-504	3937	81	-103
	April 2015 - Oct. 2015	total	-3662	7326	3664	5129	27,178	90	183
		top	-2301	1287	-1014	-1420	7405	84	-161
		middle top	-657	2720	2063	2888	7465	95	366
		middle bottom	-537	2076	1539	2154	8011	95	254
		bottom	-167	1244	1076	1507	4297	88	309
Unnamed V	Oct. 2013 - Aug. 2014	total	-134	111	-23	-32	1049	64	-20
		top	-81	24	-56	-79	675	56	-65
		bottom	-53	86	33	47	374	90	112
	Aug. 2014 - May 2015	total	-54	22	-31	-44	846	52	-27
		top	-22	12	-10	-14	558	46	-12
		bottom	-32	11	-21	-29	288	69	-70
	May 2015 - Aug. 2015	total	-61	77	15	22	989	61	13
		top	-47	24	-23	-33	694	57	-27
		bottom	-14	53	39	54	295	71	131
	Aug. 2015 - Oct. 2015	total	-23	12	-11	-16	636	39	-10
		top	-10	7	-3	-4	447	37	-3
		bottom	-13	4	-8	-12	189	46	-28

[a]: Tonnage based on dry bulk density of 1400 kg m^{-3} / [b]: Active area (erosion and deposition), percentages are in terms of total area in that section / [c]: It refers to the total area in that section. This is a lower-bound estimate for it takes no account of throughput or yield of fines in suspension.

5.4.1. Unnamed V

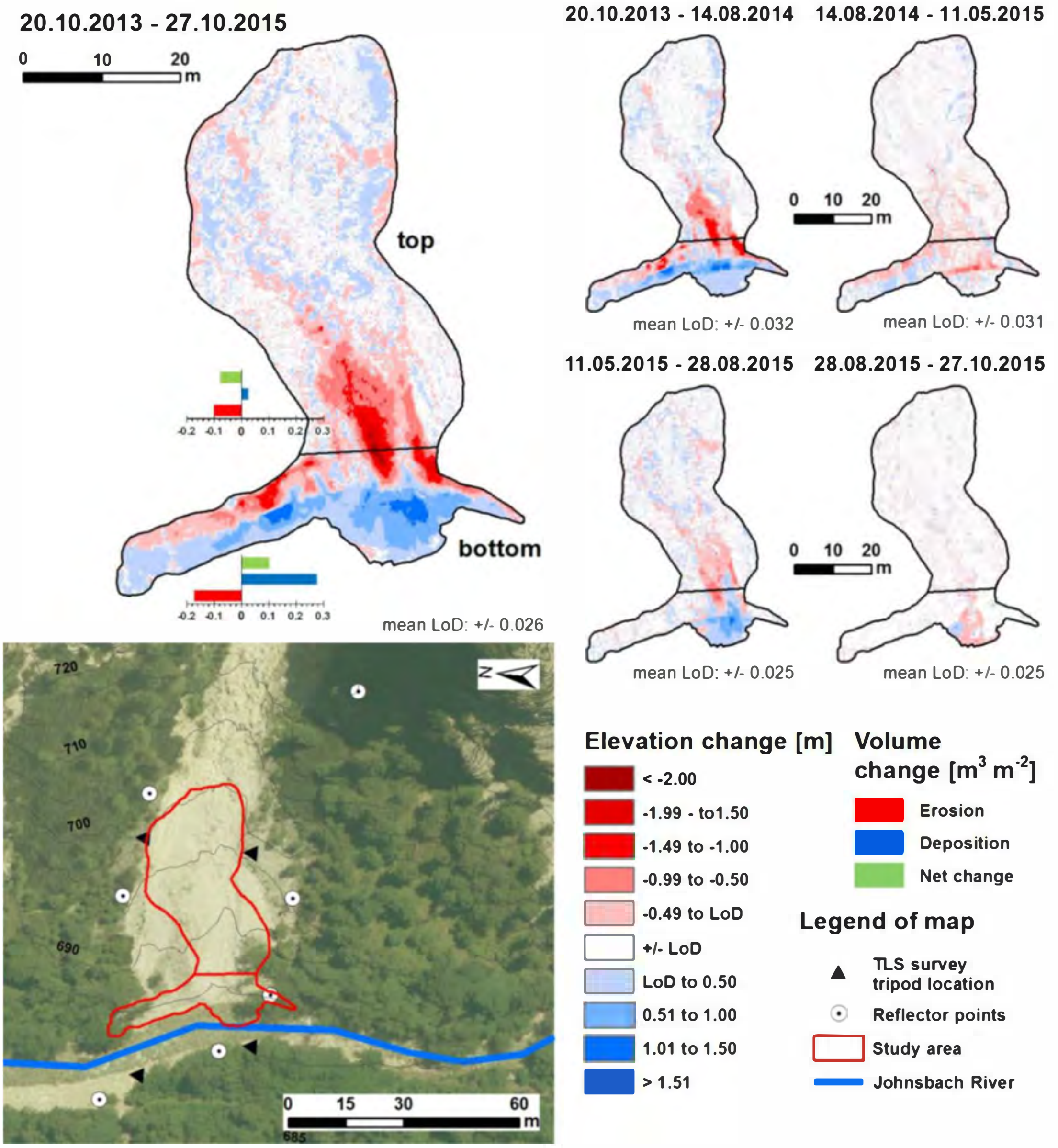

Figure 5.4: *Spatial distribution and temporal intensity of surface elevation changes in the Unnamed V side channel.* ***(Top left)*** *DoD of the total time interval and graphs of the volumetric changes normalized by area of the respective part;* ***(top right)*** *DoDs of the single periods;* ***(bottom left)*** *Aerial photograph (Bureau of the Styrian Government, 2010) showing the study site and the TLS survey locations.*

Patterns of erosion and deposition are mostly limited to the bottom part (next to the river) as well as the lower parts of the top section (Figure 5.4). This is also reflected in the size of the active area throughout all time steps which is around 50 % for the

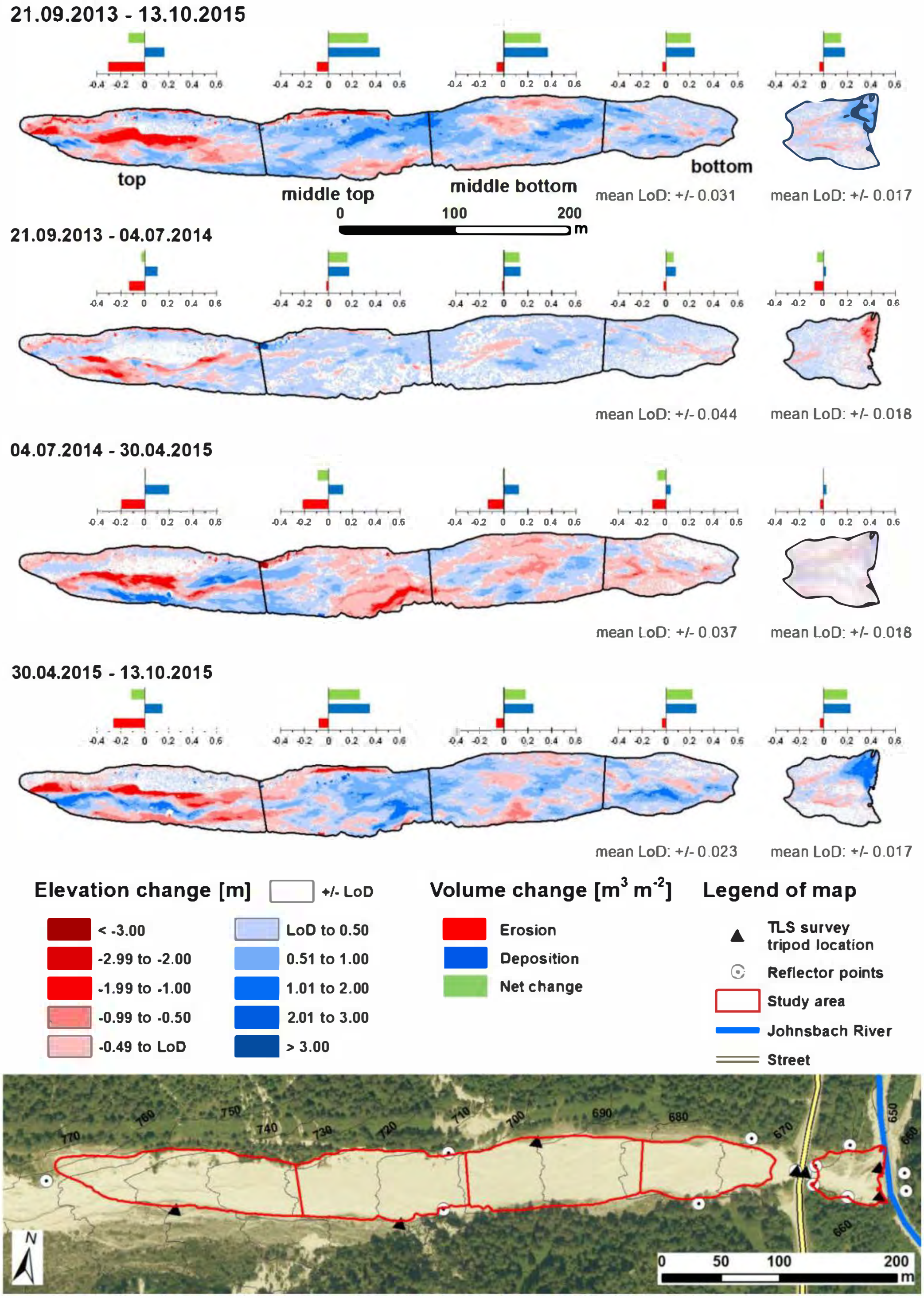

Figure 5.5: *Spatial distribution and temporal intensity of surface elevation changes in the Langgries side channel.* ***(Top)*** *DoD for the total time interval as well as for the three periods for the study sites Langgries long* ***(left)*** *and Langgries outlet* ***(right)****, included are graphs of the volumetric changes normalized by area of the respective part,* ***(bottom)*** *Aerial photograph (Bureau of the Styrian Government, 2010) showing the study sites and the TLS survey locations.*

sediment that have entered the areas of observation from above and have passed through the system without leaving a trace in the laser scans are still unknown. Thus, the mentioned quantities are the minimum amount of debris which has been delivered to the river. A detailed description of the sediment yield for each survey period and study site is given in Figure 5.7.

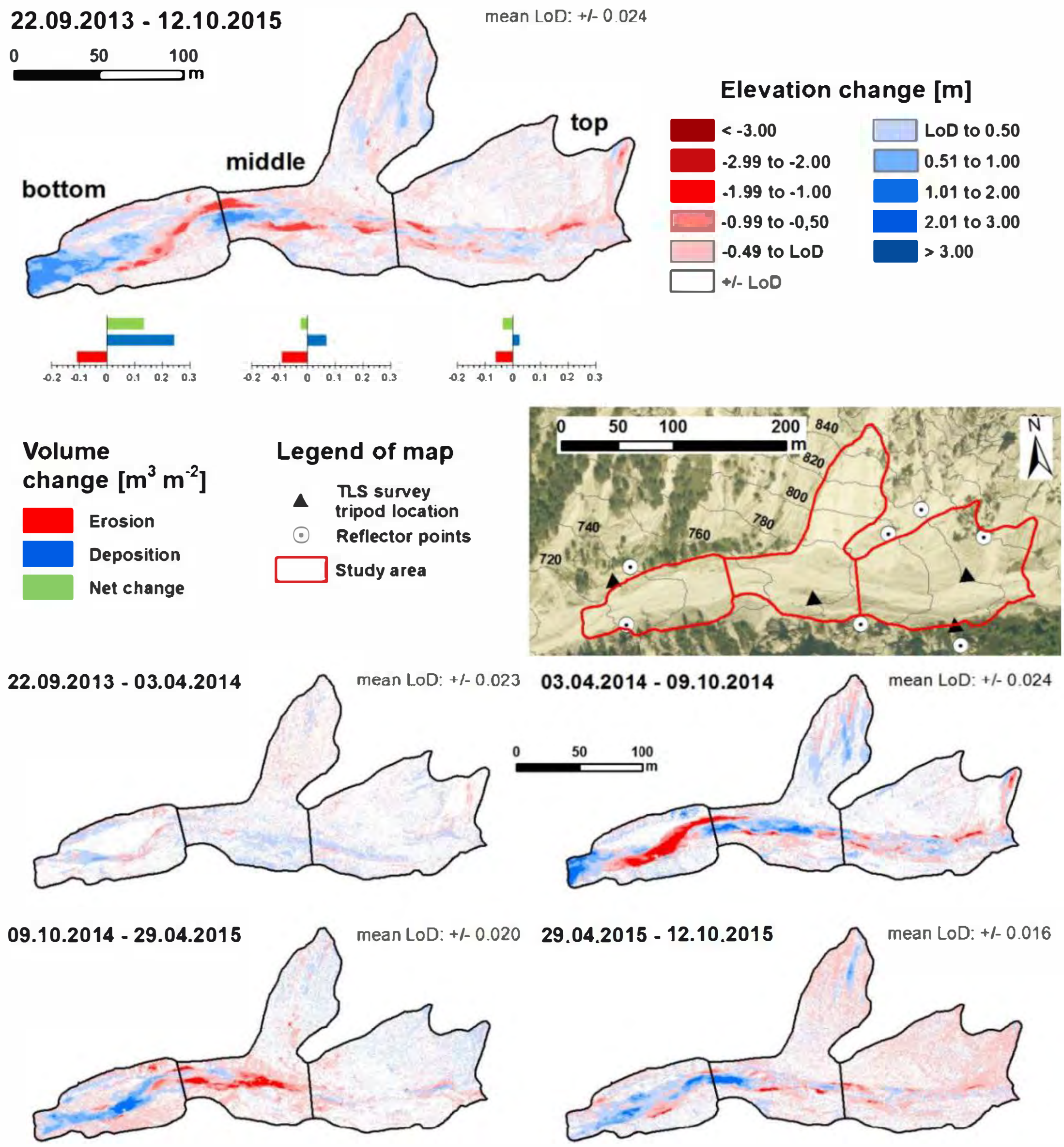

Figure 5.6: *Spatial distribution and temporal intensity of surface elevation changes in the Gseng side channel.* ***(Top)*** *DoD of the total time interval and graphs of the volumetric changes normalized by area of the respective part,* ***(middle right)*** *Aerial photograph (Bureau of the Styrian Government, 2010) showing the study site and the TLS survey locations,* ***(bottom)*** *DoDs of the single periods.*

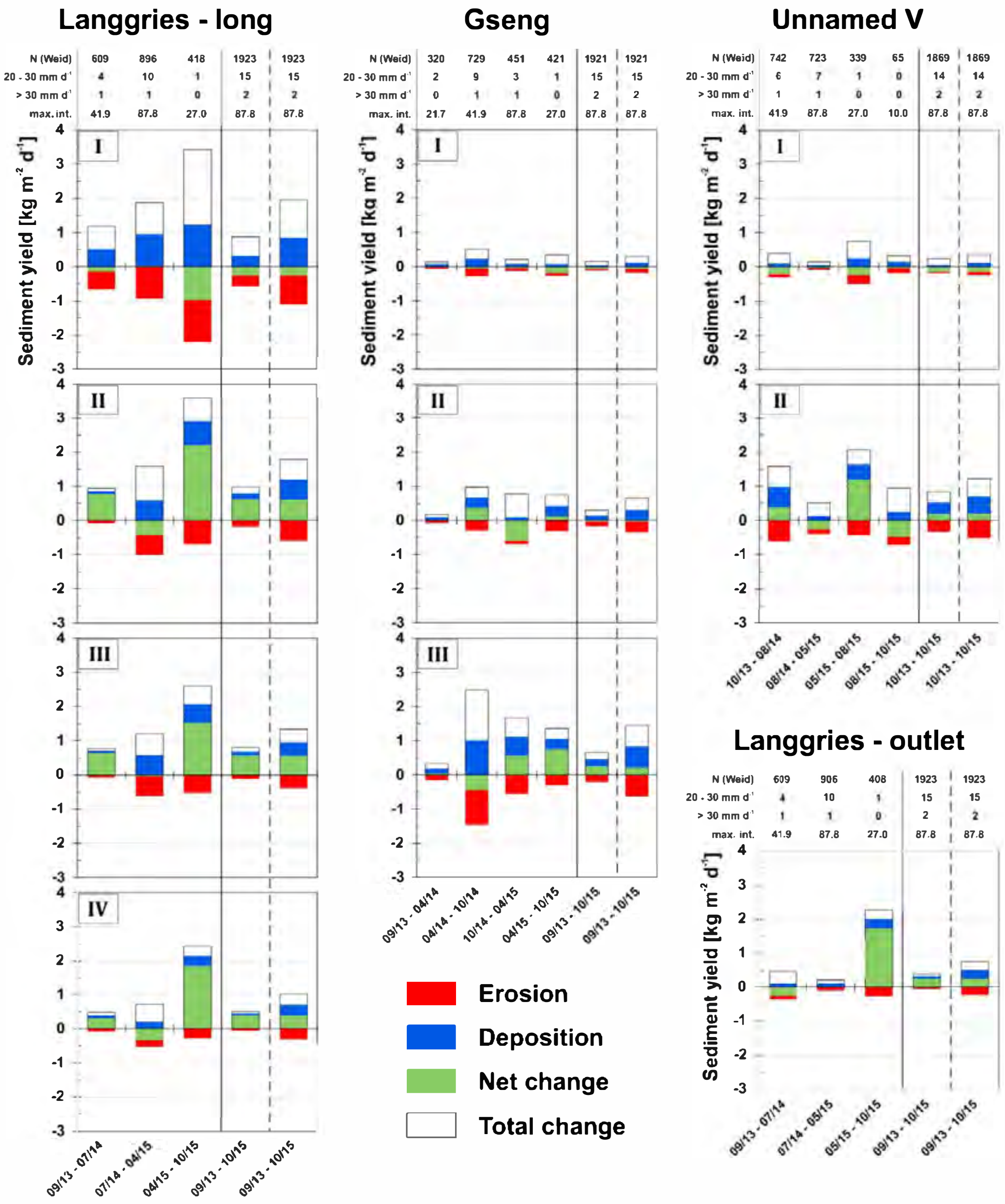

Figure 5.7: *Temporal development of the sediment yield distributed by subsections for each study site; I–IV refer to the subsections as defined in Figure 5.2 and Table 5.1; black vertical solid lines separate the total from the single intervals; black vertical dashed lines separate the stepwise approach. Precipitation parameters are given for the respective interval in the order from top to bottom: total precipitation in mm (recorded at Weidendom); number of days with 20-30 mm d*$^{-1}$*; number of days with >30 mm d*$^{-1}$*; maximal daily intensity.*

5.4.6. Comparison of volume changes and active areas considering different time intervals

The spatial distribution of surface elevation changes are depicted in Figures 5.4 to 5.6 for the different single survey intervals ("stepwise") and the total investigation period ("total") considering only the first and last survey for each study site. The time frame of the total investigation covers approximately two years at each study site (September/October 2013 to October 2015). In the stepwise investigation, shifts in erosional and depositional patterns are cancelled out to some extent when only the total interval is considered (Table 5.5). Therefore, the amount of relocated sediment for the stepwise investigation is nearly twice as high as for the total time frame (Figure 5.8 left). This applies for all study sites and for both erosion and deposition.

Areas of active change are slightly smaller when the total interval is taken into account compared to the stepwise approach (Figure 5.8 right). This means that if a certain spot apparently was not affected by surface change during the two years of observation, a shorter survey interval may reveal that this spot has in fact experienced surface change.

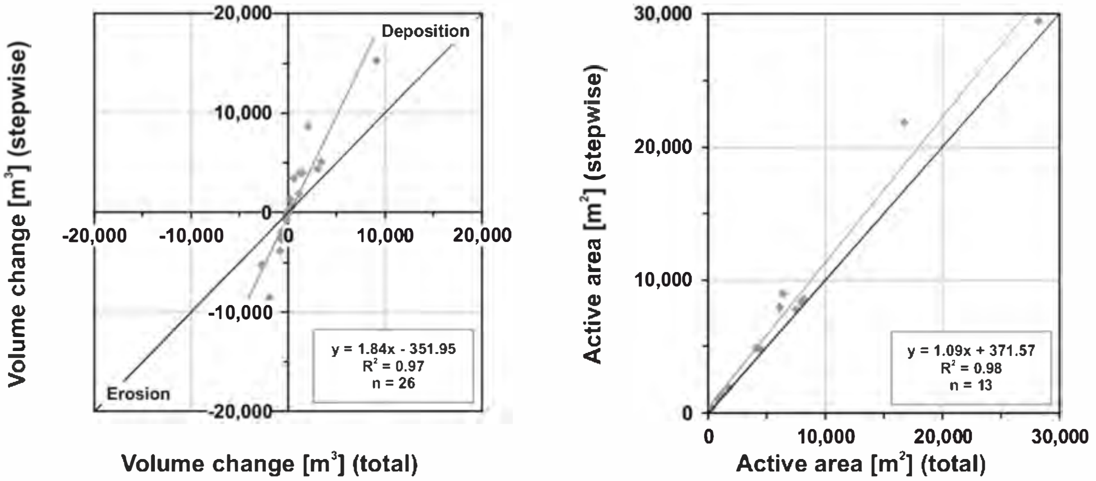

Figure 5.8: *Comparing volume changes* ***(left)****, including erosion and deposition, and deviations in active areas* ***(right)*** *considering a stepwise and a total approach for all sections at all four study sites. Note: the black line refers to the 1:1 line.*

Table 5.5: *Sediment balancing (only values outside the LoD) for the AOI at all four study sites for the overall investigation period (comparing the first to the last survey). Values in italics also consider all surveys made in between.*

Study site	**Period**	**Section**	**Volume change**				**Area**[b]		**Yielded**[c]
			[m^3]			**[t]**[a]	**[m^2]**	**[%]**	**[kg m^{-2}]**
			erosion	**deposition**	**balance**	**balance**			
Gseng	Sep. 2013 - Oct. 2015	total	-1937	2066	129	180	16,695	71	8
		top	-600	246	-355	-496	6424	65	-50
		middle	-788	591	-198	-277	6162	72	-32
		bottom	-549	1229	681	953	4109	82	189
	Sep. 2013 - Oct. 2015	*total*	*-4258*	*4297*	*39*	*55*	*21,763*	*93*	*2*
		top	*-967*	*618*	*-349*	*-489*	*9034*	*92*	*-50*
		middle	*-1614*	*1423*	*-190*	*-266*	*7836*	*91*	*-31*
		bottom	*-1677*	*2255*	*578*	*809*	*4893*	*97*	*161*
Langgries Outlet	Sep. 2013 - Oct. 2015	total	-72	373	302	423	1709	83	206
	Sep. 2013 - Oct. 2015	*total*	*-268*	*567*	*300*	*419*	*1886*	*92*	*204*
Langgries long	Sep. 2013 - Oct. 2015	total	-4109	9125	5016	7022	28,147	94	234
		top	-2695	1469	-1226	-1716	8186	93	-194
		middle top	-726	3393	2631	3684	7524	95	467
		middle bottom	-506	3097	2592	3628	7941	94	428
		bottom	-147	1166	1019	1426	4494	92	292
	Sep. 2013 - Oct. 2015	*total*	*-10,352*	*15,287*	*4935*	*6909*	*29,484*	*98*	*230*
		top	*-5250*	*4025*	*-1225*	*-1715*	*8566*	*97*	*-194*
		middle top	*-2503*	*5096*	*2593*	*3630*	*7781*	*99*	*460*
		middle bottom	*-1779*	*4332*	*2553*	*3574*	*8341*	*98*	*422*
		bottom	*-820*	*1834*	*1014*	*1420*	*4796*	*98*	*291*

Unnamed V	Oct. 2013 - Oct. 2015	total	-195	144	-51	-71	1206	74	-44
		top	-123	30	-94	-131	812	67	-108
		bottom	-72	115	42	59	394	95	143
	Oct. 2013 - Oct. 2015	*total*	*-272*	*222*	*-50*	*-70*	*1476*	*91*	*-43*
		top	*-160*	*67*	*-93*	*-130*	*1066*	*88*	*-107*
		bottom	*-111*	*154*	*43*	*60*	*411*	*99*	*144*

[a]: Tonnage based on dry bulk density of 1400 kg m^{-3} / [b]: Active area (erosion and deposition), percentages are in terms of total area in that section / [c]: It refers to the total area in that section. This is a lower-bound estimate for it takes no account of throughput or yield of fines in suspension.

5.5. Discussion

5.5.1. Total sediment in motion, seasonal patterns and missing data

Evaluating and quantifying sediment transport is highly dependent on the temporal and spatial scale of interest and the seasonal climatic influences triggering various processes, which can be different in magnitude and frequency. Many authors (e.g. Lane et al., 2003; Fuller and Marden, 2011; Blasone et al., 2014; Vericat et al., 2014) have used multi-temporal topographic surveys to derive patterns of topographic change in different environments. Lane et al. (2003) investigated a 1 km times 3.3 km gravel-bed, braided river system in New Zealand using a methodology for channel change detection coupled to the use of synoptic remote sensing. They applied digital photogrammetry, laser altimetry and image processing to gain DEMs. For the 1 year observation period they present a similar reach averaged net rate of 0.013 m^3 m^{-2} with zonal variations from -0.523 m^3 m^{-2} (dry to wet) to 0.513 m^3 m^{-2} (wet to dry) depending on how the surface has changed between surveys. More recent studies using GPS and TLS were finding net rates with comparable magnitudes over different spatial and temporal scales. Over a 3.5 year period Fuller and Marden (2011) were investigating a 21 ha wide gully system at the northern island of New Zealand. The acquired volumes of erosion and deposition for nine survey periods showed a high fluctuation resulting in an averaged net rate of approximately +0.07 m^3 m^{-2} yr^{-1} (-0.12 m^3 m^{-2} yr^{-1} of area-wide erosion and +0.19 m^3 m^{-2} yr^{-1} of area-wide sedimentation). Blasone et al. (2014) investigated a debris flow affected tributary catchment in northern Italy. Their study sites cover an upper part of an alluvial fan (1.3 ha), an active landslide (2.2 ha) and the sediment source area of the basin (20 ha). The resulting averaged yearly erosion/deposition thicknesses for the three sites were -0.11 m, -0.14 m and -0.23 m, respectively. In a sub-humid badland area in northern Spain Vericat et al. (2014) investigated a very small hillslope area (36 m^2) over different temporal scales ranging from 8 to almost 500 days. They reported a mean erosion/deposition balance for a one year investigation of -0.062 m with high variation when focusing on shorter time periods.

The magnitude and frequency of rainstorm events and their spatial distribution are of major importance for triggering sediment transport (Harvey, 2001). Spatially confined rainstorms occurred a few times during the observation period (Figures

5.3, 5.7) resulting in highly variable sediment dynamics throughout all study sites. We divided the rainstorm events in our study area into two classes: 20-30 mm d^{-1} and >30 mm d^{-1}. There is a high variability in the total amount of precipitation, the number of rainstorm events and the maximum precipitation intensity in each period (Figure 5.3). The two winter seasons are comparable in terms of amount and intensity of precipitation whereas the two summer seasons are different. During the summer of 2014 two major rainstorm events occurred (~40 mm d^{-1} and 90 mm d^{-1}) in addition to several rainstorms of lower magnitude resulting in a higher sum of precipitation during that season than in the summer of 2015. At Gseng, seasonal patterns of sediment mobility can be identified (Figures 5.6, 5.7). The highest amount of sediment relocation takes place during the summer seasons while in the winter periods, sediment mobility is rather low. Nonetheless, the highest rainstorm event (late October 2014) and the resulting changes in sediment storage took place in the winter period (survey in the beginning of October 2014). The total amount of shifted sediment significantly correlates with the total amount of precipitation (Figure 5.7) recorded during the respective period. Moreover, area-wide patterns of sediment movement can also be allocated to the different seasons (Figure 5.6) as the central trench shows the biggest changes, both during summer and winter while the contributing hillslopes (especially in the top and the middle section) are reacting substantially only during the summer season. Seasonal patterns in sediment relocation cannot be identified in the other three observed sites (Figures 5.4, 5.5) as the boundaries of surveys and seasons are inconsistent. The highest amounts in sediment yield are detected during the last survey interval at Langgries and during the summer months in 2015 at Unnamed V (Figure 5.7) without having clear evidence in the weather record (lower amount of precipitation than during other investigation periods as well as a small number of rainstorm events). These circumstances suggest that the dynamics in sediment relocation are not always reflected in the recorded weather conditions and storm events. Similar findings that a significant relationship between sediment transfer and precipitation could not be detected or remains complex were stated by Fuller and Marden (2010, 2011) describing a conceptual model of slope-channel coupling in a gully system over a 3.5 year survey period, by Vericat et al. (2014) investigating topographic change on different event scales in badlands and also by Loye et al. (2016) who focused on sediment dynamics in a debris flow catchment over a 16 month period. Due to the only 2 years of investigation and heterogeneous survey intervals, no general concept of seasonal patterns can be drawn. Still, most sediment throughout all side channels is being moved during the summer seasons which can be related to triggering rainstorm events. Remarkably, the frequency and intensity of storms in the summer of 2014 is significantly higher than in 2015 (Figures 5.3, 5.7), but besides Gseng all investigated sites show a contrary behavior in having more sediment relocated in the summer of 2015 than in 2014. This could be due to the facts that the survey interval is inconsistent between the study sites assigning relocated sediment to different seasons as well as the possibility of single rainstorm events acting only locally and therefore being recorded at the nearby Weidendom station without triggering any geomorphic activity in the study areas or vice versa.

The established relocation rates are a minimum amount as the sums of erosion and deposition over the entire time interval are lower than the cumulated sums of the shorter intervals (Figure 5.8). Thus, if the number of surveys would have been higher, the volume of transported sediments would probably increase further. Lane et al. (1994, Fig. 9) stated that a spatial point density of approx. 3-4 pts m^{-2} is necessary to avoid missing information and that higher densities do not further improve the results. We assume that a similar approach is valid for the temporal density of surveys, since the time dimension is of major importance in studying mass movements (Flageollet, 1996) and coupling behavior (Harvey, 2002). This means that above a critical amount of surveys a higher sampling frequency would not necessarily improve the results. We could show that an approximately 4-fold higher frequency of surveys ('stepwise' approach) results in roughly two times higher volumes of erosion and deposition (both affected almost to the same degree) with effects on the net change being less significant (Figure 5.7). This inter-event effect was also determined by Vericat et al. (2014) showing that a reduction of survey frequency results in topographic changes in opposite directions being cancelled out. Comparing surface changes of each survey interval with the total interval (Figures 5.4 to 5.6) reveals different patterns. During longer monitoring periods multiple topographic changes occurring at the event-scale are followed by further topographic changes in an opposite direction. Thus, an event-scale based monitoring should be aspired to avoid "missing" sediment. This "ideal" survey density to capture the (reasonably complete) amount of mobilized sediments (not taking into account if there is sediment transported without leaving a trace in the landscape) depends on the interval between significant, geomorphologically effective rainstorm events. As no defined precipitation or runoff threshold for an "effective" rainstorm can be derived from the precipitation data (Figure 5.3) and no continuous observation (e.g. webcam) is available this task remains for further investigations.

5.5.2. Current sediment dynamics of the trenches

Over the entire 2 year period, debris at Langgries is eroded in the top position of the gravel stream and deposited in the middle and lower reaches (Figure 5.5). We assign this effect to an ongoing reaction on the former gravel mining which has lowered the entire trench (as far as it could be reached by caterpillars) and thus, over-steepened the upper parts. If this process continues, sediment output into the river will increase in the future as the reach upstream of the road bridge currently increases in elevation. The deposited amounts in the lower three quarters overbalance the erosion in the uppermost quarter. This can also be due to the bridge opening, which is the lower end of the study site Langgries long, narrowing the channel and therefore impeding the sediment from moving further. As there are lateral (slopes-channel) and longitudinal linkages (between the four sections of Langgries long and continuing to Langgries outlet) sedimentological connectivity can be implied. This means that sediment from upper parts as well as from the contributing slopes entered the study site and was transported through the segments. By now it is still not clear how fast sediment transport occurs and if eroded material from one sector can be located as deposited material in another one. Furthermore, this along-channel connectivity, especially from the bottom section to the outlet, can be impeded by the road bridge as a barrier (Fryirs et al., 2007). However this barrier is not a permanent situation as the ongoing surface elevation upstream of the sill will facilitate the sediment transport in the future.

At Gseng, erosion occurs mainly linearly along the bottom of the deep gravel trench (Figure 5.6). Like at Langgries, this is still a response to gravel excavation in the lower reaches which are now gradually "filled up" again. The cut-and-fill activity in the shorter time windows clearly shows that this process takes place in batches of refilling from the side slopes and dissection during single rainstorm events. Major surface changes occurred more often during the summer months (Figures 5.6, 5.7). Alternating patterns of erosion and deposition can be found along the gravel trench throughout the whole investigation period. Since most of the sediment movement is limited to the central flow path the intensity of the longitudinal linkage exceeds the lateral one by far (Figure 5.6). Therefore, sedimentological connectivity can be

- In two large trenches, Gseng and Langgries, the relocation of sediment is probably still a reaction to the gravel mining until the establishment of the National Park Gesäuse. A change in sediment storage can be traced along the side channels implying sediment transport and longitudinal connectivity. A third tributary (Unnamed V) shows relocation of sediment only in the lower parts with no recharge of sediment from the upper catchment.
- The amount of sediment that actually reached the main torrent was very low at Langgries and nil at Gseng for this side channel is decoupled (due to mining history) to the main river system. The third side channel (Unnamed V) had no measurable sediment supply from its adjacent rock faces during the investigation period, but did react to rainstorms and was therefore able to provide pulsed sediment input to the Johnsbach River.
- The sums of erosion and deposition over the total time interval (2 year period) are lower than the cumulated sums of the shorter intervals (stepwise approach) by a factor of around two. This applies for all study sites and for both erosion and deposition. Even with the roughly half-yearly survey interval, information on surface changes was probably lost and the amounts of transported sediments were underestimated. The ideal survey interval should consider the mean time span between two significant relocation events.

Ongoing work is to transfer the results to other trenches in the catchment, to set up a quantitative sediment budget of the valley and to compare the amounts of mobilized sediments to the catchment output measured at the new bedload station at the outlet. Future TLS campaigns will focus on smaller time intervals in order to derive an optimal frequency of surveys. Furthermore, the development in the anthropogenically disturbed side channels will be further monitored in the future to observe if the current transient behavior will lead to an equilibrium stage at Gseng or Langgries when the balancing effect of filling up missing sediment is complete. This process will also influence the coupling behavior of those side channels to the Johnsbach River involving an increasing sediment input into the main stream. If these additional amounts of sediment will be positive for habitats from an ecological viewpoint or if a higher concentration of fine material e.g. would cause pore spaces to be filled and thus destroying fish spawning habitats will remain for further investigations. As sediment supply is concentrated to certain points and the river becomes partly clogged, intermittent pulses of sediment transport are to be expected during flood events.

Acknowledgements

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6. IMPACTS OF GRAVEL MINING AND RENATURATION MEASURES ON THE SEDIMENT FLUX AND BUDGET IN AN ALPINE CATCHMENT (JOHNSBACH VALLEY, AUSTRIA)

Abstract

In the Johnsbach Valley (Austria), a medium size non-glaciated torrent catchment, enormous amounts of sediment have been made available due to the brittle dolomite bedrock. This occurs mainly in the Zwischenmäuerstrecke (ZMS) (*english translation: "reach between the walls"*) and presents a major challenge to local river management. Within a renaturation project, which followed several decades of disturbance (flood protection and gravel mining) in the ZMS, it is of particular importance to understand where the sediments come from and the transport pathways through the system to prepare future forecasts.

In the present study, we investigate the recent sediment cascade in a comprehensive analysis of the ZMS that was achieved by means of airborne laser scanning campaigns in 2010 and 2015. The current bedload yield at the outlet was measured using an integrative bedload monitoring system. Historical data from 1954 was used to illustrate the effects of the mining period on the former sediment routing. Finally, we evaluated the expected sediment transport rates in the near future.

The results show that from the hillslopes sediments are mainly transported via the active side trenches to the main channel (~7000 m^3 yr^{-1}). The sediment transport in the Johnsbach River consists mainly in relocating the periodically occurring sediment entries of the side trenches. The bedload transport rates at the outlet sum up to annual bedload yields of 2000 m^3 yr^{-1} to almost 12,000 m^3 yr^{-1} during the observation period. Especially those areas inside the side trenches that were heavily affected by gravel mining (excavated amount of sediment during the mining period: ~25,000 m^3 yr^{-1}) are now accumulating sediment since the end of this period (~8000 m^3 yr^{-1}).

Future scenarios will depend heavily on the progress in the mining affected side channels. The impacts of this period are continuously being reworked and a natural

sediment flow will adjust in the near future. The sediment input into the Johnsbach River will rise significantly and could lead to a doubling in the annual sediment yield at the outlet compared to now. In particular, the reaches along the Johnsbach River following the confluences with the mining affected side trenches are already showing morphological changes due to the recently imported sediments.

6.1. Introduction

Over the last decades alluvial rivers, all over the world and especially in Europe, have been significantly affected by human disturbances (Petts, 1989). The most common forms of intervention in fluvial systems are due to land-use changes, urbanization, dams and reservoirs constructed to generate hydroelectric power, flow diversions, and gravel and sand mining. Several studies (e.g., Marston et al., 1995; Bravard et al., 1997; Liébault and Piégay, 2001, 2002; Surian and Rinaldi, 2003; Liébault et al., 2005; Rinaldi et al., 2005; Rivora et al., 2005; Spink et al., 2009; Surian et al., 2009a,b) have shown that these disturbances cause remarkable channel changes with substantial effects on flow and sediment regimes. Induced by a loss of sediment supply and recharge, a range of environmental and social effects result from channel incision and narrowing, such as undermining of structures, loss of groundwater storage or loss of habitat diversity (Bravard et al., 1999a). Especially in the Alps, this has led to the fact that only a minor portion of all rivers are still in a natural or near-natural condition (Martinet and Dubost, 1992; Ward et al., 1999). To overcome this problem, a need for sustainable sediment management arises by defining river restoration strategies (Piégay et al., 2005; Habersack and Piégay, 2008; Liébault et al., 2008; Rinaldi et al., 2009).

From historical times alluvial rivers have been attractive sources for sediment exploitation. Notably, 'in-stream mining', which involves the removal of sediment from the river bed, directly affects the channel geometry resulting in an imbalance of sediment supply and transport capacity (Sandecki, 1989). By changing the geomorphic setting many different environmental and economic impacts can be expected (Bravard et al., 1999a), which are summarized by Rinaldi et al. (2005) and Rivora et al. (2005). Throughout the literature it has been widely discussed what consequences can arise from mining the active river channel. Certainly it is not only the actions involving the river itself that cause a disturbed sediment management but also interventions (mining gravel in pits) affecting the contributing side channels and catchments that are connected to specific river reaches.

Several different human disturbances have heavily affected the alluvial channel in the Johnsbach catchment since the middle of the past century. These include works for flood and bank protection, gravel mining in sediment supplying side catchments to the main river system, and in recent years river restoration that includes an explicit sediment management. After a major flood event in 1949, which destroyed the only access into the Johnsbach Valley, the course of the river was armed with longitudinal barriers and check dams along the ZMS between 1950 and 1974 (Thonhauser, 2007; Kammerer, 2008). The goal was to compress the course of the river and to force the stream into a man-made river bed (Haseke, 2006). Former gravel mining in two of the biggest side catchments (in Gseng and Langgries since 1984 and 1991, respectively) was interrupting the sediment flux in those channels as huge amounts of sediment were excavated and used industrially. The annual amount of sediment being removed from those side catchments is reported to be 15,000-20,000 m^3 yr^{-1} (Haseke, 2011). With the establishment of the NPG in 2002, the excavation of sediment had to be abandoned but was not terminated before 2008 because of still ongoing contracts. Finally, both former mining areas were restored from 2009 to 2010. Meanwhile, the Johnsbach River was restored in the cost-intensive European Union funded river-ecological LIFE-project "Conservation strategies for woodland and wild waters in the Gesäuse" controlled by the NPG from 2006 to 2009. The main focus of this project was to dismantle and widely remove extensive engineering measures in the river and at the junctions to the side channels (Haseke, 2011). This was meant to ensure that sediment can reach the Johnsbach River and finally the River Enns in sufficient quantities according to its natural dynamics (Holzinger et al., 2012). During the LIFE-project the new concept involved several interventions: adjusting the slope of the river and avoiding high steps effectuated by building broad, but flat ground sills, expanding the obstructed banks and releasing the Johnsbach River between the sills (Haseke, 2011). In this way the Johnsbach River is now able to rebuild its original gravel banks and furcations, ballasts the new sills and therefore creates valuable habitats and ensures fish migration. Furthermore, an increase in coarse material prevents the progress of river-bed sealing through fine-grained material during the last decades and thus prevents groundwater subsidence as well as the reduction of micro habitats (Holzinger et al., 2012).

Fischlschweiger (2004) investigated the aftermath of the mining activities in the lower Langgries side catchment, concluding that 10,000 m^3 yr^{-1} needed to be excavated (in the reference period of 1993-2002) to maintain the current state. Several authors (Kammerer, 2006a,b; Zulka, 2013) were focusing on changes in the evolution of habitats due to mining and its resulting effects. They all could prove that mining activities disrupt the fragile balancing system of scree slopes, which in turn affects the habitats of certain fauna and flora. In 2013, the FWF-funded Sedyn-X project was launched to investigate sediment transport in the ensuing field of tension between nature conservation (e.g., aqua fauna habitats), hazard protection and the efficiency of hydropower stations downstream. By now, Stangl et al. (2016) have applied a sediment connectivity analysis combining upslope contributing area and downslope flow length. According to their analysis, sediment storages close to the main river are highly coupled to the outlet, whereas erodible sediments in the remote high-alpine areas are not. Rascher and Sass (2017) quantified surface changes using multi-temporal terrestrial laser scanning at the interface between the main torrent and selected tributary channels. They could show that the sediment output of tributaries is currently limited (seasonal and event based) as sediment is "missing" due to the mining history. The objective of this study is to set up a sediment budget, enabling the analysis of the impacts of gravel mining and renaturation on the sediment flux in the ZMS of the Johnsbach Valley. To this end, we investigated the recent sediment cascade focusing on several aspects. First, how much sediment is provided from rock walls to the side-catchments (quantifying the input parameter for the sediment budget). Second, where and to which extent is sediment relocation currently taking place (evaluating transport and storage in the system). Third, how much sediment is exported out of the Johnsbach Valley (quantifying and comparing the fluvial sediment transport to the sediment output). Fourth, we show the effects of the mining period on the former sediment routing by reconstructing the sediment cascade in the relevant areas. Finally, we predict the sediment transport rates in the near future once decoupled side catchments are reconnected to evaluate the overall consequences of the recent renaturation measures. Coupled investigations of sediment cascades and bedload transport have rarely been carried out. Therefore, our approach could be a showcase example describing the spatial sediment dynamics on the one hand and verifying the predicted sediment yield on the other hand, in an area that underwent significant anthropogenic modifications in the past.

6.2. Regional-scale setting and local-scale classification of the study site

6.2.1. Characterization of the study area

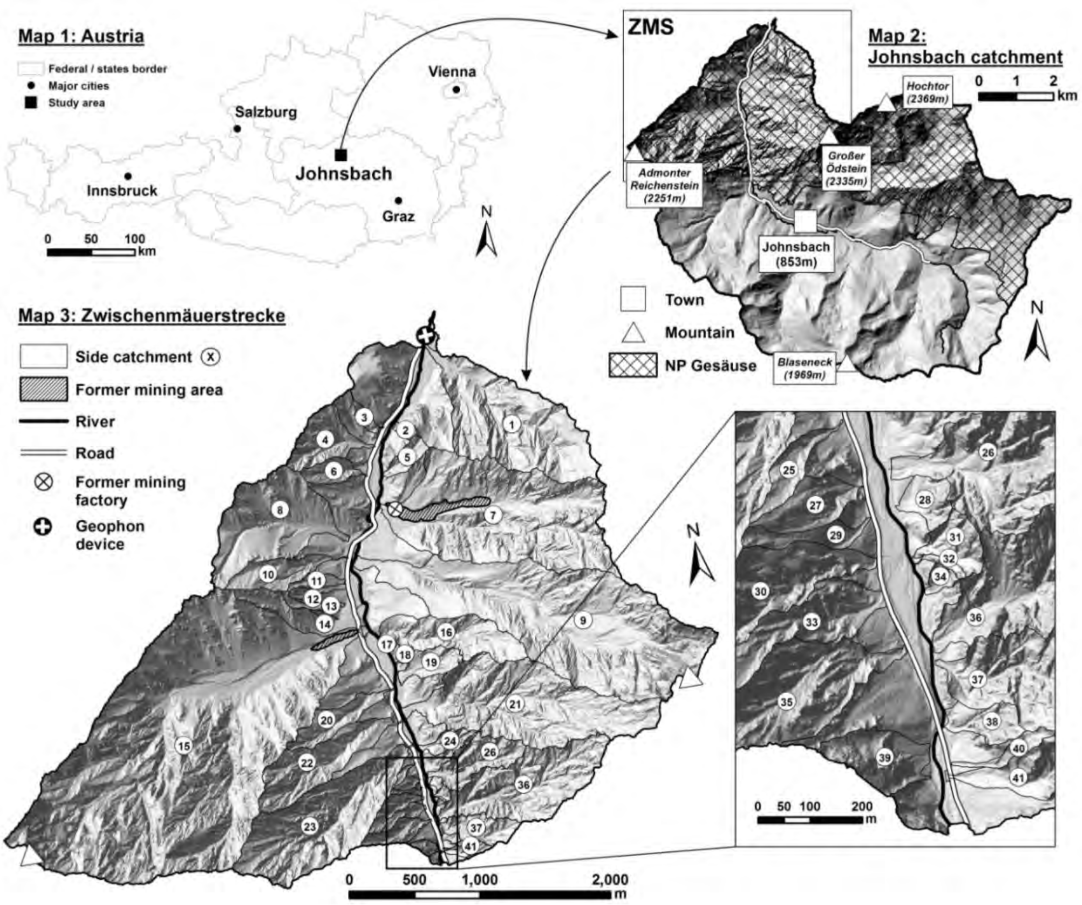


Figure 6.1: *Location of the study area (with inset map of Austria and the catchment), hillshade map of a LiDAR-derived DEM (Bureau of the Styrian Government, 2015). The numbers in map 3 correspond to the side catchments, listed in Table 6.A.2.*

The Johnsbach Valley (Figure 6.1) is a non-glaciated alpine catchment in Upper Styria (Austria) that covers an area of approximately 65 km^2 reaching from 584 m a.s.l. at the outlet to 2370 m a.s.l. (Hochtor). The valley is drained by the Johnsbach River, which runs for 14 km with a mean gradient of almost 4 % before it empties into the River Enns. The geological setting is characterized by different rock types belonging to two nappes, the Northern Calcareous Alps in the N and the Greywacke

Zone in the S (e.g., Ampferer, 1935; Hiessleitner, 1935; Flügel and Neubauer, 1984). Our area of investigation, the ZMS, is situated in Triassic carbonate rocks, mainly limestone (Dachsteinkalk) and dolomite (Wettersteindolomit) (Figures 6.2B, 6.3A). The ZMS is a 4.5 km river reach with a catchment of around 13 km² in size that is sparsely vegetated (Figure 6.3C) by fir forests and pine shrub lands, and is shaped by steep furrows and deeply incised channels (Figure 6.3B) on both sides. The majority of the sediment that is relocated and transported in the Johnsbach Valley is stored in the ZMS.

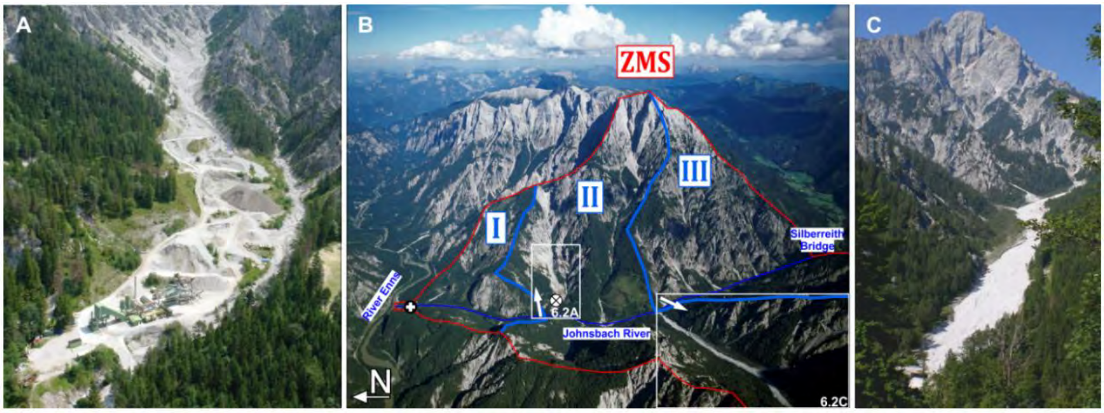


Figure 6.2: *Photographs from the Johnsbach Valley:* ***(A)*** *Gseng side catchment in eastward direction with the former mining factory in the front (picture by NPG, 07/2006);* ***(B)*** *aerial image (eastward direction) of the ZMS (red outline) with I – III indicating the three river segments; white rectangles and arrows indicate the location and direction of sight of pictures 6.2A and 6.2C, respectively; point features (location of the bedload monitoring system and the former mining factory) correspond to Figure 1 (picture by NPG, 10/2004);* ***(C)*** *Langgries side catchment (07/2013) in westward direction with the road bridge in the front and the Admonter Reichenstein in the back.*

The climate is characterized by annual mean temperatures of around 8 °C in the lower elevations of the valley and below 0 °C in the summit regions. Annual precipitation amounts to approximately 1500-1800 mm (Wakonigg, 2012a,b). Storm precipitation occurs almost exclusively in the summer months and can reach several tens of mm per hour. Thus, runoff at the Johnsbach River peaks in spring (snow melt) and summer while the tributaries show surface runoff and sediment transport only during episodic rainstorms.

The combination of the geological setting and the climatic conditions results in high morphodynamic activity, primarily in the ZMS (Strasser et al., 2013). The brittle Wetterstein Dolomite is particularly prone to weathering, providing large amounts of sharp-edged debris. This debris is being reworked and relocated by rock falls and debris avalanches from the rock walls over the steep slopes into the channels of the side catchments. Finally, this results in high sediment input rates into the Johnsbach River (Rascher and Sass, 2017).

6.2.2. ZMS – Subdivision of river sections and side-catchments

Following Lieb and Premm (2008), the ZMS can be divided into three segments (Figures 6.2B, 6.3D) according to its landscape and its morphodynamics. The southern section (III) is dominated by a very steep landscape (with mean slope angles of >50°) and characteristic erosional patterns formed into the dolomite bedrock (Figure 6.3A). It covers the side catchments ranging from the Silberreith Bridge down to Langgries side catchment at a 2 km river reach. The central area (II) is shaped more smoothly as the dolomite bedrock is largely covered by breccia that prevents the carbonate bedrock from being eroded. In this 1.5 km river reach the biggest side catchments in the ZMS (Langgries, Kainzenalbl, Koderalbschütt and Gseng) run into the Johnsbach River in which most of the sediment is being transported. In the lowest section (I), until the Johnsbach River meets the River Enns, the valley gets narrow again with limestone being the dominant bedrock type. Shortly downstream, a 500 m long alluvial plain is the last sediment storage. For the purpose of our study all three river segments were divided into two reaches (A and B) of similar morphological structure (Figure 6.3, Table 6.A.1).

Several side catchments discharge into each river segment from both sides (Figure 6.3D). Forty one side catchments (Table 6.A.2) were identified through field campaigns in combination with ArcGIS routines. The ZMS was mapped by Krenn (2016) (Figure 6.3B) with emphasis on geomorphic processes and storage types. The spatial bedrock distribution, the slope catchments (SL) (total of 131) and channel sections (CH) (total of 99) were outlined in each of the side catchments. Along the Johnsbach River, six alluvial sections (AS) where defined following the classification into the river segments and reaches.

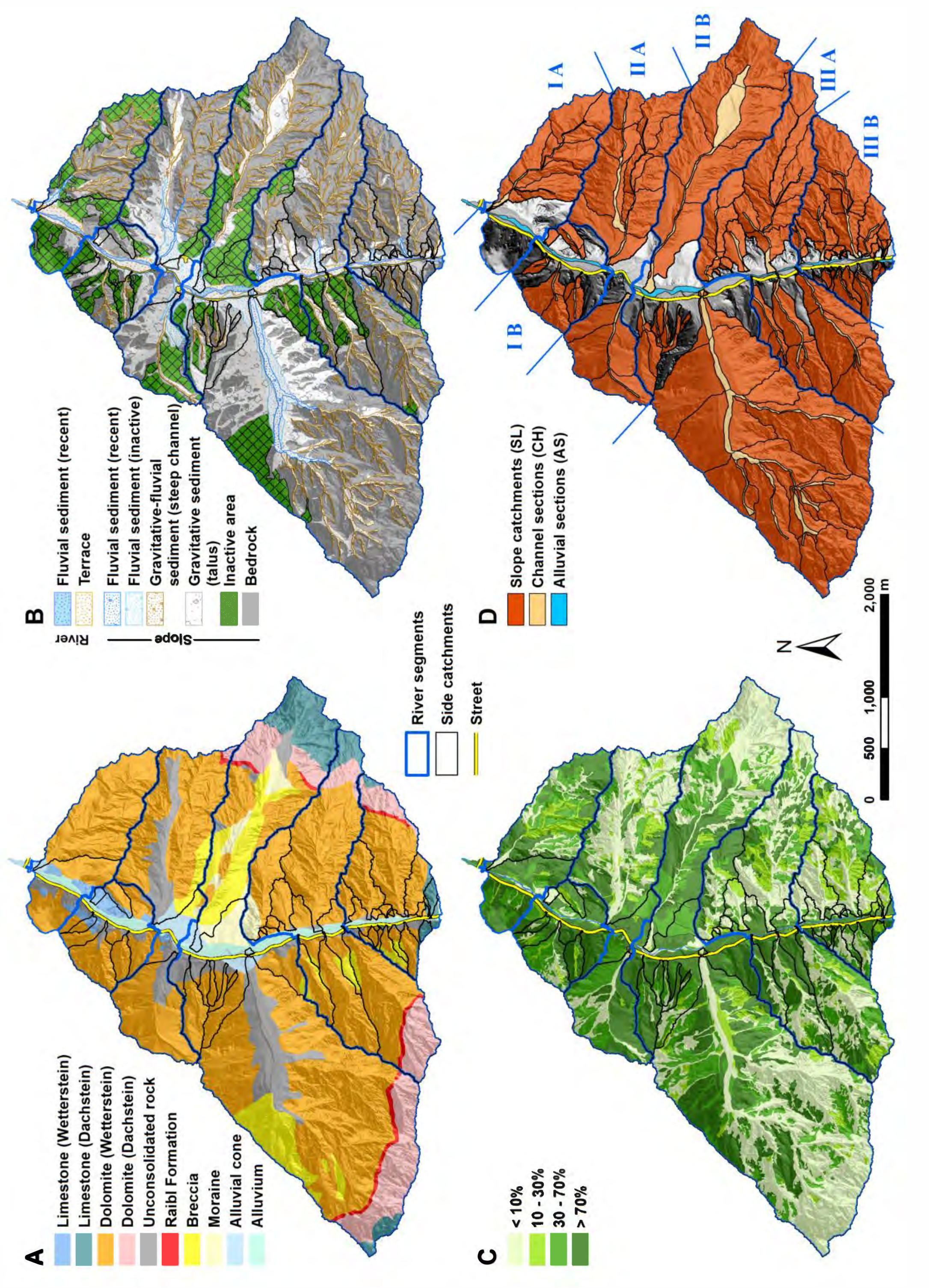


Figure 6.3: *Characteristic maps of the ZMS:* ***(A)*** *geology (modified from Ampferer, 1935);* ***(B)*** *geomorphology / sediment storage types (modified from Krenn, 2016);* ***(C)*** *vegetation cover (derived from HAPITALP mapping by NPG);* ***(D)*** *subdivision (as defined in section 6.2.2), I A to III B are the three segments and their sub-reaches; hillshade map of a LiDAR derived DEM (Bureau of the Styrian Government, 2015).*

6.3. Methodological framework

6.3.1. Reconstructing the sediment cascade

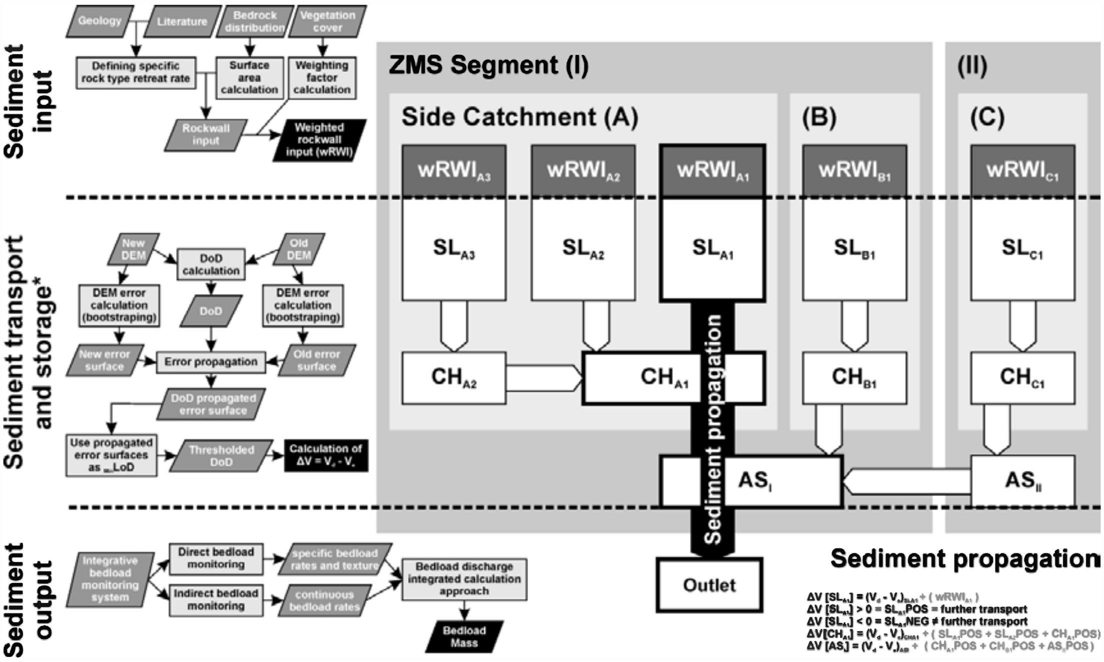


Figure 6.4: *Flow chart of the reconstructed sediment cascade and workflows for determining change detection at each stage in the sediment budget. Note: Erosion (V_e) and deposition (V_d) estimates, weighted rockwall input (wRWI), slope catchment (SL), channel section (CH), alluvial section (AS); *: simplified from Vericat et al., 2017.*

To evaluate the sediment output of the ZMS, the sediment cascade was assembled (Figure 6.4 right). Side catchments (e.g., A in Figure 6.4) inside the ZMS were outlined in which slope catchments (e.g., SL$_{A1}$ in Figure 6.4), each including its spatial bedrock extent (e.g., wRWI$_{A1}$ in Figure 6.4), and channel sections (e.g., CH$_{A1}$ in Figure. 6.4) were separated. At each side catchment sediment volumes were propagated through the system from the SL to the CH and along the CHs down to the respective alluvial section (e.g., AS$_{I}$ in Figure 6.4). Several side catchments can contribute to each AS. The same is valid for the fluvial system, where sediment input occurs from the side catchments at certain AS and is then routed downstream. Sediment propagation (according to the rules defined in Figure 6.4, bottom right) was determined as follows: if net erosion occurs in a specific SL, CH, or AS, this volume is transported farther down (to the next CH, AS, and so on), if net deposition occurs there is no further transport. Accordingly, the net storage value of a specific CH or AS can change due to the impact of an adjacent SL, CH or AS.

6.3.2. Data acquisition

6.3.2.1. Light detection and ranging (LiDAR) data

The LiDAR data used to derive the Digital Elevation Models (DEM) for 2010 (company *AVT*) and 2015 (company *Vermessung Schmid*) were recorded via Airborne Laser Scanning (ALS). The flights were carried out using two scanning systems (Riegl LMS-Q560/Q680) mounted on a Eurocopter AS350 with a desired minimum survey design point density of 4 pts m^{-2}. In 2015 the Karl-Franzens-University contracted a second LiDAR survey of the Johnsbach Valley. The survey was carried out on 26 August 2015 using a Riegl LMS-Q780 mounted on a Piper PA34 with a desired minimum survey design point density of 4 pts m^{-2} as well. Both raw point clouds were filtered into ground/non-ground points using *TerraScan* software classification routines and algorithms and finally clipped to the ZMS. The filtered point density was 7.35 and 5.50 pts m^{-2} for 2010 and 2015, respectively. Bare ground points were then triangulated into temporary Triangular Irregular Networks and finally rasterized to derive DEMs with a homogeneous resolution of 1 m using the *LAStools* software algorithms.

6.3.2.2. Historic areal data

To quantify the loss of sediment since the beginning of gravel mining in the side catchments Gseng and Langgries, 5 m DEMs were created by the company *AVT* using the areal images from 1954. For this purpose 3D ground control points were derived from an existing survey and later used in *Match-AT* for the orientation of the 1954 areal images. The following stereoscopic analysis for deriving height information was accomplished using *Summit Evolution*. The DEMs cover the channels of both side catchments where the mining took place and the adjacent areas that are directly affected.

6.3.2.3. Additional input variables

Additional input parameters, which are mostly provided by Krenn (2016), were necessary. The geological map of the study area (Figure 6.3A) was newly digitized and modified after Ampferer (1935). A map on the vegetation cover (Fig. 6.3C) was provided using the results of the HABITALP (Alpine Habitat Diversity) mapping carried out by the NP Gesäuse. A geomorphological map showing the dominant features and storage types was developed by Krenn (2016). Mapped bedrock areas were compared to the geological map to assess the type of rock present.

6.3.2.4. Integrative bedload monitoring system

An integrative monitoring system like at other sites in Austria is installed at the Johnsbach River (for location see Figures 6.1 and 6.2B) that combines direct and indirect monitoring devices (Rickenmann et al., 2014; Habersack et al., 2017; Rickenmann and Fritschi, 2017). It is not possible to monitor bedload transport processes satisfactorily using only a single measurement device, as each method has its specific advantages and restrictions (Kreisler et al., 2017). Hence, the integrative bedload monitoring system was developed to overcome this challenge. It consists of a basket sampler, bedload traps and geophone devices (see arrangement in Figure 6.5). As the deficits can be compensated by combining the different direct and indirect methods, the monitoring system offers the possibility to comprehensively monitor bedload transport processes.

Direct bedload monitoring methods enable the determination of (specific) bedload rates and the texture of the bedload material. In the following, the basket sampler and the bedload trap, both part of the integrative monitoring system at the Johnsbach River, are introduced. Mobile basket samplers have been applied in bedload monitoring for decades (Mühlhofer, 1933; Van Rijn, 1986). At the Johnsbach River an adapted type of the Bunte sampler with an intake width of 0.5 m and a net with 2-4 mm pore size is deployed (Bunte et al., 2004; Kreisler et al., 2017). Using a mobile crane, the sampler is lowered from the riverbank onto the riverbed. Measurements are conducted at defined verticals directly upstream from the geophone device and the position of the basket sampler is fixed with two tether lines (Kreisler et al., 2017). The measuring time depends on the prevailing bedload transport rate.

Figure 6.5: *Arrangement of the integrative bedload monitoring system consisting of a bedload trap and a geophone bar* ***(center and lower right)*** *supported by a basket sampler* ***(upper right)****. Bedload data acquisition and river gauging takes place in a monitoring station* ***(upper left)****. Note: views in the center and the upper right are looking upstream.*

At the bedload traps the sample box is covered by a lid with a longitudinal sampling slot. The sampling slots are 1.6 m long and 0.5 m wide. Upon start of the monitoring, the slot is opened hydraulically via manual control, the transported bed material gets trapped in the sample box and load cells automatically record the mass increase within the box. Bedload traps enable measurements at all discharge stages and thereby also the bedload can be monitored even during flood events (Habersack et al., 2017; Kreisler et al., 2017). Habersack et al. (2017) showed that both hydraulic and sampling efficiency is high. Furthermore, the simultaneous measurement of bedload rates and the determination of bedload texture is possible. Disadvantages of the bedload trap are its fixed position in the stream bed and the high maintenance efforts required.

Geophones are vibration sensors originating from seismic technology. To detect bedload transport, the geophone sensors are mounted on the bottom side of 0.36 m long, 0.5 m wide and 0.015 m thick steel plates (Habersack et al., 2017). These steel plates are embedded in the stream bed. Bedload particles moving over the steel plates produce vibrations which are registered by the geophone sensors. The geophone signal is sampled continuously at a rate of 10 kHz. Geophone data and bedload mass correlate well when the bedload material is larger than 10-30 mm (Rickenmann and McArdell, 2007, Wyss et al., 2016).

6.3.3. Data processing

6.3.3.1. Rock wall retreat as sediment input

Sediment input into the system derives from the rock walls surrounding the ZMS. As only fragmentary measurements of rock wall retreat rates are available in the study area, rates from other investigations (Sass and Wollny, 2001; Glade, 2005; Sass, 2005b, 2007; Vehling, 2016) working in similar settings or rock types were used. This is a very simplified approach not taking into account spatial variability due to, for example, singular events, joint density or dip of strata. The real bedrock surface area was calculated and combined with retreat rates of 1.0 mm yr^{-1} and 0.3 mm yr^{-1} for dolomite and limestone dominated rock types, respectively. Finally, the input values were weighted using the vegetation cover as a proxy for erosivity in a reverse proportional manner (100 % vegetation cover = 0 % erosivity, and vice versa), which is a simplifying assumption (Figure 6.4, top left).

6.3.3.2. DEM of difference (DoD) and volume calculation

Because the morphology of our study area is complex and the available DEMs are heterogeneous in their quality and accuracy, the assessment of erosion and deposition volumes needs a robust approach to discriminate between actual surface elevation changes and the inherent noise. We therefore consider DoD uncertainties by following the three main steps proposed by Wheaton et al. (2010): (1) estimating the magnitude of individual DEM uncertainty in a spatially variable way using a bootstrapping approach; (2) propagating the identified uncertainties into the DoD, and (3) assessing the significance of the propagated uncertainty (Figure 6.4, middle left).

The spatially variable uncertainty assessment was performed by applying a bootstrapping experiment, which is basically a statistical resampling technique. The principle is that a sub-sample is removed from the sufficiently large data set and the DEM is reconstructed without it (Wheaton, 2008). The removed sub-sample is then used to estimate the elevation uncertainty through comparison. In our study, a random sample of 10 % of the points was removed from the original data set. The thinned data set was then triangulated and converted into a 1 m DEM (for 2010 and 2015) and a 5 m DEM (for 1954), respectively. The elevations of the sub-sample points (Z_{xy}) were compared to the DEM values (Z_{DEM}) such that the mean difference ($\overline{|Z_{xy} - Z_{DEM}|}$) is an indication of elevation uncertainty. This was repeated with three different random sub-samples to ensure consistency in the results (Table 6.1). Finally, point clouds representing the areas of interest (AS, SL and CH) were separated from the original ALS data set. Using the elevation uncertainty information (Table 6.2) in the sub-samples, 1 m error surfaces were created (via triangulation).

Table 6.1: *Point survey and sampling statistics for bootstrapping approach. Note: GS = Gseng, LA = Langgries, SL = slope catchments, CH = channel sections, AS = alluvial sections.*

		1954 (GS)		**1954 (LA)**		**2010 (ZMS)**		**2015 (ZMS)**	
		count	**[%]**	**count**	**[%]**	**count**	**[%]**	**count**	**[%]**
Original	total	13,832	100.0	12,640	100.0	140,841,374	100.0	72,626,846	100.0
sub sample 1	total	1389	10.0	1261	10.0	13,744,287	9.8	7,316,341	10.1
	SL	1201	8.7	744	5.9	4,174,705	3.0	2,227,759	3.1
	CH	189	1.4	516	4.1	737,478	0.2	398,144	0.6
	AS	n.a.	n.a.	n.a.	n.a.	89,021	0.1	58,429	0.1
sub sample 2	total	1388	10.0	1263	10.0	13,744,287	9.8	7,316,341	10.1
	SL	1199	8.7	783	6.2	4,174,407	3.0	2,228,222	3.1
	CH	190	1.4	479	3.8	737,681	0.5	398,211	0.6
	AS	n.a.	n.a.	n.a.	n.a.	88,990	0.1	58,464	0.1
sub sample 3	total	1373	9.9	1263	10.0	13,744,287	9.7	7,316,341	10.1
	SL	1184	8.6	775	6.1	4,174,583	3.0	2,228,362	3.0
	CH	188	1.4	488	3.9	737,662	0.5	398,234	0.6
	AS	n.a.	n.a.	n.a.	n.a.	88,950	0.1	58,480	0.1

Assuming a normal distribution of errors, we follow the existing approaches for propagating uncertainties into DoDs (Taylor, 1997; Brasington et al., 2003; Fuller et al., 2003; Lane et al., 2003) according to the equation:

$$\boldsymbol{U_{crit} = t\left(\sqrt{(\delta z_{new})^2 + (\delta z_{old})^2}\right)} \tag{6.1}$$

where U_{crit} is the critical threshold in the DoD (or the minimum level of detection (LoD) threshold) and δz_{new} and δz_{old} are, respectively, the elevation uncertainty in the newer and the older DEM. U_{crit} is based on a critical Student´s t-value at a chosen confidence interval:

$$\boldsymbol{t = \frac{\left|Z_{DEM_{new}} - Z_{DEM_{old}}\right|}{\delta u_{DoD}}} \tag{6.2}$$

where δu_{DoD} is the propagated error in the DoD and $\left|Z_{DEM_{new}} - Z_{DEM_{old}}\right|$ is the absolute value of the DoD. The 95 % confidence interval was used as a threshold throughout this paper. For each DoD raster cell, a critical threshold error was then calculated with equation 6.1 to derive a LoD that was finally subtracted from all DoD cells to derive maps of significant elevation change and calculate volumes of erosion and deposition (by multiplying with the appropriate raster cell size value). The final DoD maps were derived according to the above mentioned methodology using the GCD (Geomorphic Change Detection) v6.1.6 software ArcGIS plugin developed by Wheaton et al. (2010).

Table 6.2: *Summary of elevation uncertainty [m] statistics. Note: GS = Gseng, LA = Langgries, SL = slope catchments, CH = channel sections, AS = alluvial sections.*

		1954 (GS)		**1954 (LA)**		**2010 (ZMS)**			**2015 (ZMS)**		
		CH	**SL**	**CH**	**SL**	**AS**	**CH**	**SL**	**AS**	**CH**	**SL**
sub sample 1	min	0.01	0	0.01	0.01	0	0	0	0	0	0
	max	3.82	16.29	13.76	6.49	7.34	51.40	73.16	6.35	50.53	68.17
	mean	0.48	0.94	0.52	0.70	0.13	0.43	0.49	0.12	0.44	0.50
	std.-dev.	0.52	0.91	0.85	0.80	0.20	0.81	0.73	0.18	0.87	0.76
sub sample 2	min	0.01	0.01	0.01	0.02	0	0	0	0	0	0
	max	5.44	15.71	9.67	7.70	7.33	47.66	72.93	6.12	60.25	62.52
	mean	0.49	0.92	0.54	0.62	0.13	0.43	0.49	0.12	0.45	0.50
	std.-dev.	0.61	0.93	0.77	0.64	0.20	0.81	0.73	0.19	0.86	0.77
sub sample 3	min	0.02	0.01	0.02	0	0	0	0	0	0	0
	max	4.07	8.82	11.23	14.84	7.26	48.60	63.21	6.38	44.93	67.15
	mean	0.46	0.98	0.54	0.62	0.13	0.43	0.49	0.12	0.44	0.50
	std.-dev.	0.49	0.81	0.74	0.79	0.20	0.81	0.73	0.19	0.5	0.78

6.3.3.3. Calculating the total bedload mass

The amount of bedload mass V_b at the Johnsbach River was calculated using the Bedload Discharge Integrated Calculation Approach (Habersack et al., 2017). Direct measurement devices were used to determine the bedload discharge q_b (kg m^{-1} s^{-1}). By combining geophone data from a plate located directly downstream of the direct measurement devices, geophone calibration could be undertaken (Figure 6.4, bottom left). Using the geophone information of the spatial distribution, the cross-sectional bedload discharge Q_b (kg s^{-1}) could be calculated by integrating the specific bedload discharges q_b over the stream width w_{cs}:

$$\boldsymbol{Q_b = \int_{w_{cs}=1}^{w_{cs}=n} q_b \, dw_{cs}} \qquad (6.3)$$

To determine the total bedload mass V_b, the cross-sectional bedload discharge Q_b was integrated over a specified time period t:

$$\boldsymbol{V_b = \int_{t=1}^{t=n} Q_b \, dt} \qquad (6.4)$$

6.4. Results

6.4.1. Rock wall retreat as sediment input

Sediment input from rock walls was calculated by applying published rock wall retreat rates to the geological setting and the particular types of rock (Figure 6.3A). Volumetric sediment input values were calculated for each slope catchment downslope of rock walls (Figure 6.6). The annual input rates vary between 0 and 340 m^3 yr^{-1} depending on the type of rock, the relevant retreat rate, and the areal amount of bedrock in the slope catchment. High amounts of sediment input correspond with the higher retreat rates of the widespread dolomite bedrock (Figure 6.3A). Nevertheless, the highest rates were calculated for the Dachstein Limestone areas at higher altitudes (in the SE and SW of ZMS) with steep slopes and therefore large bedrock areas.

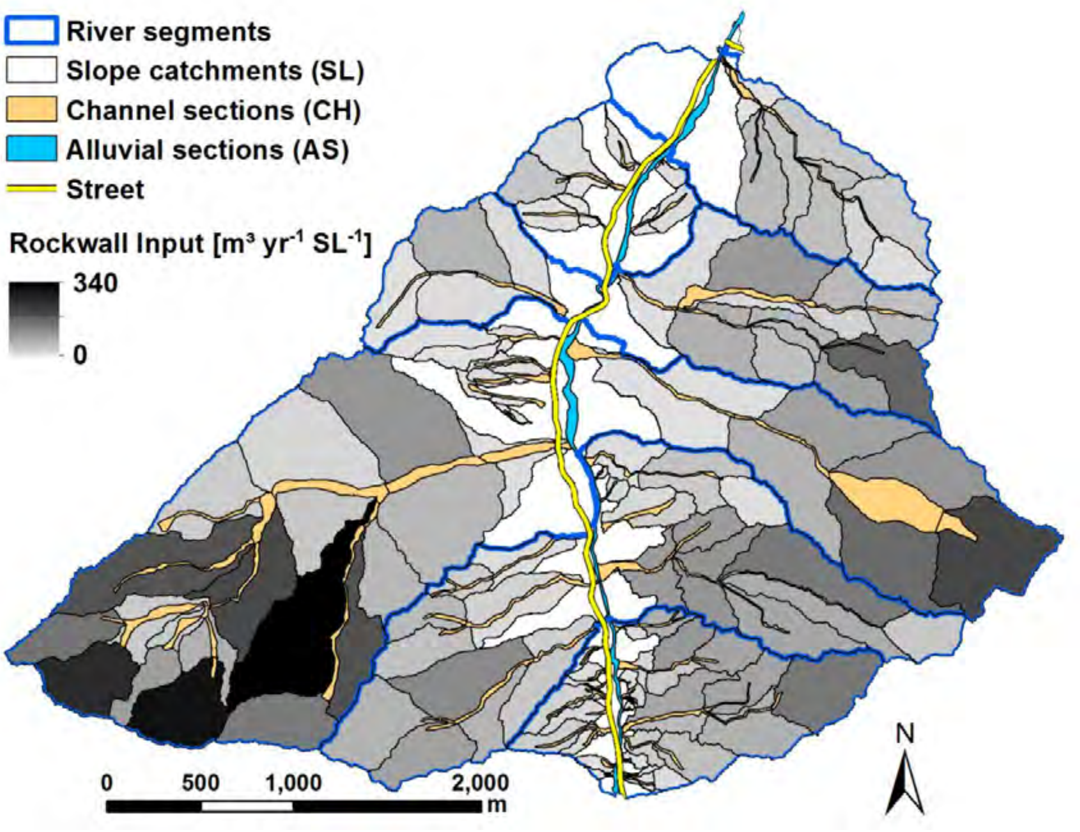


Figure 6.6: *Amount of sediment input through weathering processes from rock walls in the ZMS for each slope catchment.*

6.4.2. DEMs of difference (DoDs)

DoDs (Figures 6.7 to 6.9) for the ZMS (2010-2015, 1 m raster cell size) and for two main side channels (1954-2010, 5 m raster cell size) show the spatial patterns of geomorphic change in the ZMS and the effects of the gravel mining during the period 1954-2010. In the following, the two time periods before (Figures 6.7A and 6.8A) and after 2010 (Figures 6.7B, 6.8B and 6.9) are presented separately.

6.4.2.1. Historic (1954-2010)

At Gseng, mainly erosion (debris removal) prevails especially in the area of former gravel mining (Figure 6.7A). Elevation differences in the affected channel section range from -17.8 to +5.2 m with a mean height change of -8.5 m. The adjacent slope catchments directly involved in the mining experienced elevation changes from

-22.6 to +9.0 m, with a mean of -4.3 m. In the slope catchment closer to the outlet, elevation differences result from the preparation of the surrounding area to set up the former mining factory as well as the piling up of mined gravel (Figure 6.2A bottom). In contrast, the slope catchment above talus cones (Figure 6.2A top) reacts to the excavation of gravel at their footslopes. The remaining channel sections (range = -10.6 to +4.4 m, mean = -1.0 m) and slope catchments (range = -12.1 to +7.6 m, mean = -1.6 m) show, on average, rather small height differences besides some local extremes.

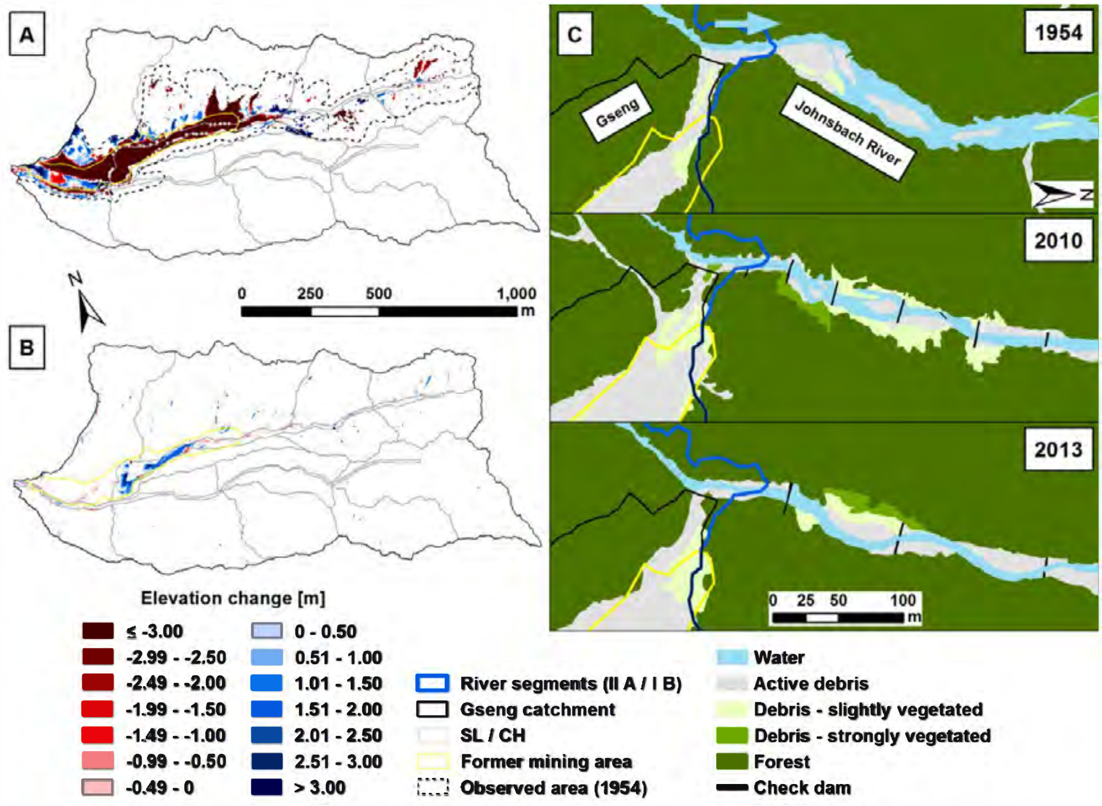


Figure 6.7: ***(Left)*** *DoD maps of the Gseng side catchment:* ***(A)*** *1954-2010;* ***(B)*** *2010-2015. Color scale ranges from red (erosion) to blue (deposition). DoD (1954-2010) was computed within a perimeter (dashed line) that includes areas featuring evidence of gravel mining and (resulting) geomorphic activity via photo interpretation and witness reports.* ***(C)*** *Maps of the Gseng outlet and the adjacent downstream river reach in 1954, 2010 and 2013 (for orientation see Figure 6.9). Note: the blue arrow is indicating the direction of flow.*

In the Langgries side catchment (Figure 6.8A), sequences of erosion and deposition alternate along the channel sections. On average, processes of erosion/removal caused a mean elevation difference of -2.9 m (range = -7.9 to +3.0 m) in the lower parts. Channel sections farther upstream show a slight increase in elevation change (mean = +0.9 m) with peaks from -8.9 to +6.6 m at local extremes. Only those parts of the slope catchments bordering the channel sections are part of the observation area. Elevation changes in these areas range from -9.5 to +14.1 m with extreme values mainly recorded in the rear section of the Langgries catchment with a mean difference of +1.8 m.

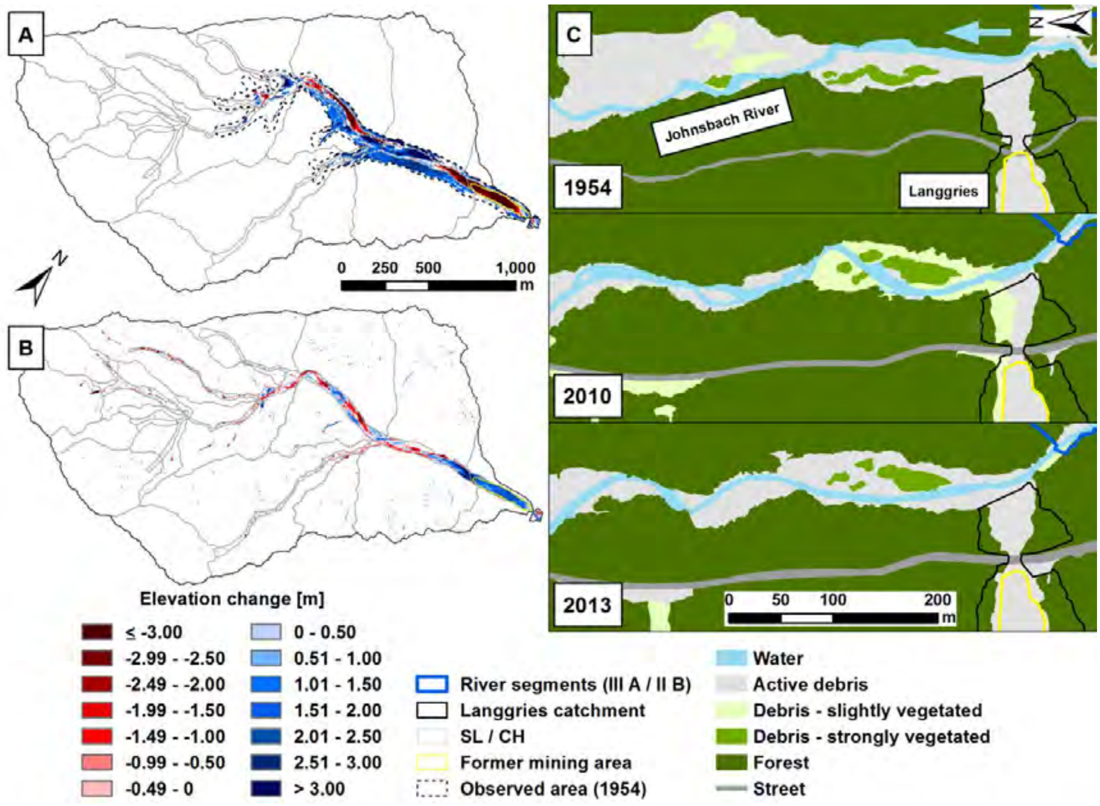


Figure 6.8: (Left) *DoD maps of the Langgries side catchment:* ***(A)*** *1954-2010;* ***(B)*** *2010-2015. Color scale ranges from red (erosion) to blue (deposition). DoD (1954-2010) was computed within a perimeter (dashed line) that includes areas featuring evidence of gravel mining and (resulting) geomorphic activity via photo interpretation and witness reports.* ***(C)*** *Maps of the Langgries outlet and the adjacent downstream river reach in 1954, 2010 and 2013 (for orientation see Figure 6.9). Note: the blue arrow is indicating the direction of flow.*

6.4.2.2. Recent (2010-2015)

Areas of elevation differences (Figure 6.9) are mostly (but not only) limited to channel and alluvial sections during the observation period from 2010 to 2015. Elevation differences in slope catchments occur at smaller spatial scales where small scale processes are reworking debris or rock fall accumulates. Only a few side catchments (e.g., Buckletschneider, Gseng, Kainzenalbl, Kaderalblschütt, and Langgries) show changes of larger extent at some of their slope catchments. The mean height change throughout all slope catchments is -0.5 m, but differences occur focusing on the three segments of the ZMS. Deposition (mean = +0.6 m) prevails in segment III, whereas slope catchments belonging to segments II and I show erosion on average with mean height changes of -0.8 m and -0.7 m, respectively.

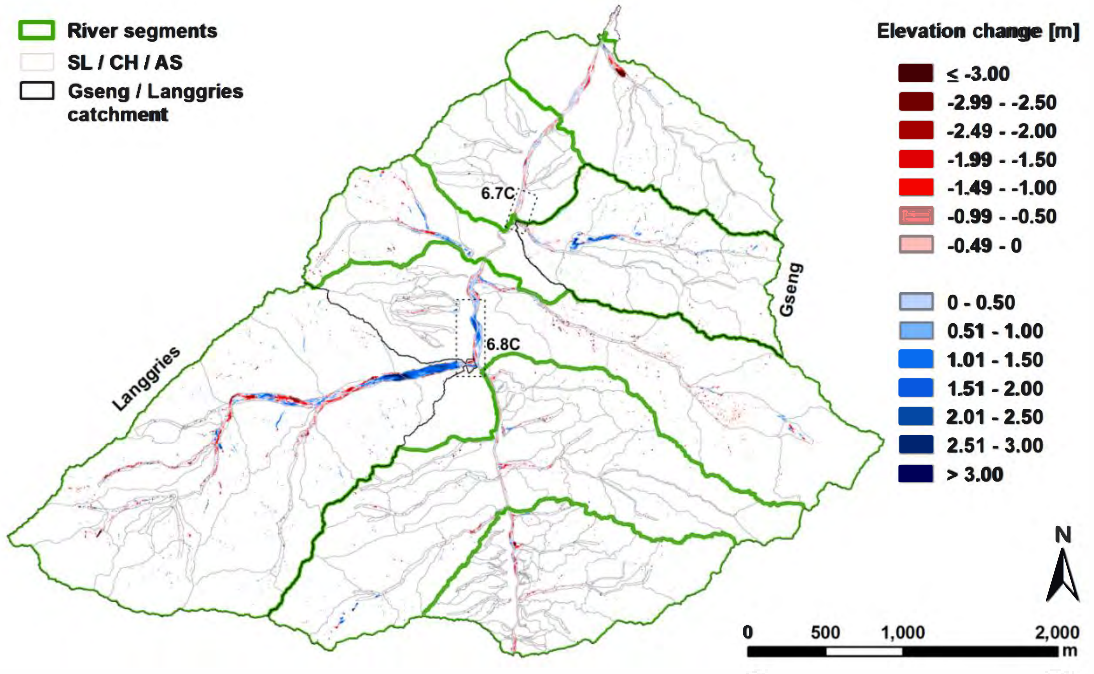


Figure 6.9: *DoD map of the ZMS (2010-2015). Color scale ranges from red (erosion) to blue (deposition). Note: dashed rectangles indicate the positions of Figures 6.7C and 6.8C.*

Elevation changes in channel sections have a larger spatial extent compared to slope catchments. Some of these channel systems inside a side catchment clearly show alternating patterns of erosion and deposition (e.g., Gseng, Kaderalblschütt, Langgries) over longer distances. Predominant erosion can be detected in channel sections mainly on the eastern side of segments I and III with direct access to the fluvial system. Channel sections on the western side (in segments I and III), mainly being barred by the road, show little change in elevation. Mean height changes throughout all channel sections add up to -0.1 m. On average, erosion and deposition seem to cancel each other out. Only channel sections at segment I clearly indicate an average loss in height (mean = -2.2 m), which is however largely influenced by the side catchment in the far north (Humlechner) where sediment has been removed anthropogenically during 2010-2011 (personal communication with NP Gesäuse). Focusing on the two most influential side catchments (Gseng, Figure 6.7B and Langgries, Figure 6.8B), with its channel sections being involved in the gravel mining show a vast area of accumulation. At Gseng these height changes range from -3.3 to +4.4 m (mean = +1.0 m) and are roughly limited to one channel section. The Langgries "conveyor belt" is continuously transporting sediment over a distance of nearly 1.5 km, showing alternating areas of erosion (down to -6.5 m) and deposition (up to +4.4 m), but eventually resulting in an average mean deposition of +0.2 m. In the final section (mainly affected by former mining) height changes range from -3.2 to +4.0 m with an average of +1.5 m.

The alluvial sections of the Johnsbach River are influenced by their neighboring sections and by the side catchments. The two segments III A and III B are characterized by erosion on average (III A: -0.2 m, III B: -0.5 m), with elevation differences ranging from -2.8 to +1.7 m and -7.5 to +1.7 m, respectively. Highest erosion values do usually occur at the edge of the alluvial sections where channel sections intersect with the fluvial system, whereas deposition can generally be detected on the opposite side of those confluences. The alluvial section of segment II B marks the only river reach where mean deposition (+0.4 m) can be assessed covering elevation differences in a range from -5.3 to +3.1 m. Typical fluvial patterns of erosion and deposition can be observed, which develop as the course of the river shifts in its river bed. The next alluvial section in flow direction (II A) hardly shows any elevation change. The last two alluvial sections (river segments I A and I B) are similar in their behavior showing a meandering river course. Both sections are equivalent in terms of their mean elevation change (-0.3 m) and their local extremes (from -2.5 to +1.2 m).

6.4.3. Annual bedload transport

The bedload transport (of the fraction with grain sizes larger than 10 mm) at the Johnsbach River could be computed through the calibration of the geophones for the years 2016 and 2017. As an example, the average daily calculated bedload transport correlated well with measured daily mean water levels in the year 2016

(Figure 6.10A). The annual bedload yield (m³ yr⁻¹) for the years 2016 and 2017 was derived by integrating the bedload transport over the time. The annual bedload yield of the years 2012 to 2015 could also be computed by correlating the water levels with the geophone data (Figure 6.10B). The annual bedload yield of the grain fraction 1 mm to 10 mm was estimated on the basis of the medium particle size distribution from the slot sample measurements. Summing them up for the time period of 2012 to 2017, we determined an average bedload yield of about 6100 m³ yr⁻¹ at the Johnsbach River.

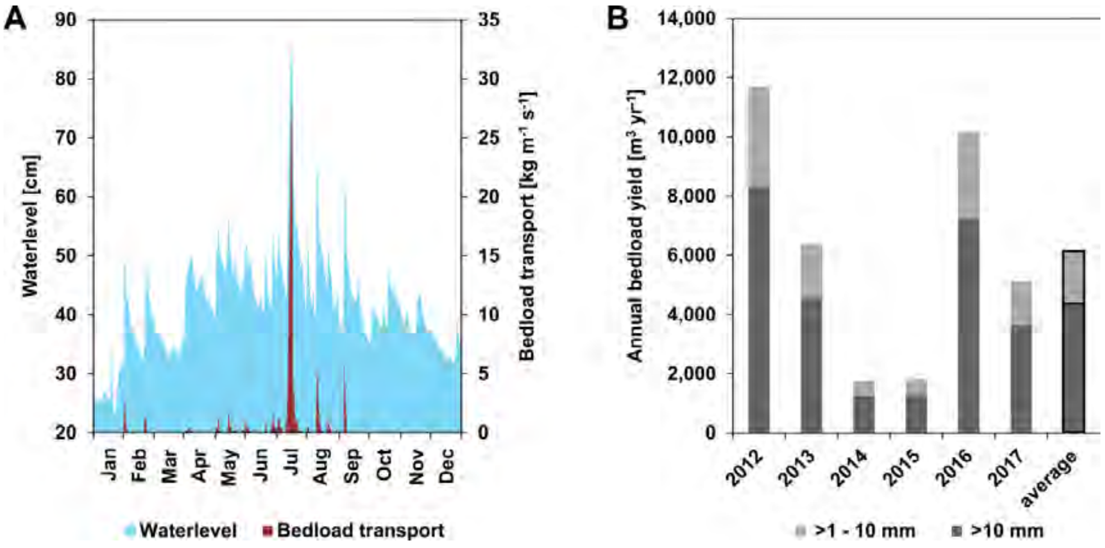


Figure 6.10: ***(A)*** *Water level (blue) and bedload transport (brown) of the Johnsbach River for the year 2016;* ***(B)*** *annual bedload yield at the outlet of the Johnsbach River for the years 2012 to 2017 for two grain size fractions.*

6.5. Discussion

6.5.1. Methodological progress – A new routing approach

Transported sediment volumes were routed along the cascading system chain (bedrock - slope catchment - channel section - alluvial section) in all side catchments and river segments. Sediment input was expected to occur due to rock fall events. Annual input rates were calculated using rock wall retreat rates for different rock types according to the geological setting. These sediment input volumes affect the net volume changes of the adjacent slope catchments (or channel sections and so on) derived from surface differencing. If net erosion prevails, sediment transport is routed farther through the system to the next compartment, for net deposition sediment transport is interrupted. Thus, a final sediment output volume is derived for each side catchment and river segment. As a result, it is possible to capture sediment dynamics from source to sink.

The novelty of the presented work lies in the combination of the sediment cascade investigation with the measurement of the bedload transport at the outlet of the catchment. Numerous qualitative geomorphometric approaches have addressed sediment connectivity (Cavalli et al., 2013) or the analysis of sediment routing (Stangl et al., 2016), but tend to miss the quantification of the sediment dynamics. With our novel routing approach, sediment is quantified and propagated through the system and compared to actual measurements of bedload at the outlet. Furthermore, reconstruction of the former sediment cascade allows the evaluation of historical mining activities as well as their impact on recent sediment dynamics.

6.5.2. Sediment budget scenarios

Three sediment budget scenarios were developed (Figure 6.11): (A) the period before 2010, representing the time of active gravel mining, (B) the time between 2010 and 2015, which reflects the current situation, and (C) a future scenario, assuming that the side catchments affected by mining will be finally coupled to their full extent.

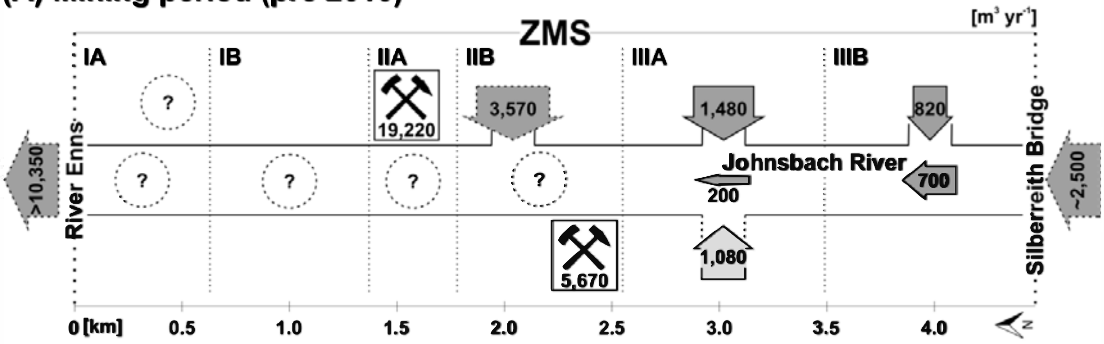
6.5.2.1. Mining period (pre-2010)

During the time of active gravel mining (from 1984 and 1991, for Gseng and Langgries, respectively, to 2008) (Figure 6.11A, Table 6.3) both side catchments were heavily affected. Calculated annual volumes that were excavated can be specified as 19,224 m^3 yr^{-1} at Gseng and 5672 m^3 yr^{-1} at Langgries (Table 6.4). The effects of gravel mining can be detected clearly in the DoD maps (Figures 6.7A and 6.8A). The spatial extent of erosion/excavation corresponds very well with the outline of the former mining activities. Even though the DoD covers a longer period of time, the changes are still remarkable. In the southern part of ZMS (II B to III B), volumes of sediment input from the eastern side channels (in total 5870 m^3 yr^{-1}) as well as net erosion inside the Johnsbach River (in total 900 m^3 yr^{-1}) were assumed to be similar to the DoD of 2010-2015 since we have no observation for these reaches before 2010. The same is valid for sediment input into the ZMS from the catchment area above (~2500 m^3 yr^{-1}), which is provided almost exclusively by a side catchment that is connected directly to the beginning of the ZMS. An estimation of volumetric change in the river reaches downstream of the Langgries side catchment (I A to II B) cannot be made. Since no sediment was delivered by Gseng and Langgries, the main channel has probably eroded the available sediment in the downstream direction leading to a narrowing of the active channel bed that can be seen in Figures 6.7C and 6.8C. Accordingly, the final sediment output might be substantially larger than the estimated 10,350 m^3 yr^{-1}.

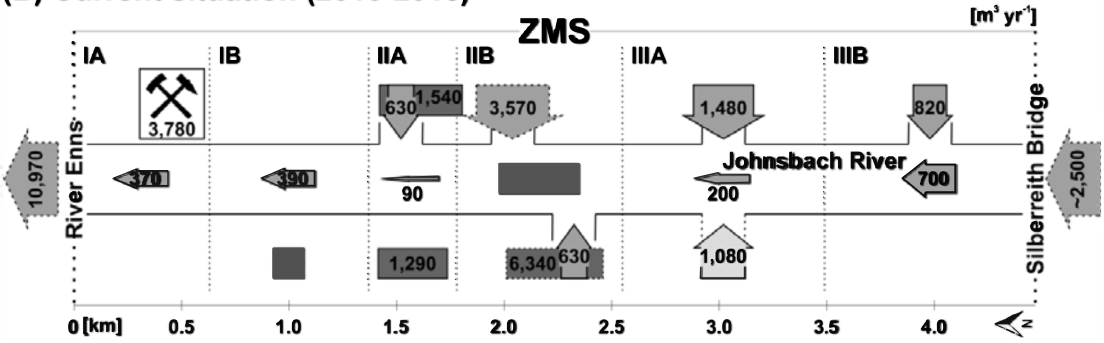
Table 6.3: *Volumetric rates of change (separated between slope catchments and channel sections, values are not propagated and represent the sum of each) and output at Gseng and Langgries side catchment only in the observed area of 1954 (see Figures 6.7 and 6.8 for orientation). Note: time intervals marked (*) present the actual mining period with annual volumetric rates being calculated based on the period 1954-2010.*

Side Catchment	**Slope catchments [m^3 yr^{-1}]**		**Channel sections**		
	Erosion	**Deposition**	**Erosion**	**Deposition**	**Output**
Gseng					
1954-2010	5330	1014	3550	40	8737
2010-2015	1913	1922	663	2605	626
1984-2008*	12,438	2366	8284	93	19,224
Langgries					
1954-2010	222	3078	2175	1571	4622
2010-2015	5662	5218	8169	13,248	629
1991-2008*	733	10,140	7166	5176	5672

(A) Mining period (pre 2010)



(B) Current situation (2010-2015)



(C) Future perspective (2030+)

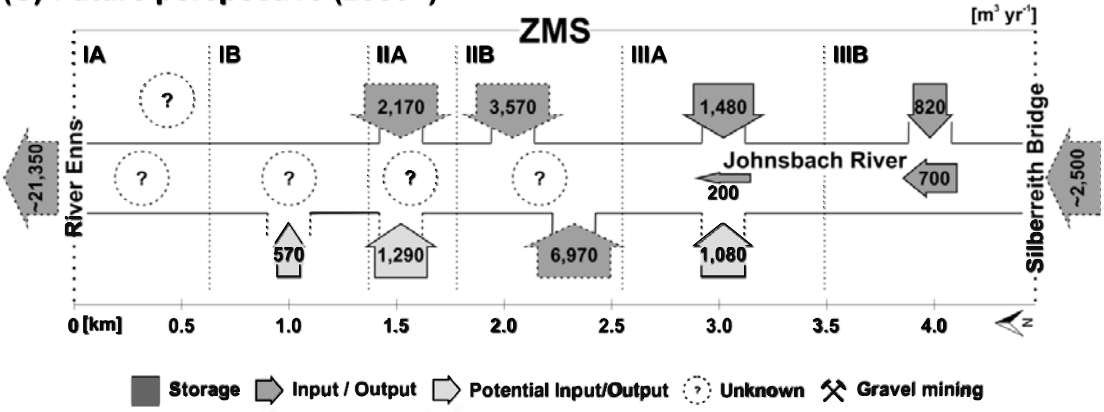


Figure 6.11: *Flow charts of annual sediment budget scenarios along the Johnsbach River between the Silberreith Bridge and the confluence with the River Enns (I A to III B refer to the river segments and reaches as defined in section 6.2.2):* ***(A)*** *time of active gravel mining,* ***(B)*** *2010-2015,* ***(C)*** *future scenario. Note: solid border of box or arrow is for true value/size ratio, dashed border is for untrue.*

6.5.2.2. Current situation (2010 – 2015)

At present (Figure 6.11B), both side catchments experiencing former gravel show sediment output (with 630 $m^3 yr^{-1}$ at each) that directly affects the river reaches downstream from those confluences. Especially downstream of Langgries the river section II B is characterized by area-wide deposition (Figure 6.9) of 1490 $m^3 yr^{-1}$. River reach I B, following the intersection with Gseng, shows a slightly different situation (Figure 6.9 and Figure 6.7C) as net erosion prevails at 390 $m^3 yr^{-1}$. Still there are large amounts of sediment being deposited in the areas formerly influenced by excavation (Figures 6.7B and 6.8B), which sum up to 1540 $m^3 yr^{-1}$ at Gseng and 6340 $m^3 yr^{-1}$ at Langgries (Table 6.4). The southern half of ZMS, similar to pre-2010, shows high input from eastern side catchments and also from the area to the south entering the ZMS. On the western side of the Johnsbach River there are 1080 $m^3 yr^{-1}$ potentially entering section III A from the side catchments Breitschütt, Mitterriegl and Buckletschneider. Due to medium-sized bridge openings it is not certain that the entire amount of sediment makes its way to the main river system. Farther downstream on the western side (sections I B and II A), undersized bridge openings completely block the sediment flow, which leads to deposition of sediment close to the street in orders of magnitude of around 2000 $m^3 yr^{-1}$. At both river reaches in section I (A and B), net erosion occurs with 370 $m^3 yr^{-1}$ and 390 $m^3 yr^{-1}$, respectively. In the northernmost side catchment (Humlechner) connected to river reach I A on the eastern side, 3780 $m^3 yr^{-1}$ were eroded or removed from the area. This loss can be attributed to anthropogenic removal and is therefore not considered in the sediment budget. These observations lead to a current sediment yield of almost 11,000 $m^3 yr^{-1}$ that is being delivered by the Johnsbach Valley to the River Enns. However, bedload monitoring occurring at the outlet of the ZMS reveals an annual bedload yield of 6100 $m^3 yr^{-1}$. Explanations for the discrepancy of these two values can be found in section 6.5.3.

6.5.2.3. Future scenario (2030+)

In a future scenario (Figure 6.11C) with an anthropogenically undisturbed sediment flow, much more sediment will be contributed by the side catchments to the main river system and potentially be washed out of the Johnsbach Valley. Once the side catchments with former gravel excavation (Gseng and Langgries) are fully connected, sediment output rates will rise to ~2200 $m^3 yr^{-1}$ at Gseng and ~7000 m^3

yr^{-1} at Langgries. This will of course take some time since the mining history has caused enormous sinks that have to be refilled. Taking into account how much sediment has been excavated in the past and how fast the sediment bodies in both channel sections are now aggrading, this will take up to 300 years at Gseng and about 15 years at Langgries (Table 6.4). Besides that, several side catchments on the western side of the Johnsbach River (sections I B to III A) could contribute their output material (currently ~3000 m^3 yr^{-1}) to the main fluvial system if access would be enabled by means of wider bridge openings. As the sediment input volumes from the side catchments of the lower ZMS are changing, the adjacent river reaches will certainly react to a currently unknown degree and probably be transformed into a gravel-bed braided river system. Additionally, considering the sediment relocation from the southern half of the ZMS (assuming similar magnitudes as today), the total sediment output would likely increase to as much as 21,000 m^3 yr^{-1}.

Table 6.4: *Gravel excavation capacities and sediment delivery of the former mining areas in Gseng and Langgries. Note: *: propagated volume in the former mining areas.*

	Gseng	**Langgries**
Mining area [m^2]	58,600	16,400
Mining period (1984/91 - 2008)		
Total excavated volume [m^3]	461,300	96,400
Years of excavation	24	17
Annual excavated volume (AEV) [m^3 yr^{-1}]	19,220	5670
Excavation rate [m^3 m^{-2} yr^{-1}]	0.33	0.35
Current situation (2010 - 2015)		
Total deposited volume [m^3]	7700	31,700
Years of observation	5	5
Annual deposited volume (ADV) [m^3 yr^{-1}]*	1540	6340
Replenishment rate [m^3 m^{-2} yr^{-1}]	0.03	0.39
Future scenario		
Recovery ratio (AEV/ADV)	12.5	0.9
Years to reach a balanced state	(300)	15

6.5.3. Sources of uncertainty

Constructing a sediment budget is associated with several uncertainties that can arise from comparing measured to predicted amounts of sediment or by making assumptions for longer time periods than covered by the observations.

Since sediment input from rock wall retreat was calculated on the basis of reference values from the literature, there is the potential for uncertainty and spatial inhomogeneity in estimates of rock wall retreat. The latter point is not expected to change the budget significantly as local variations in sediment input are probably attenuated because of the integration in progressively larger units.

The current annual sediment yield at the outlet of the Johnsbach Valley can on the one hand be predicted to be almost 11,000 m^3 yr^{-1} (2010-2015) by the sediment budget model, and on the other hand be measured as ~6000 m^3 yr^{-1} (2012-2017) by the integrative bedload monitoring system. This deviation can result from the different observation periods.

The predicted amounts of excavated sediment at the formerly mined areas are derived from differencing DEMs over a long time period. These volumes are subject to qualitative uncertainties as there is no information available on sediment distributing processes or events during that time span for the study area.

Taking into account the actual area on which sediment was excavated, annual export rates are similar with 0.33 m^3 m^{-2} yr^{-1} and 0.35 m^3 m^{-2} yr^{-1} for Gseng and Langgries, respectively (Table 6.4). Since the mining activities ended, both side channels are reacting to the sediment supplied from upstream. Therefore, the main control on channel response and recovery appears to be the ratio between the former sediment extraction rate and the current replenishment rate (Rinaldi et al., 2005). During the observation period (2010-2015), sediment was deposited in the former mining areas with annual rates of 0.03 m^3 m^{-2} yr^{-1} and 0.39 m^3 m^{-2} yr^{-1} for Gseng and Langgries, respectively (Table 6.4). Assuming a constant rate of recharge, calculated recovery ratios (annual excavated volume divided by annual deposited volume) for Gseng (12.5) and Langgries (0.9) indicate that the time to reach a balanced state will be approximately 300 years (Gseng) and 15 years (Langgries), respectively. However, the current sediment transport direction at Gseng does not appear to follow the former channel as it goes around the area of the former mining factory (Figure 6.7) to converge with the already existing channel

(Figure 6.2A). Thus, it can be assumed that a full connection to the fluvial system will be achieved much sooner than calculated.

6.5.4. Comparison to other catchment budgets

Kondolf (1994) described the procedure of sediment transport connecting zones of erosion and deposition in an idealized watershed using the term conveyor belt. Sediment is being moved in those zones of transport and added and subtracted from temporary storage sites in ways commonly not recognized. Similar findings were also reported by Calle et al. (2017), who observed channel changes in a Mediterranean river reach over a period of almost 70 years following extensive in-stream gravel mining. They explained in detail the evolution at the interplay between gravel excavation and sediment recharge through floods. This trend can be observed in the Johnsbach Valley as well, especially in the Langgries area where sediment transport is now able to connect the sediment production zone to the outlet of the side catchment, thereby re-establishing sediment fluxes that cause significant changes in river reach morphology.

Other sediment budget studies in alpine areas have mainly focused on proglacial zones (e.g., Warburton, 1990) or worked on much longer timescales, preferably in closed settings without sediment export (Mueller, 1999; Hinderer, 2001; Götz et al., 2013) and are, thus, not fully comparable to our approach. Rainato et al. (2017) derived their budget of the Rio Cordon catchment from a monitoring station at the outlet of the catchment only, without regarding sediment fluxes internal to the catchment. Similarly, Hinderer (2001) estimated modern denudation rates from river loads and delta surveys and published catchment-wide denudation rates of 30-360 mm ka^{-1}. Denudation rates for the Johnsbach catchment are well within the range of these values (168 mm ka^{-1} currently and up to 327 mm ka^{-1} in the future). However, taking into account that most of the exported sediment is supplied from the ZMS, as the sediment budget (Figure 6.11) reflects, denudation rates for the ZMS aggregate to 843 mm ka^{-1} currently and 1641 mm ka^{-1} in the future, which confirms this is a highly morphodynamic system.

6.5.5. Morphological changes in mined area

At Langgries, sediment was continuously excavated in the first 300-400 m upstream of the road (Figure 6.8A) resulting in a topographic depression that is being refilled episodically since the end of the mining period. It appears that the over-steepened knickpoint at the upper end of the mining pit has eroded farther upstream since the total length of the depression is much longer than the actual mining area (Figure 6.8B). The current sediment dynamics have been investigated by Rascher and Sass (2017) during a two year observation period showing that although sediment transport varies at different sections along the lower Langgries side channel, there is a clear tendency for refilling the mining gap. The Gseng catchment was affected rather differently by gravel excavation because the lower parts were prepared to set up a factory to process the gravel immediately. The actual sediment mining occurred about 500 m inside the side catchment. While excavating at the footslopes of the talus cones and sheets (Figure 6.7A), retrograde erosion is causing the exhumation of the talus-covered bedrock by continuously refilling the actual working zone. This principle is described by Calle et al. (2017) as floods of different magnitudes reshape formerly mined areas by incising into the fresh sediment exposing cemented alluvium and bedrock. Currently, sediment relocation inside Gseng is limited to the main channel where a constant shift of erosion and deposition occurs (Rascher and Sass, 2017) developing a lobe-shaped sediment front that slowly reclaims the flat area of the former mining factory (Figure 6.7B). Therefore, the current sediment output can only be attributed to the unaffected sub-channel (Figure 6.2A) on the orographic left side of the catchment.

6.5.6. Impact on river morphology

Assuming that the condition in 1954 represents a near-natural situation (Figures 6.7C and 6.8C top), river reaches downstream from the confluences of the Johnsbach River and either Gseng or Langgries show large alluvial plains with active debris and a partially braided river system. During the mining period sediment input from those two side catchments was lacking, resulting in incision of the main river into the available sediments and, subsequently, channel narrowing. Some parts inside the channel gained vegetation cover that stabilized the formerly active debris. This situation culminated around 2010 (Figures 6.7C and 6.8C middle) when active mining was finally prohibited and river restoration measures were showing their impact. Subsequently, both river reaches show aggradation and channel widening again by refilling the missing sediment from the two side catchments (Figures 6.7C and 6.8C bottom). These sequences of river degradation/aggradation and channel narrowing/widening are well known in this context of gravel mining and were already described by many authors in either perennial (e.g., Rinaldi et al., 2005; Rivora et al., 2005; Martín-Vide et al., 2010) or ephemeral river reaches (e.g., Sandecki and Avila, 1997; Downs et al., 2013; Calle et al., 2017) all around the world. For the future it is difficult to predict sediment dynamics, especially in the alluvial sections I A to II B, as this depends on the connectivity of the adjacent side catchments and the associated sediment input rates. On the one hand, sediment is stored adjacent to the road on the western side of the river, which could be made available if the coupling behavior of the corresponding supplying catchments improved. On the other hand, stored sediment was removed from the Humlechner catchment (Section I A) in 2011 because it posed a potential threat to the infrastructure downstream. Therefore, the natural sediment dynamics cannot be fully predicted.

6.5.7. Consequences for river ecology, natural hazards and hydropower

Intensified sediment transport inside the fluvial system was one of the main goals of the river restoration LIFE-project. It will remain for future investigations to determine how this increased bedload will influence habitat creation and fish migration, as considered in the restoration plan; the first investigations by the NPG are encouraging. Moreover, the increased sediment yield will widen the riverbed and thus, put the new reduced river training measures to a test. The additional sediments will considerably impact the mouth of the Johnsbach River into the River Enns and will be recognizable in the dam basin of the hydropower plant some kilometers downstream, causing higher maintenance costs. Sediment availability will not be a limiting factor in the Johnsbach Valley because the ZMS provides large amounts of sediment already, and most certainly if the full connection of the two formerly mined side catchments persists. It remains to be seen how the ZMS will continue to develop ecologically and in terms of extreme events and natural hazards as the entire system is still responding to the renaturation measures.

6.6. Conclusion

During the past 70 years, anthropogenic action in the Johnsbach Valley has interfered with natural sediment dynamics. River engineering measures were installed to protect the local population and infrastructure from flood disasters. Gravel mining in two of the largest side channels was preventing sediment from being delivered to the main fluvial system. The resulting sediment deficiency in the Johnsbach River was one of the main causes leading to river restoration strategies and river management. In the present study sediment dynamics were investigated in the ZMS by use of a sediment budget to characterize the past, present and future sediment flows. The main results can be summarized as follows:

- During the mining period the annual amount of sediment retained was ~25,000 $m^3 yr^{-1}$, which resulted in a deficit of sediment available for refilling in the fluvial system. Nevertheless, with the sediment supply from the undisturbed side catchments in the ZMS (~9500 $m^3 yr^{-1}$) an annual sediment export can be adjusted to ~10,000 $m^3 yr^{-1}$.
- Currently sediment is refilling the sinks resulting from gravel excavation in the Gseng and Langgries side catchments at a rate of ~8000 $m^3 yr^{-1}$. Furthermore, both side channels are again connected to the fluvial system (~1200 $m^3 yr^{-1}$), though not yet to its full extent. Adjacent river reaches are now responding differently to this changed sediment transport behavior leading to a final sediment export of ~11,000 $m^3 yr^{-1}$.
- If in the near future all side channels are coupled to the full extent, increased sediment availability will probably cause sediment relocations and supply to the fluvial system at higher rates. Therefore, sediment transport within the Johnsbach River will increase and could lead to a doubling of the annual sediment output compared to the current situation.
- In addition to the positive effects of increased sediment availability on river restoration, a higher sediment flux could also be evaluated as critical. River managers in the future must be aware of an increased sediment supply to the nearby road as well as to the hydroelectric power plant at the River Enns downstream. Higher costs for maintenance at both would then have to be expected.

Acknowledgements

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Table 6.5: *Alluvial sections with specific parameters and volumetric rates (2010-2015) of sediment input (from the reach above as well as from the adjacent side catchments), storage change and sediment output (to the reach below and at the outlet of the catchment, respectively).*

Alluvial Sections	**Area [m²] plan**	**surface**	**Elevation [m a.s.l.] min**	**max**	**Slope [°] mean**	**Input [m³] annual**	**Erosion**	**Deposition**	**Output**
I A	16,689	17,186	585	591	10	9532	580	209	9903
I B	18,048	18,778	601	628	13	9145	603	216	9532
II A	6057	6782	618	636	27	9051	117	28	9141
II B	29,737	30,839	631	660	12	9917	892	2383	8425
III A	13,279	14,018	652	678	15	5517	306	103	5719
III B	16,008	16,932	676	723	16	3331	965	262	4033

Table 6.6: *Side catchments (grouped into alluvial sections) with specific parameters and volumetric rates (2010-2015) of sediment input (sum of all slope catchments as defined in Fig. 6.6), storage change (divided between slope catchments and channel sections, values are not propagated and represent the sum of each) and sediment output. Note: Bed = bedrock, Veg = vegetation, In = input, Ero = erosion, Dep = deposition, Out = output, SL = slope catchments, CS = channel sections, River = riverside, Connect = connection.*

#	Side catchments	Area		Elevation		Slope	Bed[a]	Veg[b]	In	Ero SL	Dep SL	Ero CS	Dep CS	Out	River	Connect[c]
		[m²]		[m a.s.l.]		[°]	[%]	[%]	[m³]							
		plan	surface	min	max	mean	total	mean	annual							
	I A															
1	Humlechner	704,130	1,183,195	590	1336	60	49	66	248	1247	1079	3231	125	3778	right	Excavation
	I B															
2	Unnamed XI	13,990	36,881	603	932	76	65	25	7	1	7	0	2	0	right	River
3	Amtmanngalgen	22,855	33,399	607	868	53	17	79	2	9	26	6	33	0	left	Street
4	Neuweg	162,495	253,374	610	1027	53	45	59	56	110	105	181	18	234	left	Street
5	Unnamed XII	48,548	76,701	613	931	56	45	75	7	28	29	4	4	4	right	River
6	Unnamed X	63,745	97,951	617	974	55	23	90	3	263	76	157	17	332	left	Street
	II A															
7	Gseng	1,137,886	2,010,926	619	1623	67	58	40	809	2340	2251	676	2652	626	right	River
8	Kaderalblschütt	509,849	710,646	638	1197	51	20	69	84	2590	1114	539	827	1293	left	Street
	II B															
9	Kainzenalbl	1,511,767	2,820,887	636	2334	74	58	48	673	3394	1569	2165	795	3569	right	River
10	Unnamed XIV	131,026	183,491	642	1189	49	12	89	5	289	68	9	5	231	left	Street
11	Langgriesrunse II	32,391	53,671	648	999	64	30	74	4	178	336	12	96	0	left	Street
12	Langgriesrunse I	25,701	39,370	649	1000	60	50	69	6	17	8	172	79	109	left	Street
13	Unnamed XV	23,022	31,235	662	1010	45	27	77	4	58	2	9	28	41	left	Forest
14	Unnamed XVI	7694	10,690	680	842	45	24	64	2	0	0	10	9	3	left	Forest
15	Langgries	3,302,159	6,011,413	652	2251	71	56	44	2352	7646	6506	8847	14,016	629	left	River

	III A															
16	Petergstammplan II	262,325	441,216	655	1346	61	57	66	100	493	235	228	42	544	right	River
17	Unnamed I	2713	6074	657	762	69	67	24	3	1	5	0	1	0	right	River
18	Unnamed III	13,318	23,790	659	825	61	82	25	14	1	1	12	3	23	right	River
19	Petergstammplan I	81,208	140,928	663	1075	65	38	36	44	103	81	334	226	175	right	Forest
20	Breitschütt	118,035	177,898	664	1178	54	28	69	36	421	110	69	79	337	left	Street/River[d]
21	Petergstamm	818,222	1,640,497	669	2164	70	78	41	706	573	824	639	286	916	right	River
22	Mitterriegel	294,617	488,937	671	1431	61	54	59	149	309	246	203	239	199	left	Street/River[d]
23	Buckletschneider	661,448	1,200,644	676	1564	68	73	49	445	1221	1710	447	320	539	left	Street/River[d]
	III B															
24	Bucklet opposite	44,753	134,673	677	1140	79	70	17	87	56	93	83	294	11	right	River
25	Unnamed XVII	8593	13,860	683	903	55	23	85	1	9	31	2	8	0	left	Street
26	Unnamed V	158,426	449,195	686	1359	78	81	19	268	198	590	193	289	178	right	River
27	Unnamed XVIII	12,869	22,149	687	906	63	42	67	6	1	39	1	29	0	left	Street
28	Unnamed XIII	7079	16,137	686	823	75	49	79	4	2	10	0	1	0	right	River
29	Unnamed IV	7633	11,324	689	930	49	74	86	1	0	0	1	3	0	left	Street
30	Fehringerkreuz III	46,740	87,132	692	1135	65	73	54	21	31	16	30	86	0	left	Street
31	Unnamed VI	8826	20,666	689	855	73	70	21	13	11	2	32	8	46	right	River
32	Unnamed VIII	1350	2951	689	798	72	48	11	2	0	0	0	2	0	right	River
33	Fehringerkreuz II	26,578	47,931	694	1056	63	83	59	17	4	22	8	14	0	left	Street
34	Unnamed VII	2214	4517	690	796	72	51	37	2	0	2	0	1	0	right	River
35	Fehringerkreuz I	60,426	120,177	699	1174	73	78	49	39	58	30	69	68	68	left	Street
36	Roteneder	483,155	1,077,723	695	1818	74	83	39	480	454	922	348	120	500	right	River
37	Unnamed IX	100,787	204,295	696	1222	69	85	40	86	132	263	30	53	66	right	River
38	Straussenalbl I	8311	17,577	700	890	67	85	51	6	3	6	25	6	22	right	River
39	Unnamed II	17,137	37,014	706	946	74	70	69	2	5	16	1	0	2	left	River
40	Straussenalbl II	3897	7079	710	954	61	78	39	1	0	1	7	5	1	right	Street
41	Straussenalbl III	27,924	63,984	708	1078	77	69	38	9	19	57	13	17	0	right	River

[a]: in percent of total area / [b]: mean degree of vegetation cover / [c]: defines the sink of sediment output / [d]: uncertain due to undersized bridge openings.

PART C

enhancements until "SedInConnect: a stand-alone, free and open source tool for the assessment of sediment connectivity" (Crema and Cavalli, 2018) has been released. Cavalli et al. (2019) summarized many of those studies using the IC in different settings as well as at various spatial and temporal scales. In the case of the present study (Stangl et al., 2016) the IC model helped to understand the sediment pathways inside the catchment and to define the main areas of erosion and their connection to the fluvial system (Figure 4.10). However, since connectivity itself and the way of evaluating it qualitatively and (semi-) quantitatively has been of major interest during the last years a lot of different indices of sediment connectivity (in terms of evaluation and application) appeared for use in geomorphology and related disciplines (Heckmann et al., 2018).

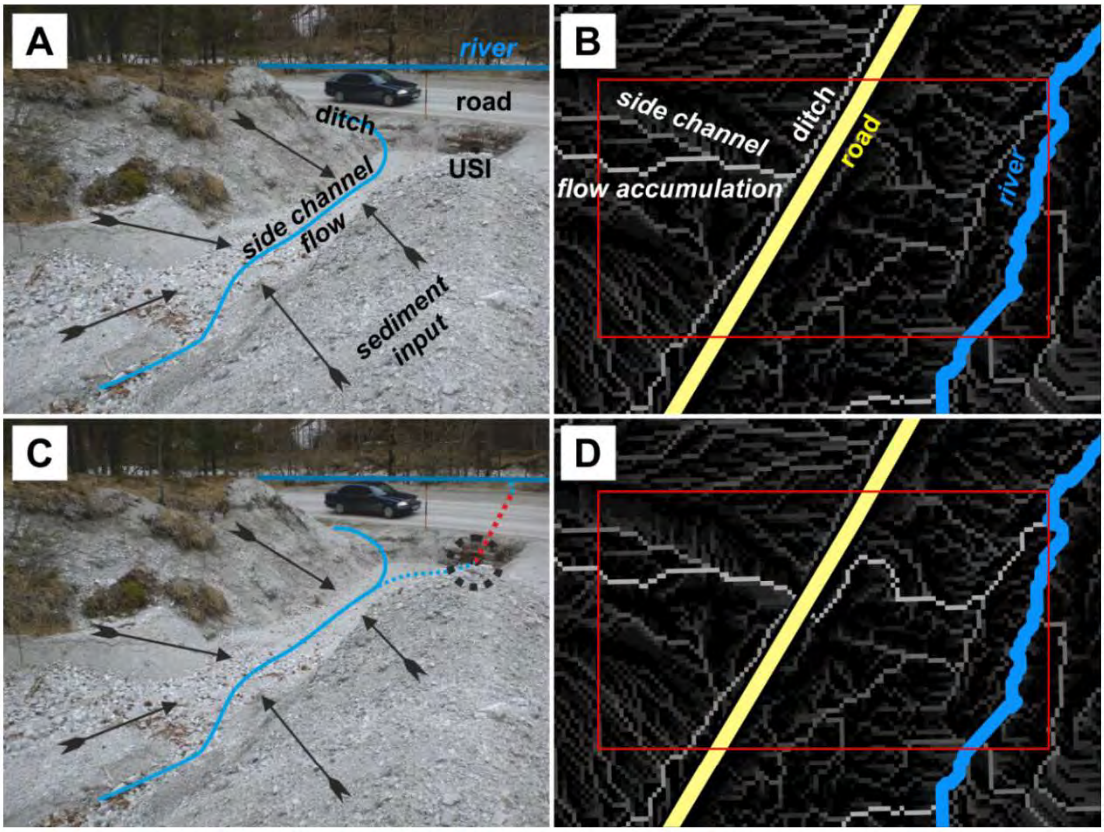

Figure 7.1: *Flow scenario in a side channel in the Johnsbach Valley.* ***(A)*** *Real situation with no use of USI;* ***(B)*** *flow accumulation with no use of USI;* ***(C)*** *real situation with use of USI;* ***(D)*** *flow accumulation with use of USI. Note: USI = underground stormwater infrastructure.*

In chapter 5 ("Evaluating sediment dynamics in tributary trenches in an alpine catchment (Johnsbach Valley, Austria) using multi-temporal terrestrial laser scanning") an investigation is introduced which focuses on linkages of landscape units by sediment transport. Multi-temporal TLS data was used to produce high-resolution DEMs to derive seasonal patterns of sediment dynamics at the junction from tributary trenches to the main river system. Therefore, the degree of coupling between both compartments can be assessed. For error estimation of the TLS data, and further managing DEM uncertainties, a minimum LoD value was derived for each raster cell. Using this approach a spatially distributed error for each investigation period was achieved. This well-established work flow (Vericat et al., 2017) has been widely applied in geomorphological change detection (e.g. Milan et al., 2011; Milan, 2012; Eltner et al., 2015; James et al., 2017; Pasternack and Wyrick, 2017).

In order to recognize seasonal variations in sediment dynamics, suitable periods of investigation have to be set. However, it often is not easy to ensure this consistency in the surveys due to a variety of circumstances, e.g. logistics in equipment and manpower availability, longer travel distances and sometimes in combination with that unexpected weather conditions. Therefore, summer and winter periods, with a uniform separation, are not available. Another fact that is closely related to that, involves the temporal development of the sediment yield. Rascher and Sass (2017) have argued that more surveys in between a defined observation period could lead to a higher amount of sediment being noticeably relocated. In turn, this means having a longer time period between surveys could increase the amount of "missing" sediment (Figure 5.8). This is an important and challenging approach which has to be taken care of particularly in systems where erosion and sedimentation takes place simultaneously and side by side.

The third survey in chapter 6 ("Impacts of gravel mining and renaturation measures on the sediment flux and budget in an alpine catchment (Johnsbach Valley, Austria)") follows an interdisciplinary and multi-method approach. The aim was to describe the recent sediment dynamics and budget of the Johnsbach Valley with respect to anthropogenic actions of the past. To do so a workflow was developed (Figure 6.4) dividing the area of interest (this study: ZMS) in sequential sections (section 6.2.2) and determining change detection at each stage of the sediment budget. A sediment routing approach was used to evaluate the sediment dynamics starting at the source areas (rock walls) and following the sediment to the "final" sink (this study: the outlet of the Johnsbach Valley). At this point bedload measurements were used to evaluate the predicted output.

In general, methodological sources of uncertainty have already been summarized in section 6.5.3. Since all stages of the sediment budget request different methods, and therefore different ways in gathering and evaluating data, discrepancies between modeled and measured results can occur to some extent. However, the applied sediment routing model represents a novel approach in tracing sediments through a system. Besides stand-alone sediment routing models (e.g. Rickenmann et al., 2006), with specific input variables, the presented approach is coupling various possibilities in collecting information about sediment dynamics and morphological change for the whole catchment. Similar studies in sediment routing did exclude the slope component and were focused on the fluvial system (Gran and Czuba, 2017; Walley et al., 2018) or on specific geomorphological units and sequences (Chapuis et al., 2015; Vericat et al., 2017).

7.2. Résumé with regards to research questions

The overarching goal of this thesis is to describe the recent sediment dynamics in unglaciated alpine catchments in which anthropogenic and environmental change occurred in the past. Therefore, the Johnsbach Valley (Austria), in which extensive interventions have taken place with a significant impact on the sediment fluxes during the last decades, was chosen exemplary to overcome this issue. The research questions of this thesis will be discussed in the following by referring to the results of the previously presented investigations and manuscripts.

(1) *Can we infer patterns of sediment connectivity and (sedimentary) coupling effects between different morphological compartments?*

Stangl et al. (2016) have exemplarily shown in two unglaciated alpine catchments how the sediment connectivity routing has changed if anthropogenic structures were eliminated from an ALS DEM data base and adapted to the current status, respectively, if they are not presented accordingly (Figure 4.6). Obviously, there is an effect on the flow accumulation, and therefore on the implied sediment flux as well, if man-made structures are considered or discarded. Some examples of human biased changes in the landscape are obstructions, dams and roads that can cause a restricted connectivity and a shift in coupling between different units. In Figure 7.2 two examples of the IC analysis are extracted for the ZMS showing the impact of transportation routes on the sediment transfer. If these barriers are adjusted in a suitable way (e.g. road passages) a "nearly natural" sediment flux can still be guaranteed.

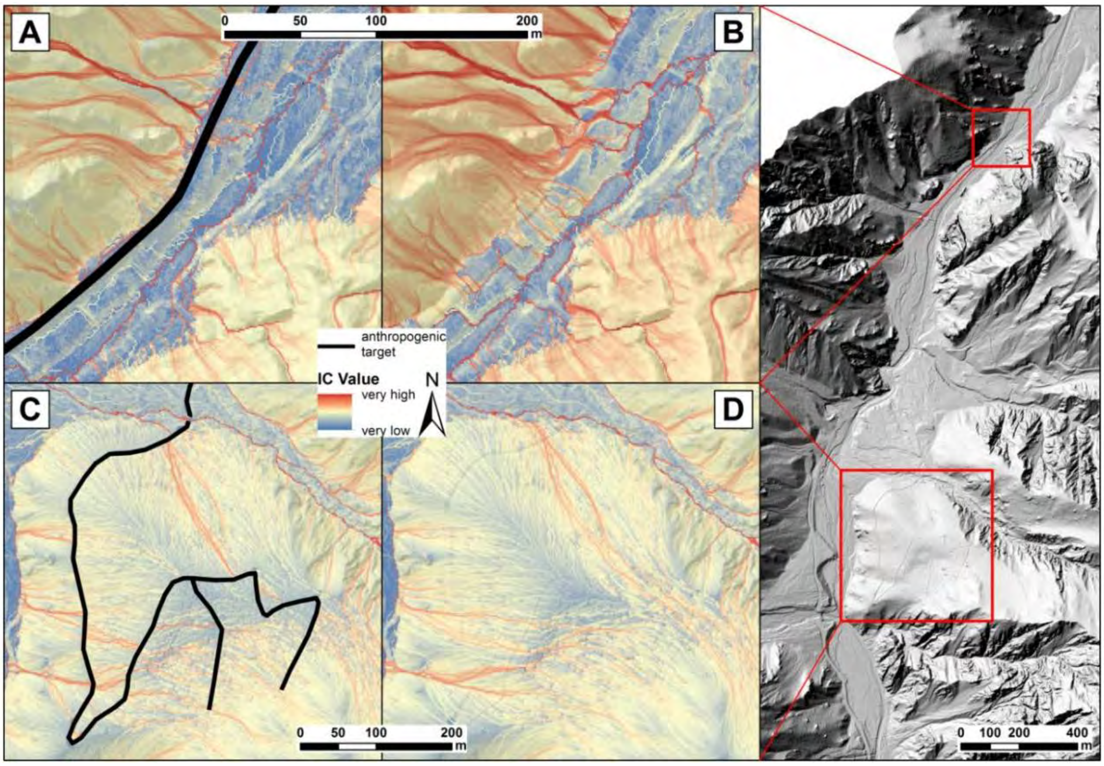

Figure 7.2: *Scenarios of IC routing in the ZMS, Johnsbach Valley with respect to the human impact. The locations of A-D can be specified in the overview (hillshade of the ZMS) on the right side. The impact of the main street in sediment routing to the Johnsbach River (comparable with Figure 7.1) is shown in* ***A*** *and* ***B****; how forest roads are affecting the sediment flow on the slopes is shown in* ***C*** *and* ***D****.* ***(A/C)*** *Routing with the original ALS data;* ***(B/D)*** *routing with the near-natural-DEM, as explained in chapter 4.*

The IC is though based on a hydrological component using ArcGIS routines and implies and displays sediment dynamics on fluvial pathways. However, since most of the transported sediment in the investigated catchment is moved as a component of the fluvial or semi-fluvial load the IC model is an option to understand the sediment fluxes on a catchment scale. Therefore, it is a useful tool to quickly demonstrate which areas in a catchment seem to be coupled to others and how connectivity can be deflected. To further investigate actual coupling of e.g. slope to channel in situ measurements on smaller scales are helpful for verification compared to this rather theoretical approach (IC) on sediment connectivity.

In chapter 5 three locations inside the ZMS were used to demonstrate how the sediment flow is connected between different geomorphological units. The connection of the slope to the main river channel is exemplified with the side channel Unnamed V (Figure 5.4). How sediment is almost exclusively being passed along a side channel can be seen at the Langgries site (Figure 5.5) whereas the impact of the adjacent slopes to the main transportation route inside the side channel is demonstrated at the Gseng site (Figure 5.6). The latter two have been suffering from extensive sediment mining during the past decades. However, after stopping the mining activities, they recently show an active sediment transport behavior depending on the different seasons. Locations of erosion and deposition are altering throughout all sections implying a certain sediment flux in-between the investigated area. Schöttl et al. (2018) have shown scenarios at Langgries where overland flow is carving different terrace levels into the deposited sediments which are then relocated through time (see appendix). Likewise, a connection between the slope and the main channel can be assumed at Unnamed V during the investigation period. As the river erodes at the foot-slope of the side channel sediment is being passed on downslope replenishing the resultant gaps.

The Johnsbach Valley clearly shows a sedimentary flow connection from the source areas to the final conveyor belt (the main river system) and further to the outlet. This is especially evident considering shorter time periods (up to a couple of years) as the calcareous bedrock structures in the ZMS are subject to more intense weathering than the silicate bedrocks from the rest of the Johnsbach Valley. In contrast, anthropogenic disturbances are rather a sign of interruption of the sediment flow. Though, this disturbed sediment flux has recently passed due to several actions and restoration measures concerning a more sufficient sediment flow.

The assessment of sediment connectivity and coupling effects between different morphological compartments is very essential for evaluating sediment dynamics inside a catchment. These characteristics show the linkages between sediment source and sink areas and are of fundamental importance for a qualitative sediment management especially in populated alpine areas.

(2) What can the sediment budget tell us about the internal sediment dynamics and the spatial and temporal variations?

Sediment budgets describe the input, storage, transport and output of sediment in a geomorphic system. Using the knowledge of connectivity and coupling behavior of different compartments inside a catchment, a sediment budget flow model can be achieved. Spatial and temporal changes of the sediment budget are depending on the methods of data assessment and its accuracy. In turn, this leads to the assumption that small-scale investigations with high-resolution data allow much more accurate predictions in sediment budgeting. However, questions concerning budgeting approaches in alpine areas are usually application-oriented and aim at larger scales, typically covering whole river catchments. In this context, sediment budgets play an important role illustrating shifts due to seasonal changes, variations following extreme precipitation events or after (external) perturbations in the system itself. Chapter 6 describes such an issue in which the sediment flux inside the ZMS, Johnsbach Valley, was investigated following the impact of extensive gravel mining and renaturation measures during the past decades. Knowing the history of the ZMS (described in detail in chapter 3) it seems obvious, that the sediment dynamics in this part of the Johnsbach Valley were not uniform over a long time period. This is, of course, *a* result of the anthropogenic disruptions the ZMS was exposed to since the early 1950s.

The sediment budget along the Johnsbach River (Figure 6.11) has been specified for three different periods and classified spatially in six alluvial sections (IA to IIIB) with its adjacent slope areas. This approach allows differentiating the internal sediment dynamics in space and time (for similar approaches see e.g. Brewer and Passmore, 2002; Fuller et al., 2003; Erwin et al., 2012) compared to other budget approaches which e.g. quantify the sediment dynamics of different geomorphological processes to a total flux value in a certain area (e.g. Roberts and Church, 1986; Beylich, 2008; Beylich and Kneisel, 2009). As previously lined out, the resolution of the sediment budget determines the amount of information one can extract to describe the sediment flow. The current sediment budget of the ZMS (Figure 6.11B) clearly shows how specific areas in the whole river reach are contributing to the total sediment flux. Accordingly, the sediment budget distinguishes between input (through the slope areas to both sides of the main river and from upstream), transport (in the Johnsbach River) and storage (at different spots inside the fluvial system of the main river and in side-channel-systems), and output (from the

Johnsbach River into the River Enns), as already delineated in the beginning of this section. Using the associated quantities of sediment for each river reach helps to understand how the system (ZMS) works.

The overall interpretation of the sediment budget has been presented in section 6.5.2. However, using this particular case as a general example for alpine catchments, this sediment budget shows primarily that sediment is transported in the fluvial system at different quantities per reach. The total section is fed from upstream and further transports this matter by simultaneous input from adjacent slopes. Inside the fluvial system sediment is eroded and (re)deposited, depending on geomorphological structures, leading to an altering amount of sediment in transport and in deposition. At the side channels and slopes sediment is provided from rock walls via weathering and erosion at different quantities. The sediment is transported downhill and finally added to the main river system which leads to changing values (of sediment flow) as well. In contrast, sediment is stored at some side channels at relatively large quantities. Finally, a certain amount of sediment is exported from the system. Concerning the spatial interpretation of a sediment budget it indirectly displays the basic settings of the catchment: e.g. geologic structures, storage types and sediment availability, vegetation cover, local meteorological phenomena. The temporal variations in sediment budgets need to be addressed via multi-temporal measurements and information about interventions and shifts inside the catchment and future predictions, respectively.

At the ZMS two main side channels currently store most of its sediment in anthropogenically induced sinks as a result of the gravel mining activities during the past years. Today only a small amount of sediment is making its way into the fluvial system. If, at some point, these two side channels will be fully connected to the rest of the system the total amount of sediment in motion in the ZMS will change significantly as the adjacent river reaches will also be adjusted.

(3) Can we observe the consequences of anthropogenic impact and climate change on the sediment budget and how can both be separated?

In times of intense discussions on the effects of climate change on landscape development it is worth taking a look at the current sediment dynamics in alpine catchments, where change is happening constantly. An accurate definition and allocation of the triggers to those changes would help to understand the future landscape evolution. Taking the Johnsbach Valley as an example a change in sediment dynamics during the last 60 to 70 years is clearly visible (chapter 6). However, to distinguish whether these changes have been caused solely by effects of (constructional) human impact on the natural system or by changes in climatic conditions is hardly possible, as the effects of both on earth surface processes are almost inseparable.

A short digression into global warming and climate change should help to understand the importance of the problem. The IPCC (2014, p. 2-4) stated: "[that] human influence on the climate system is clear, and recent anthropogenic emissions of green-house gases are the highest in history [Figure 7.3]. Recent climate changes have had widespread impacts on human and natural systems." They further point out, that "warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia [...]. Anthropogenic greenhouse gas emissions have increased since the pre-industrial era, driven largely by economic and population growth, and are now higher than ever. This has led to atmospheric concentrations of carbon dioxide, methane and nitrous oxide that are unprecedented in at least the last 800,000 years. Their effects, together with those of other anthropogenic drivers, have been detected throughout the climate system and are extremely likely to have been the dominant cause of the observed warming since the mid-20th century [Figure 7.3]." It is also outlined that "in recent decades, changes in climate have caused impacts on natural and human systems on all continents and across the oceans. Impacts are due to observed climate change, irrespective of its cause, indicating the sensitivity of natural and human systems to changing climate [...]. Changes in many extreme weather and climate events have been observed since about 1950. Some of these changes have been linked to human influences, including a decrease in cold temperature extremes, an increase in warm temperature extremes, an increase in extreme high sea levels and an increase in the number of heavy precipitation events in a number of regions" (IPCC, 2014, p. 6-7).

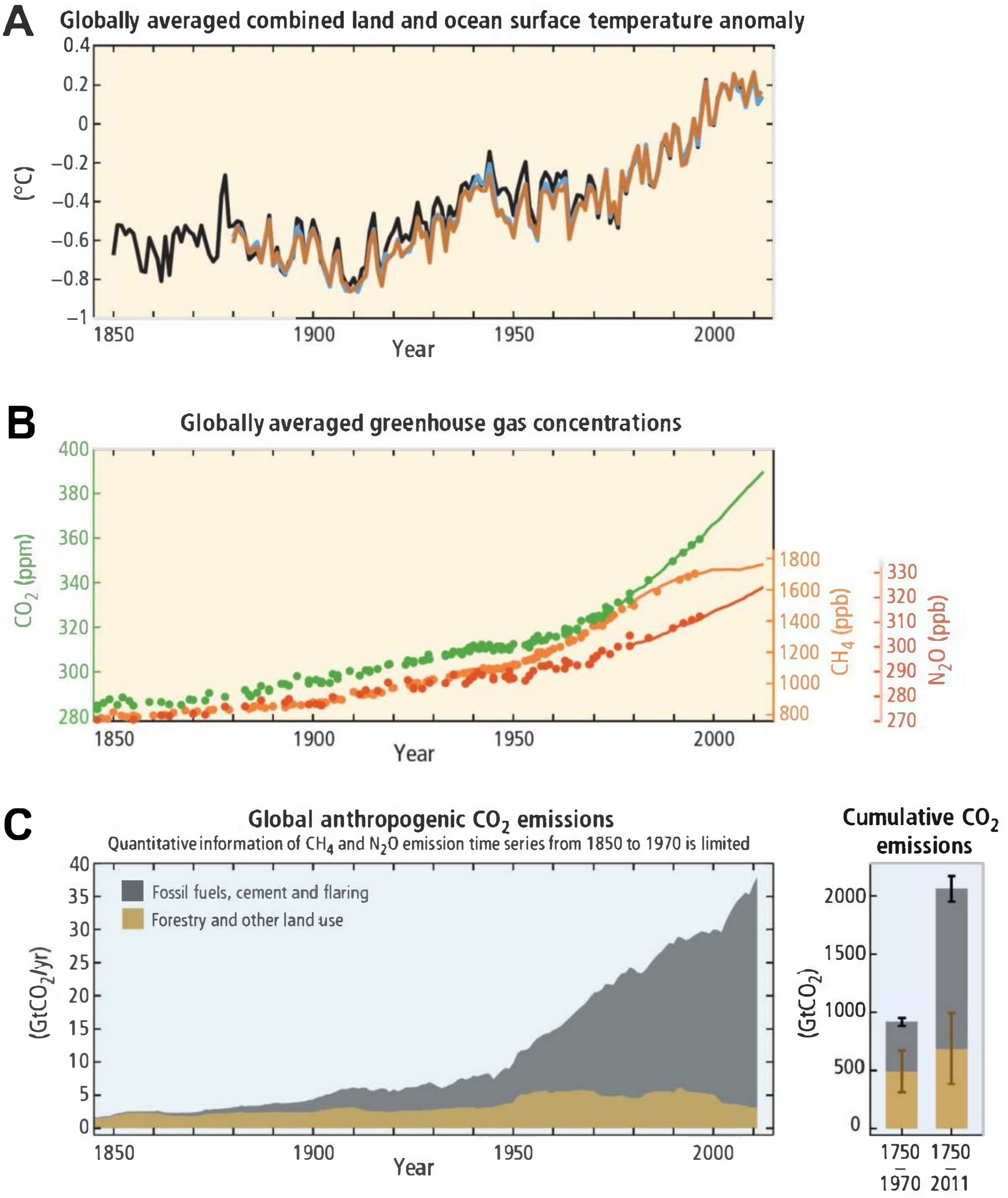

Figure 7.3: *Observations and other indicators of a changing global climate system.* ***(A)*** *Annually and globally averaged combined land and ocean surface temperature anomalies relative to the average over the period 1986 to 2005. Colors indicate different data sets.* ***(B)*** *Atmospheric concentration of the greenhouse gases carbon dioxide (CO_2, green), methane (CH_4, orange) and nitrous oxide (N_2O, red) determined from ice core data (dots) and from direct atmospheric measurements (lines).* ***(C)*** *Global anthropogenic CO_2 emissions from forestry and other land use as well as from burning of fossil fuel, cement production and flaring. Cumulative emissions of CO_2 from these sources and their uncertainties are shown as bars and whiskers, respectively, on the right hand side (after IPCC, 2014).*

The arguments presented above, with several observations and indicators for changing climatic conditions, mainly since 1950, can be translated into causes for shifts in natural systems. Relating to the history of the Johnsbach Valley, which has been investigated for approximately the same period, a changed behavior in sediment dynamics could most certainly be related to changes in climatic forces. However, climate change cannot be the essential reason for the changes in the presented sediment budget. To infer climate change long-term high resolution meteorological data for the ZMS would be necessary which is not available. Even in shorter time periods a clear sign of climate change cannot be assessed (Figure 7.4). Up to this point the human impact in the ZMS is undeniable and apparently the cause of a modified sediment flux.

Infrastructure prevents the sediment from being transported naturally to the fluvial system. Sediment mining in the side channels leads to new sediment sinks, such that a substantial amount of sediment is not being transported further and is missing in the total budget. In the channel obstructions ensured a regulated and direct sediment transport with no interactions leading to an ecologically and sedimentologically disrupted fluvial system. All of these causes interrupt the connectivity and therefore the interplay of sediment deposition and erosion in a natural system. On the contrary, the restoration of the ZMS (which in contrast to its goal still is an anthropogenic impact) had an opposite effect on the sediment dynamics. As man-made structures had to be removed trapped sediment was finally released and natural sediment flow paths were reactivated eventually leading to an undisturbed sediment flux in the near future.

Can climate change actually be detected and what evidence would apply, so that changes in sediment dynamics could be assigned to climate change? A separation of causes simultaneously affecting the same process is barely achievable and rather a problem of system state and theory. Therefore, if one cause can be excluded, the other one can be investigated meaning if the landscape has "recovered" in the future (Table 6.4) changed sediment dynamics can be assigned differently (e.g. to climate change). In that case other changes (next to temperature and precipitation) shoud be detectable as well, e.g. weathering and discharge behavior, adjustment of sediment transport and differences in sediment coupling.

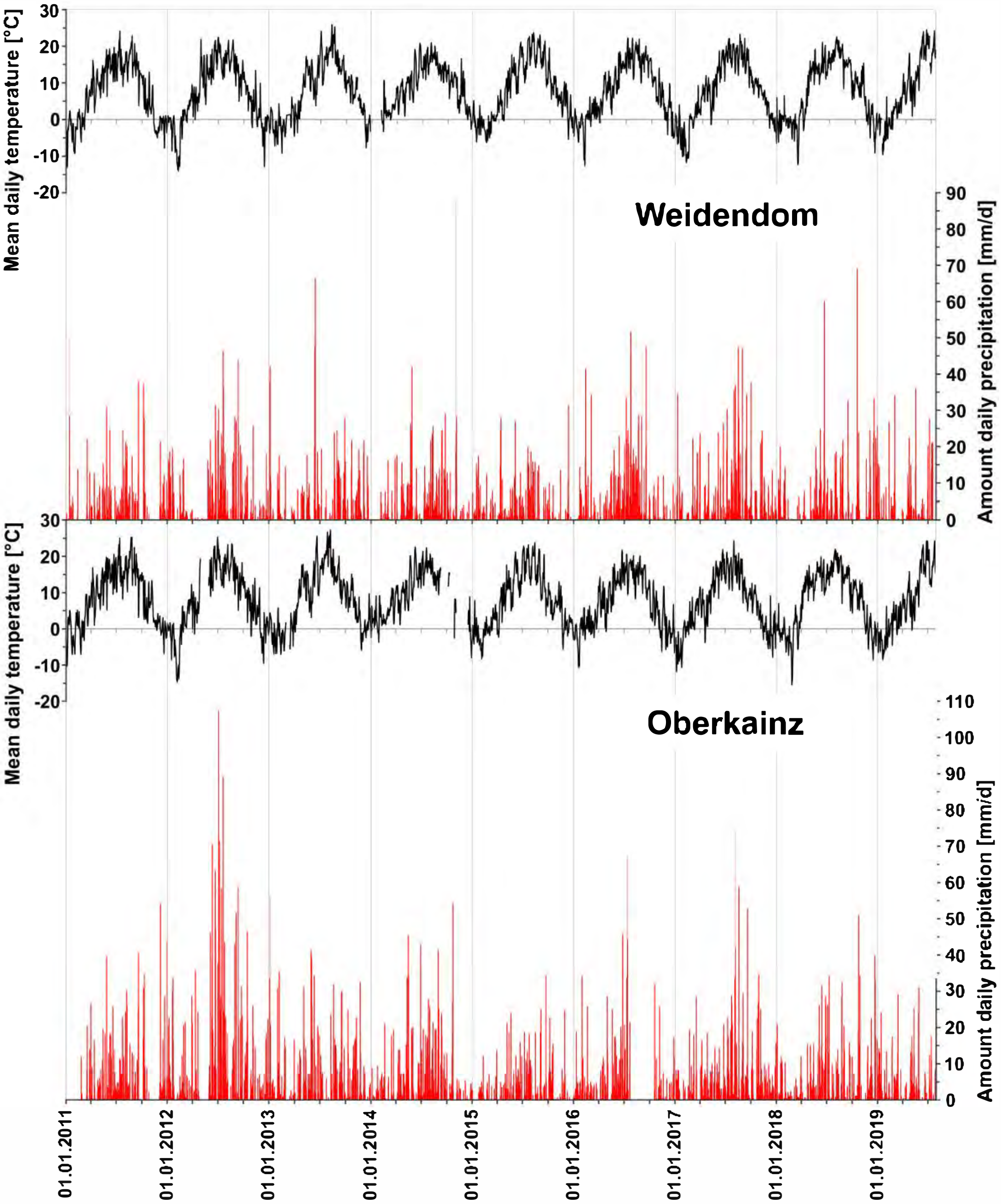

Figure 7.4: *Development of temperature and precipitation in the ZMS for the last decade for two climate stations:* ***(top)*** *Weidendom,* ***(bottom)*** *Oberkainz (for location see Figure 3.1). The black curve represents the mean daily temperatures and the red columns represent the amount of daily precipitation. Note: snow is not considered in the precipitation amounts.*

(4) What are appropriate sediment management strategies concerning the future sediment flux and the related landscape development?

The impact and the effects of climate change on specific catchments or even on process-chains in certain areas in between are ultimately not predictable. Besides rising temperatures, with resulting consequences on glacier melt and permafrost degradation, a changing behavior in the magnitude and frequency of rainstorm events could have a significant impact on sediment connectivity and geomorphological processes (Figure 7.5D). Different scenarios show an increase in precipitation during the winter and a decrease during the summer season (Gobiet et al., 2014), though, Schroeer and Kirchengast (2018) predict a rising intensity of rain storms in the summer. All this might lead to more extreme events in the near future. In addition, the sediment availability is an important factor which is usually responsible for most of the environmental damage and costs. Assuming a limited amount of sediment a rising number of rain storms don't inevitably mean having a higher frequency of harmful debris flows (Figure 7.5A, B). In general, sediment storages on the slopes and in the side channels could be eroded more intensely by more frequent rain storms. Still, a system like the ZMS in the Johnsbach Valley will stay limited due to the weathering potential of the surrounding rock walls (supply limitation). Furthermore, there is no indication suggesting a greater debris production in this area, distant to glaciers and permafrost, especially since frost events tend to be mitigated and a clear tendency for greater moisture penetration is not given (Rode et al., 2016). In the ZMS there is already an enormous amount of sediment deposited on the slopes and in the side-channels though being ready for transport (Figure 7.5C). This high charging stage of the system was achieved by restraining the sediment and keeping it from being washed out during the past decades. Catchments with such high sediment availability and strong coupling effects between source zones and the fluvial system ("rotating conveyor belt", Figure 2.7) could potentially show a strong response to climate change if there is an actual increase in magnitude and frequency of local rain storm events (Figure 7.5D).

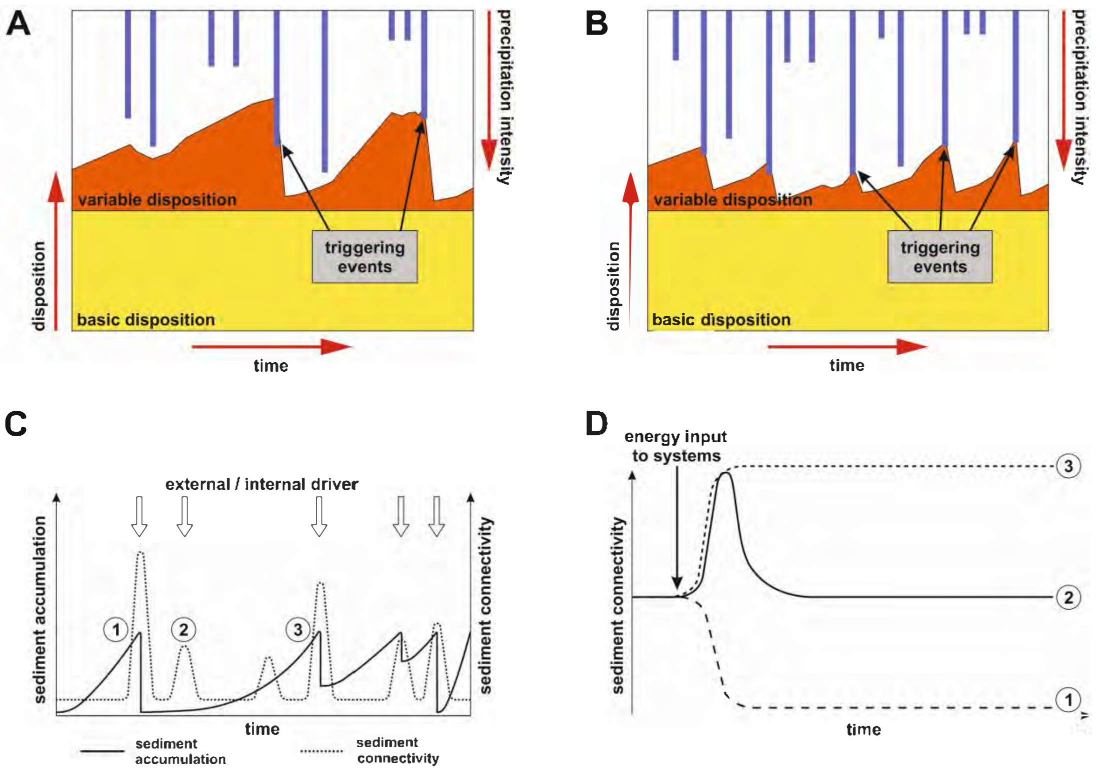

Figure 7.5: Conceptual ideas of system adjustment to future sediment dynamics. ***(A)*** Hypothetical impact of climate change on the release of debris flow events assuming finite sediment resources. Events are only triggered if the system is sufficiently "charged"; ***(B)*** a higher frequency of heavy precipitation events leads to more frequent but smaller debris flows. ***(C)*** The linkage between sediment accumulation and sediment connectivity, and the dependence of the latter on the sequence of previous events. Event (1) produces a significant amount of sediment connectivity because of the extensive sediment accumulation before its occurrence, but event (2), shortly afterwards is limited by the sediment supply. Sediment connectivity is subsequently stronger when accumulation has again reached a suitable level, as in event (3). ***(D)*** The effect of infrequent, high-magnitude events on sediment connectivity: (1) the system may experience a dramatic decrease in sediment connectivity when parts of the system become disconnected; (2) the system may experience a pulse in sediment connectivity as sediment is mobilized and transported during high-energy events, after which sediment connectivity will return more or less to baseline conditions; and (3) the system experiences much stronger subsequent connectivity. Note: A and B are adopted and modified from Zimmermann et al., 1997 and Sass et al. 2019; C and D are adopted from Bracken et al., 2015.

The area of the ZMS in the Johnsbach Valley has been part of the NPG since 2002. The LIFE project (section 3.2.3) was finished in 2011 and ever since the course of the natural development should be ensured and guaranteed in the long term. Areas with characteristic flora and fauna should be preserved and anthropogenically influenced areas should be able to develop into a natural landscape and be promoted where necessary (Holzinger et al., 2012). The requirements and actions for managing the future sediment flux have been summarized by Holzinger et al. (2012) on a legal basis. It also states that the removal of sediment is only allowed for the purpose of ensuring the protection of settlement areas, traffic routes and infrastructure facilities. Further, measures for protection against natural hazards must be carried out such that it requires the least interference with the natural landscape. Furthermore, by ensuring these principles, there will be an enhanced sediment transport during the next years (section 6.5.2.3) leading to changes in the landscape. On the contrary, more sediment in transport will inevitably have an impact at neuralgic spots. These will be mainly the street into the Johnsbach Valley in general and specifically the bridge openings and the underground stormwater infrastructure. Since most of them are technically poor constructed (e.g. too small in size, mounted too low, sharp bend in slope or flattening at the roadway passage) more sediment will be accumulated there. This will potentially lead to more damages and an increased clearing work by the road maintenance service which will store it temporary and will subsequently delivery it to the river. Similar procedures will be approached concerning deadwood as actions will only be allowed at imminent danger.

8. CONCLUSION AND OUTLOOK

Environmental sedimentology has been described by Perry and Taylor (2007) as the new sub-discipline of the earth sciences that focuses on the impact of man and environmental change upon active surface sedimentary systems. As both kinds of implications are often connected to certain extend its effects on earth surface processes are usually inseparable as well. To investigate this issue in mountain regions the ZMS in the Johnsbach Valley has been chosen exemplarily. The valley represents an unglaciated alpine catchment, which often appear less important when it comes to analyzing the impact of climate change on slope and fluvial system processes. The ZMS, a river reach comprising the lower third of the Johnsbach River, is geologically demarcated from the rest of the Johnsbach Valley and therefore has its own character in sediment supply and dynamics. Conditioned by the historical development of the anthropogenic impact in that area combined with future challenges from changing environmental conditions it offers the perfect surroundings to study environmental sedimentology. The main results of this thesis can be summarized as follows:

- Human actions in fluvial systems can either promote (e.g. stream restoration) or constrain (e.g. stream obstruction) sediment transport and can therefore have a major impact on the sediment dynamics in alpine catchments (especially the connectivity and the coupling behavior). This can lead to severe geomorphological and ecological consequences.
- Early interventions in the fluvial systems as well as sediment mining near the source areas led to disturbed sediment fluxes; today's management strategies partially support the idea of restoring a natural sediment flow.
- Variations in environmental conditions due to climate change, e.g. an increase in precipitation anomalies, could lead to tremendous sediment transport if weathered material is provided in sufficient quantities.
- Currently, effects of climate change and anthropogenic impact on the sediment flux in alpine areas are not easily separated, especially when internal sediment dynamics are adapting to restoration strategies and reacting to external forcing at the same time.

In the future it remains to be seen, how the whole system will further develop as several points will have an impact on the sediment flux. The (infrastructural) human impact was reduced as far as possible by establishing the NPG in an area which has been anthropogenically shaped over several decades. By doing so there is the ambition to keep the hands off the system and let the landscape develop itself. However, this seems to be a challenging task as a need for control is essential and certain interventions will be inevitable especially if infrastructure and property has to be protected. Further, the amount of local extreme rainstorm events could potentially rise in the future according to climate change scenarios. This could lead to significant consequences on the sediment flux in this particular area.

Concluding there is a need for continuative, long-term monitoring programs and research especially to observe the evolution of the river restoration measures in combination with the adapting sediment flow. This, in turn, will show, if river restoration has improved the critical management situation on the long term and if a good ecological status of the river has been ensured, as reinforced by the EWFD. An intensified monitoring, especially of the increased sediment flux, could also be of great importance for local stakeholders (e.g. road maintenance service, hydroelectric power station operator). They are usually closely related to changes in sediment transport and would show a huge interest in assessing upcoming hazard possibilities.

This work has been focusing on one specific unglaciated, alpine catchment, explaining in detail how sediment dynamics have been evolving over the past 70 years. However, if temperatures are rising in the near future leading to a thawing cryosphere (e.g. melting glaciers and permafrost), more and more catchments will soon reach a similar status. Therefore, the following questions emerge: What is the current status in sediment dynamics in those areas? How are they already reacting to certain environmental or anthropogenic circumstances? How will these different impact sources affect the future sediment transport processes? What are the effects of an altered sediment transport behavior? An increased research effort and attention should lie in already unglaciated alpine areas because they are examples for future challenges to this specific target. Further, insights into future sediment flux scenarios (in both currently glaciated und unglaciated catchments) are of great importance for the everyday life and the maintenance of infrastructure as almost every alpine catchment is populated to some extent.

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APPENDIX I

SEdiment DYNamik – Xeis: Eine interdisziplinäre Untersuchung zum Sedimenthaushalt im Johnsbachtal

Figure A.1.1: *Die Zwischenmäuerstrecke im Johnsbachtal ist geprägt von vielen sedimentzuliefernden Seitengräben, wie hier in Höhe des Buckletschneidergrabens.*

Sedimenttransport (Sediment: Mischung aus Körnern unterschiedlicher Größe, Form und Beschaffenheit) in Flusssystemen stellt ein wiederkehrendes Problem für geomorphologische Sedimentstrom-Analysen, Naturgefahren-Bewertung, Flussökologie und Flussbau dar. Jede dieser Disziplinen hat eigene Werkzeuge und Modelle zur Erfassung von Sedimenthaushalten. Dadurch ist für ein komplexes Thema wie dieses eine interdisziplinäre Kooperation vonnöten. In dem Projekt Sedyn-X versuchen wir, einen integrativen Ansatz umzusetzen. Unser Ziel ist es, in enger Zusammenarbeit zwischen Geomorphologie (Institut für Geographie und Raumforschung, Universität Graz) und Flussbau (Institut für Wasserwirtschaft, Hydrologie und konstruktiver Wasserbau, Universität für Bodenkultur, Wien), Sedimentmanagement- Strategien für das Johnsbachtal und dessen Einzugsgebiet zu entwickeln. Ein Teil des Johnsbaches wurde in den letzten Jahren unter Aufwendung von hohen Kosten renaturiert. Jedoch sind die gewünschten Effekte dieser Maßnahmen, wie zum Beispiel ein funktionierender Fischaufstieg, möglicherweise durch einen zu niedrigen Sedimenteintrag gefährdet. Zu Beginn des

APPENDIX II

Johnsbach in Bewegung

Figure A.2.1: *Das Johnsbachtal von oben: In den Zwischenmäuern geprägt von mächtigen Schuttströmen aus dem Dolomitfuß der Gesäuseberge (Foto: ZeppCam).*

Das Johnsbachtal

Schotter überall – das mag der erste Eindruck sein, wenn man sich in der „Zwischenmäuerstrecke“, dem von Norden nach Süden verlaufenden Teil des Johnsbachtals, befindet. Die breiten Schuttströme von Langgries- und Gsenggraben und die vielen, teils namenlosen Gräben, die zwischen den bizarren Felstürmen von Ödstein und Reichenstein herabziehen, münden mit Schuttkegeln in den Johnsbach – eine Landschaft, der man die dynamische Veränderung förmlich ansieht.

Dennoch war das Johnsbachtal seit jeher eine Landschaft, die den Menschen anzog. Waren es zuerst die wichtigen Rohstoffe Kupfer und Eisenerz, so folgten bald auch die Holzkohleproduktion und die lebenswichtige Landwirtschaft. Erst sehr spät kamen die ersten Touristen, die den Reiz der Landschaft und der Berge zu ihrer Erholung nutzten. Der hintere Teil des Johnsbachtals mit der Talweitung, in der sich das Siedlungsgebiet zwischen den Kalkwänden im Norden (Hochtorgruppe, 2369 m) und den bewaldeten Rücken der Grauwackenzone im Süden ausdehnt, wurde über

Die Forschungsplattform

Die natürlichen Rahmenbedingungen und die Lage im Nationalpark machen das Johnsbachtal besonders interessant für Monitoring- und Forschungsprojekte. Schon in der Planungsphase des Nationalparks begann die Universität Graz mit Diplomarbeiten und Exkursionen ihre wissenschaftlichen Aktivitäten in diesem Gebiet. Durch die Gründung des Nationalparks und die Zusammenarbeit mit der Fachabteilung Naturschutz & Naturraum der Nationalpark Gesäuse GmbH wurde diese Forschungstätigkeit noch verstärkt und führte schließlich zur Gründung der Interdisziplinären Kooperationsplattform Johnsbachtal im Jahr 2009.

Wie der Name andeutet, stellt diese kein begrenztes Forschungsprojekt, sondern eine offene Initiative dar, die für verschiedene Forschungsaktivitäten einen Rahmen schafft. Dies dient der inter- und transdisziplinären Vernetzung zum Vorteil aller beteiligten Partner, von Wissenschaftlern, Studierenden, lokalen Akteuren und der Bevölkerung vor Ort. Der Startschuss wurde mit Investitionsmitteln der Universität Graz und der Steiermärkischen Landesregierung gegeben, mit denen die notwendige Infrastruktur geschaffen wurde. Diese besteht aus einem Netz von Klimastationen, von welchen die erste – Zinödl – seit 2009 Daten liefert; die Stationen Oberkainz, Schröckalm, Blaseneck und Kölblwiese kamen in den folgenden Jahren hinzu. Dazu kommen die schon seit 2006 bzw. 2008 bestehenden Nationalpark- Stationen Weidendom und Gscheidegg, die Stationen am Tamischbachturm des Lawinenwarndienstes Steiermark, die ZAMG-Station Admont und die Abflussmessstationen Gstatterboden (Hydrographischer Dienst) und Gsengbrücke (Uni Graz). Die Daten der meisten dieser Stationen lassen sich seit 2015 über ein Datenportal in Echtzeit abrufen.

Das Stationsnetzwerk erlaubt die flächenhafte Modellierung z. B. von Temperatur, Strahlung, Wind und Niederschlägen sowie ein Verständnis von hydrologischen Niederschlags-Abfluss-Beziehungen. Karstprozesse stellen eine hydrologische Besonderheit des Gebiets dar – dies lässt sich schon daran feststellen, dass der Johnsbach im Verlauf der Zwischenmäuerstrecke nach ersten Stichtagsmessungen einen erheblichen Teil seines Abflusses an den Untergrund verliert. Ein karsthydrologisches „Gustostück" ist auch die Etzbach- oder Kölblquelle. Deren Schüttung und Chemismus wird in einem Quellmonitoring des Instituts für Erdwissenschaften der Uni Graz untersucht. Aber auch integrative Themen zwischen Natur- und Gesellschaftswissenschaften werden im Johnsbachtal untersucht. So wurde am Institut für Geographie und Raumforschung ein Mensch-Umwelt-Interaktionsmodell der Almwirtschaft erarbeitet, und das Tal ist eines der

Johnsbachtal-Plattform

https://geographie.uni-graz.at/de/forschung/forschungsgruppen/aladyn/projekte/johnsbachtal/uebersicht/

Datenportal

http://www.bogner-lehner.net/xeis_datenportal.php

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APPENDIX III

Der Langgriesgraben - Ein dynamischer Raum im Gesäuse und Gegenstand intensiver Forschung

Figure A.3.1: *Ein Blick in den Langgriesgraben zeigt eindrucksvoll das sich verzweigende Schuttstromnetz, welches wie ein Fließband Sediment von den Felswänden bis zum Johnsbach transportiert.*

Einleitung

Dem aufmerksamen Besucher des Nationalparks ist mit Sicherheit der mächtige Schuttstrom, der aus dem Massiv des Admonter Reichensteins herauszieht und die Johnsbachstraße quert, aufgefallen – der Langgriesgraben. In der Vergangenheit wurde in diesem Seitengraben massiv Schutt entnommen. Heute laufen die Prozesse in diesem dynamischen System vom Menschen ungestört ab; die historische Nutzung beeinflusst jedoch auch heute noch das Geschehen. Unter diesem Blickwinkel wird der Langgriesgraben zu einem sehr interessanten Untersuchungsgebiet für die geomorphologische Forschung.

Woher kommt der ganze Schutt?

Ein lang gestreckter Schutt(Gries-)Strom, das ist der erste Eindruck, wenn man sich den Langgries von der Nähe ansieht. Tatsächlich zählt dieser zu den größten und längsten Schuttrinnen im Gesäuse. Die enormen Schuttmengen sind vor allem auf das vorherrschende Dolomitgestein, welches zu starker, kleinstückiger Verwitterung (Vergrusung) neigt, zurückzuführen. Das Gestein löst sich durch Frostsprengung und andere Verwitterungsprozesse aus den zahlreichen Felswänden im Einzugsgebiet und wird in weiterer Folge von Sturzprozessen, Kriechprozessen, Murgängen und fließendem Wasser, der Schwerkraft folgend, weiter in Richtung Johnsbach transportiert. Der Weg des Sediments (Sediment: Mischung aus Gesteinsbruchstücken unterschiedlicher Größe, Form und Beschaffenheit) von den Felswänden des Reichsteinmassiv in Richtung Johnsbach kann jedoch ein langer sein. Das Sediment kommt oft zunächst am Wandfuß in einer Schutthalde für einige Zeit zum Liegen, in der Geomorphologie spricht man von Zwischenspeichern. Durch eine Mure kann das Sediment dann zum Beispiel in den Hauptgraben transportiert werden und von dort kann es durch oberflächlich fließendes Wasser erneut mobilisiert werden. Ein Prozess greift mit dem nächsten ineinander und wie diese Prozesse miteinander wechselwirken kann sich über die Zeit auch ändern. Wasser ist dabei ein sehr effektives Transportmedium. Wenn man den Langgriesgraben besucht wird man jedoch die meiste Zeit des Jahres vergeblich nach fließendem Wasser suchen. Oberflächenabfluss kann man nur während der Schneeschmelze (typischerweise im Frühjahr) und nach Starkregenereignissen (gehäuft im Sommer) beobachten, es handelt sich somit um ein Gerinne mit episodischer Wasserführung. Die schönen Formen, welche durch das Wasser in Verbindung mit Sediment in der

Figure A.3.2: *Der mächtige Schutt-strom des Langgriesgrabens mit der Reichen-steingruppe im Hintergrund (Foto: D. Kreiner).*

Geländeoberfläche entstehen kann man dadurch jedoch umso besser erkennen. Der Langgriesgraben ist ein geomorphologisch sehr aktiver Raum, welcher sich nach jedem Abflussereignis zumindest teilweise verändert. Die hohe Prozessdynamik ist auch der Grund dafür, dass die aktiven Bereiche völlig frei von Vegetation oder nur spärlich mit Vegetation bedeckt sind.

Figure A.3.3: *Auf dem Weg von der Felswand zum Bach kann das Sediment über lange Zeiträume in Schutthalden (wie hier im Schwarzschiefergraben) zwischengespeichert werden.*

Figure A.3.4: *Ein Blick in den Langgriesgraben während eines starken Regenereignisses. Der Oberflächenabfluss transportiert Sediment und verändert somit die Oberflächenformen (Foto: H. Haseke).*

Figure A.3.5: *Das fließende Wasser modelliert Terrassen unterschiedlicher Niveaus in die lockeren Ablagerungen.*

Figure A.3.6: *Aus der Vogelperspektive (Drohnenaufnahme aus rund 100m Höhe) lassen sich deutlich die fluvialen Formen im Gerinnebett erkennen (Foto: KFU Graz, Institut f. Geo. und Raum.).*

Der Schotterabbau und seine weitreichenden Folgen

Der Langgriesgraben wurde seit 1991, wie auch weitere Areale im Gesäuse (zum Beispiel der Gsenggraben) zur kommerziellen Schotterentnahme genutzt. Bis zum Jahr 2008 wurden im unteren Bereich des Schuttstromes etwa 6000 m^3 pro Jahr (Rascher et al., 2018) abgetragen. Durch die Schotterentnahme erreichte zudem kaum Sediment den Johnsbach. Dies hatte auch Auswirkungen auf die Flussmorphologie im Bach selbst. Ein weiteres Ergebnis dieser menschlichen Aktivität ist, dass die Geländeoberfläche in den Abbaubereichen heute tiefer liegt als dies vor der Nutzung der Fall war. Die Böschungen, welche an das Gerinne angrenzen, sind übersteilt und anfällig gegenüber Erosion. Diese erodierte Material sowie der Nachschub aus dem hinteren Einzugsgebiet des Grabens sorgen dafür, dass die übertieften Bereiche momentan wieder mit Sediment aufgefüllt werden (Rascher und Sass, 2017). Der Transport von Sediment ist meist saisonal verschieden und wird hauptsächlich durch die Schneeschmelze im Frühjahr und die starken Regenereignisse im Sommer begünstigt. In der Zukunft wird dadurch vermutlich auch die Menge des in den Johnsbach eingetragenen Sediments wieder erhöht werden (Rascher et al., 2018). Jedoch ist auch heute noch die Konnektivität (= Durchlässigkeit eines Fließgewässers für Sedimente; Hooke, 2003) vermindert und die natürlichen Verhältnisse stellen sich erst langsam wieder ein. Die Auswirkungen des Schotterabbaus zeigen sich aber nicht nur im Langgriesgraben selbst, sondern werden auch im Johnsbach sichtbar. Im Bachabschnitt, nachdem der Langgries in den Johnsbach mündet, ist deutlich eine Abnahme des Sedimenteintrags zwischen 1954 und 2010 sowie eine Zunahme von 2010 bis 2013 zu erkennen. Die spiegelt sich v.a. in der flächenhaften Ausdehnung des aktiven Schotters wieder. Die großflächig bewachsenen Schotterbänke im Jahr 2010 verdeutlichen, dass bis dahin eine Beeinflussung dieses Bachabschnittes durch den Sedimenteintrag aus dem Langgriesgraben kaum stattgefunden hat.

Figure A.3.7: *Die übersteilte Böschung an der orographisch linken Seite des Langgriesgrabens ist massiv von Erosion betroffen (Foto: S. Schöttl).*

Die Vermessung des Schuttstromes

Figure A.3.8: *Der Schotterabbau dominierte über einen langen Zeitraum die Gestaltung des Langgriesgrabens. Die Auswirkungen werden derzeit auf natürlichem Wege langsam beseitigt (Foto: D. Kreiner).*

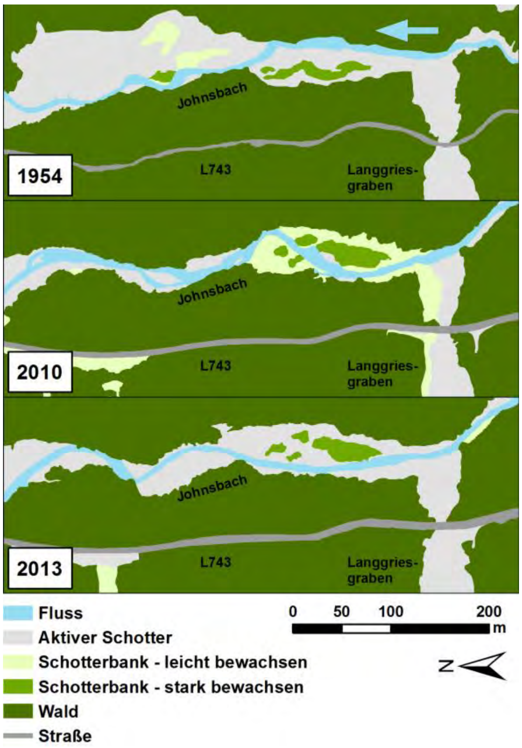

Figure A.3.9: *Entwicklung des Mündungsbereiches des Langgriesgrabens und der sich anschließenden Flusslaufstrecke des Johnsbaches. Der blaue Pfeil markiert die Fließrichtung (Grafik aus: Rascher et al, 2018, verändert).*

Wie kann man nun Veränderungen der Gerinneoberfläche feststellen und diese auch in Zahlen fassen? In Rahmen des vom Österreichischen Forschungs- und Wissenschaftsfonds geförderten Sedyn-X Projektes wurden vom Institut für Geographie und Raumforschung der Uni Graz hierzu verschiedene Methoden eingesetzt. So werden etwa seit 2013 jeweils im Frühjahr nach der Schneeschmelze und im Herbst nach den sommerlichen Starkregenereignissen terrestrische Laserscanaufnahmen vom Unterlauf des Langgriesgraben durchgeführt. Die Messungen sollen dabei vor allem Aufschluss zur aktuellen Sedimentdynamik geben und der Frage nachgehen wieviel Sediment im Mündungsbereich aktuell tatsächlich ankommt. Die Oberfläche wird bei dieser Methode mit einem Laserstrahl abgetastet. Das Ergebnis dieser Messung ist eine Punktwolke

(Millionen von Messpunkten mit bekannten Raumkoordinaten). Im Jahr 2015 wurden im Rahmen einer Masterarbeit Luftbilder des Gerinnes von einem unbemannten Luftfahrzeug aus aufgenommen. Aus den sich stark überlappenden Bildaufnahmen lassen sich mit Methoden der Photogrammetrie ebenfalls Punktwolken ableiten. Aus den Punktwolken werden in beiden Fällen digitale Modelle der Geländeoberfläche berechnet. Im Jahr 2015 wurde zudem im Rahmen des Projekts eine luftgestützte Laserscan Befliegung beauftragt. Für das Jahr 2010 sind ebenfalls solche Daten aus einer Steiermark weiten Befliegung vorhanden. Die Methode ist dabei dem terrestrischen Laserscannen sehr ähnlich; der Scanner befindet sich jedoch hierbei auf einem Hubschrauber oder einem Flugzeug und ist im Vergleich zum terrestrischen Scanner in Bewegung. Für das Jahr 1954 wurden historische, schwarzweiße Luftbilder herangezogen, aus denen ebenfalls mit Methoden der Photogrammetrie Geländemodelle erstellt wurden. Die luftgestützten Laserscan-Geländemodelle und das Oberflächenmodell aus den historischen Luftbildern wurden vor allem dazu verwendet um längerfristige Veränderungen im Gerinne festzustellen.

Figure A.3.10: *Der Terrestrische Laserscanner bei der Arbeit. Der Scanner nimmt dabei pro Sekunde bis zu 11.000 Punkte auf und operiert im Infrarotbereich; der Laserstrahl ist somit für das menschliche Auge nicht sichtbar (Foto: S. Schöttl).*

Durch den Vergleich der Geländemodelle von unterschiedlichen Zeitpunkten können Veränderungen der Geländeoberfläche festgestellt und diese auch quantifiziert werden. Dabei wird das ältere Modell (z.B. 2010) vom jüngeren Modell (z.B. 2015) subtrahiert, so dass ein Differenzmodell entsteht. In diesem Ergebnis lässt sich erkennen, in welchen Bereichen Abtragung (Erosion) und in welchen Bereichen Ablagerung (Akkumulation) stattgefunden hat.

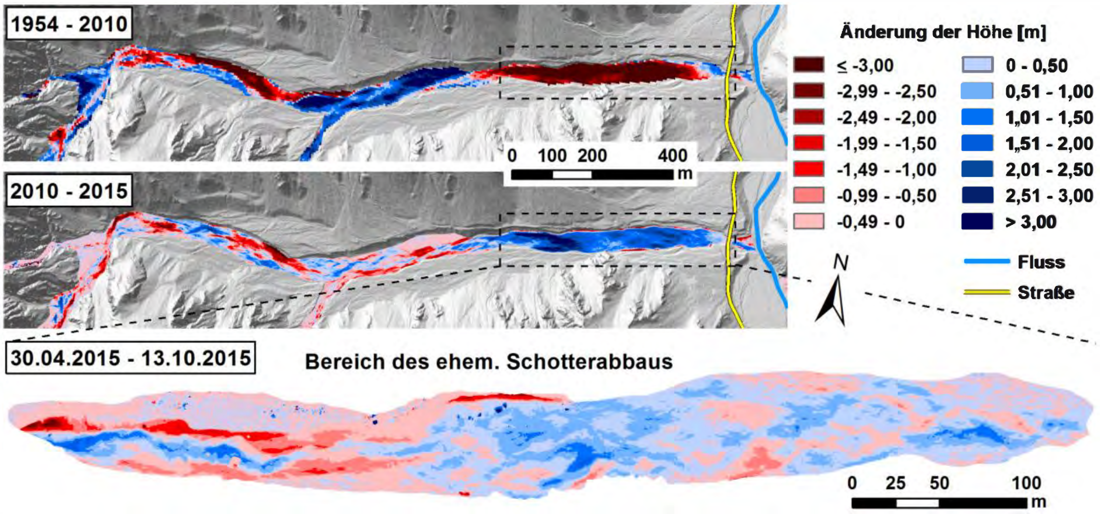

Figure A.3.11: Höhen-Differenzmodelle, berechnet aus luftgestützten und terrestrischen Laserscandaten. Deutlich erkennbar sind die Veränderungen, über längere Zeiträume und auch innerhalb eines halben Jahres, im Bereich des ehemaligen Schotterabbaus. Blaue Bereiche stehen für Ablagerung (Akkumulation von Sediment), rote Bereiche für Abtragung (Erosion von Sediment).

Quellen

Hooke, J., 2003. Coarse sediment connectivity in river channel systems: a conceptual framework and methodology. In: Geomorphology 56, 79–94.

Rascher, E., Sass, O., 2017. Evaluating sediment dynamics in tributary trenches in an alpine catchment (Johnsbachtal, Austria) using multi-temporal terrestrial laser scanning. In: Zeitschrift für Geomorphologie, Supplementary Issues 61(1), 27-52.

Rascher, E., Rindler, R., Habersack, H., Sass, O., 2018. Impacts of gravel mining and renaturation measures on the sediment flux and budget in an alpine catchment (Johnsbach Valley, Austria). In: Geomorphology 318, 404-420.

CURRICULUM VITAE

Eric Rascher

Date of Birth: 17th July 1983
in Karl-Marx-Stadt (today Chemnitz), Germany

Research and Teaching Experience

University of Graz, Austria 05/2013 – 07/2017	**Scientific research assistant** Project: "SEDYN-X - Interdisciplinary sediment flux research in the Johnsbach Valley". Research Group: Alpine Landscape Dynamics (Prof. Dr. Oliver Sass)
University of Graz, Austria 03/2016 – 03/2017	**Lecturer** Field courses on Applied Geomorphology Research Group: Alpine Landscape Dynamics (Prof. Dr. Oliver Sass)
University of Graz, Austria 02/2013 – 04/2013	**Student research assistant** Project: "SEDYN-X - Interdisciplinary sediment flux research in the Johnsbach Valley". Research Group: Alpine Landscape Dynamics (Prof. Dr. Oliver Sass)
Martin Luther University of Halle-Wittenberg, Germany 01/2012 – 09/2012	**Student research assistant** Project: "PROSA - High-resolution measurements of morphodynamics in rapidly changing proglacial Systems of the Alps". Research Group: Geomorphology/Hydrology (Prof. Dr. Karl-Heinz Schmidt)
Martin Luther University of Halle-Wittenberg, Germany 02/2009 – 12/2011	**Student research assistant** Project: "Effects of extreme events on the function of sediment stores and sediment sources, on sediment mobility and transport in an Alpine river system". Research Group: Geomorphology/Hydrology (Prof. Dr. Karl-Heinz Schmidt)

Education

University of Graz, Austria 05/2013 – 01/2020	**Doctorate Studies in Natural Sciences** Thesis: "Environmental sedimentology of mountain regions - Human impact on sediment dynamics in unglaciated alpine catchments (Johnsbach Valley, Austria)" Supervisor: Prof. Dr. Oliver Sass
Martin Luther University of Halle-Wittenberg, Germany 10/2005 – 04/2013	**Study of Geography (Diploma)** Thesis: "Investigating the application of sediment transport formulae in an alpine catchment" Supervisor: Prof. Dr. Karl-Heinz Schmidt
Georgius-Agricola Gymnasium, Chemnitz, Germany 09/1990 - 06/2003	**School (German Abitur)**

Scholarships, Grants & Awards

PhD Scholarship of the University of Graz, May - August 2018.

Travel grant of the Austrian Research Association on Geomorphology and Environmental Change (geomorph.at) for the annual meeting, Johnsbach, Austria, September 28-29, 2017.

Trainee and travel grant of the European Cooperation in Science and Technology (COST) for the COST ACTION ES1306 PhD Training School on "Water and Sediment Connectivity in Mountain Environments", Laas, Italy, July 25-29, 2016.

Trainee and travel grant of the Volkswagen Foundation (German: VW Stiftung) for the Summer School on Geomorphology on "Sediment dynamics in high-mountain environments", Kaunertal, Austria, August 31 - September 6, 2015.

Poster Award of the AK Geomorphologie at the annual meeting, Eichstätt, Germany, October 7-9, 2013.

Travel grant of the AK Geomorphologie for the EGU general assembly, Vienna, Austria, April 22-27, 2012.

LIST OF PUBLICATIONS
(THESIS RELATED)

International peer-reviewed publications:

Rascher, E., Rindler, R., Habersack, H., Sass, O., 2018. Impacts of gravel mining and renaturation measures on the sediment flux and budget in an alpine catchment (Johnsbach Valley, Austria). In: Geomorphology 318, 404-420.

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Stangl, J., Rascher, E., Sass, O., 2016. Comparative analysis of sediment routing in two different alpine catchments. In: Beylich, A.A., Dixon, J.C., Zwolinski, Z. (Hg.), Source-to-sink-fluxes in undisturbed cold environments. Cambridge University Press, Cambridge, 364-377.

Science-to-public contributions:

Rascher, E., Kellerer-Pirklbauer, A., 2018. Interview and shots by Servus TV on research in the Gesäuse. Johnsbach Valley, July 27, 2018.

Schöttl, S., Rascher, E., Sass, O., 2018. Der Langgriesgraben - Ein dynamischer Raum im Gesäuse und Gegenstand intensiver Forschung. In: Im Gseis 30, 4-7.

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Rascher, E., Rode, M., 2014. Forschung im Johnsbachtal – Forschungsprojekte im Nationalpark Gesäuse. Interview with Radio Frequenns, Nationalparkradio, Liezen, April 2, 2014.

LIST OF CONFERENCE CONTRIBUTIONS

(THESIS RELATED)

Oral presentations:

Rascher, E., Sass., O., 2017. Sedimenttransport im Johnsbachtal - Erkenntnisse zur Sedimentdynamik und zum Sediment Budget der Zwischenmäuerstrecke. 13th Annual Assembly of Austrian Research Association on Geomorphology and Environmental Change (geomorph.at), Johnsbach, September 28-29, 2017.

Rascher, E., Stangl, J., Sass, O., 2014. Comparative analysis of sediment routing in two different alpine catchments. 8th I.A.G./A.I.G. working group SEDIBUD Workshop, Zugspitze/Reintal, Bavaria/Germany, September 1-4, 2014.

Rascher, E., 2013. Interdisziplinäre Untersuchung von Sedimentströmen im Johnsbachtal (Steiermark) unter dem Blickwinkel der Renaturierung. Kickoff Meeting Sedyn-X Project, Admont, May 24, 2013.

Poster presentations:

Rascher, E., Sass, O., 2016. Constructing a Sediment Budget for the Johnsbach, Styria. Adding numbers and drawing arrows? Geophysical Research Abstracts, Vol. 18, EGU2016-13144. EGU General Assembly, Vienna, April 17-22, 2016.

Rascher, E., Sass, O., 2015. Untersuchung der Hang-Gerinne-Kopplung in einem alpinen Einzugsgebiet mittels Terrestrial Laserscanning. 41st Annual Assembly of the Arbeitskreis Geomorphologie, Berlin, October 3-4, 2015.

Rascher, E., Sass, O., 2015. Detecting surface changes of slope to channel coupling in an alpine catchment using terrestrial laser scanning. Geophysical Research Abstracts, Vol. 17, EGU2015-13037. EGU General Assembly, Vienna, April 12-17, 2015.

Rascher, E., Stangl, J., Sass, O., 2014. Temporal Comparative Analysis of Spatial Sediment Connectivity in two Different Alpine Catchments. Geophysical Research Abstracts, Vol. 16, EGU2014-5809. EGU General Assembly, Vienna, April 27 – May 2, 2014.

Rascher, E., Sass, O., 2013. Interdisciplinary sediment flux research in the Johnsbach Valley, Gesäuse, Austria – First Steps to a Sediment Budget. 39th Annual Assembly of the Arbeitskreis Geomorphologie, Eichstätt, October 7-9, 2013.

Rascher, E., Sass, O., 2013. Interdisciplinary sediment flux research in the Johnsbach Valley. Schweizerisch-Österreichische Allianz für Gebirgsforschung - Gebirgstage, Mittersill, June 11-13, 2013.

Rascher, E., Sass, O., 2013. Interdisciplinary sediment flux research in the Johnsbach Valley. 9th Annual Assembly of the Austrian Research Association on Geomorphology and Environmental Change (geomorph.at), Krems a. d. Donau, June 6-8, 2013.